Mirza Hasanuzzaman *Editor*

Climate-Resilient Agriculture, Vol 1

Crop Responses and Agroecological Perspectives

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Preface

Climate change has been identified as one of the most significant threats to biological systems. Recent climate change patterns indicate that the earth is witnessing unprecedented levels of warming. Climate change has a profound impact on agriculture, altering food production and food security. Numerous environmental stresses have been accelerated due to rapid changes in the climatic patterns that affect crop growth and productivity, as well as increase the chances of crop failure. The extreme climate conditions that are imposed on plant species result in significant physiological, biochemical, morphological, and molecular changes, which eventually hinder plant growth and yield attributes. For example, wheat yields are likely to drop by 4–6% for every degree of global temperature increase, while maize productivity is projected to decline by the end of the century in areas producing 56% of the world's maize. Moreover, increased soil erosion and nutrient loss are common phenomena caused by changes in temperature and precipitation, which have an adverse effect on soil health. As a result, it becomes harder to cultivate crops, and the productivity of global agricultural land is declining.

Climate change is projected to worsen the issue of future food security by putting more pressure on agriculture. Climate change is expected to have a considerable influence on agriculture and food security. With a growing global population and in the face of persistent and worsening climate change, it has become crucial to investigate sustainable adaptation mechanisms that can address the adverse effects of stressful environments on plants. Therefore, it is urgent to find strategies to reduce the impacts of climate change through mitigation and adaptation for improving the resilience of agriculture. Adoption of climate-resilient agriculture might be the most sustainable way to address this climate change-related agricultural loss. The goal of climate-resilient agriculture is to increase long-term agricultural yields and productivity by sustainably exploiting the natural resources already accessible through crop and livestock production systems. It reduces and/or eliminates greenhouse gas emissions while also responding to climate change and fostering resilience in the agricultural sector.

Changes in agronomic practices, the introduction of improved crop varieties, and alterations to plant physiology and biology are all examples of adaptation strategies. The introduction of genomics and other ‘omics technologies and the modulation of transcription factors in the crop breeding strategies may be some effective way to increase the environmental stress tolerance of many crops, and targeting these within traditional and new breeding technologies could be an effective strategy to produce better crops. The adaptation of agronomic management methods to climate change encompasses a wide range of activities such as soil nutrient management, tillage intensity, crop choice and rotation, water management, and agricultural diversification. Understanding plants’ physiological, cellular, and molecular mechanisms to climate change, which include significant alterations in the transcriptome, proteome, and metabolome of plants, has advanced significantly. With the rapid technological advancements, likewise in other sectors, it is now possible to overcome the detrimental effects of climate change in agriculture by the adaptation of tolerant crop varieties, sustainable agronomic practices, and improved crop physiology and biology. However, the success rate of crop breeding strategies is still slow because the issues in public perception and policy remain as limitations to the effective use of the tools like genome editing. Therefore, there still remains huge scope for crop improvement for the future adaptation to climate change for this ever-growing global population.

This is the first volume (Crop Responses and Agroecological Perspectives) of the two-volume book *Climate-Resilient Agriculture*. It contains 42 comprehensive chapters on crop responses and agroecological perspectives of crop plants under changing climates.

I would like to give special thanks to the contributors for their outstanding and timely work in producing such fine chapters. We are highly thankful to Kenneth Teng (Senior Book Editor) and Shanthini Kamaraj (Project Coordinator) Springer Nature, New York, and all other editorial staff for precious help in formatting and incorporating editorial changes in the manuscripts. We acknowledge my research students, Md. Rakib Hossain Raihan and Ayesha Siddika, Department of Agronomy, Sher-e-Bangla Agricultural University, Bangladesh, for their generous help in formatting the manuscripts. Special thanks to Dr. Rajib Roychaudhury, University of Haifa, Israel, for his valuable help during the initial proposal writing. The editors and contributing authors hope that this book will include a practical update on our knowledge of climate-resilient agriculture.

Dhaka, Bangladesh Mirza Hasanuzzaman

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Chapter 1
Global Prospects of Climate-Resilient Agriculture

Nadeem Iqbal, Malik Tahir Hayat, Adnan Ahmad Tahir, Shamim Akhtar, Nazneen Bangash, Abdul Nazeer, Aansa Rukya Saleem, and Riyazuddin Riyazuddin

Abstract Climate change is the main reason for the different abiotic and biotic stresses in agriculture, and it adversely affects crop production and yield. Fluctuating climate conditions such as rainfall, drought, and temperature can cause global changes in atmospheric carbon dioxide levels and sea level rise. These alarming global events have attracted the attention of agronomists because of the detrimental impacts of climate change on the agriculture sector and food security under increasing global food demand. Therefore, climate-resilient agriculture is the only possible and most appropriate solution to mitigate the negative impacts of climate change. Therefore, it is imperative to focus on global food production and its security under changing climatic conditions to meet the needs of the fast-growing population. To deal with climatic fluctuations, different global agricultural practices including water, land, crop, and livelihood management strategies are being adopted worldwide to improve climate-resilient agricultural crops. In addition, the modifications in the plant genetic material such as genomics (molecular plant breeding), genetic

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engineering, and other genome editing approaches are practices to develop climate-resilient transgenic crops to enhance crop productivity and yield. Moreover, conservation agriculture can also be effectively converted into sustainable agriculture through different land management practices and resource utilization. Plants also use various adaptive strategies such as physiological, biochemical, and molecular mechanisms to cope with harsh environmental conditions. However, more research is required to design and develop more climate-resilient management strategies and eco-friendly and resistant agricultural crops under changing climatic conditions.

Keywords Climate change · Sustainable agriculture · Conservation agriculture · Food security

1 Introduction

Climate change refers to the persistence of continuous changes of the Earth's climate over a prolonged period. The primary energy source of planet Earth is the sun which is absorbed in various states, and surplus energy is sent back to the space. The proportion of obtained and liberated energy from the atmosphere of the Earth is designated as the Earth's energy budget (Garrett et al. 2015; Fahad et al. 2019). There are several human activities that result in the absorption of extra energy and, hence, a warmer climate. These human activities are mainly accountable for the shifting of the Earth's energy budget towards positively enhancing climatic temperature with adverse impacts on humans, animals, and agriculture (Zhang et al. 2014; Fahad et al. 2018). The demand for agricultural production will be increased to feed the fast-growing human population. However, climate change adversely affects different forms of agriculture and causes disorders in ecosystem functioning. However, some adaptive strategies showed beneficial outcomes for some crops under moderate climatic conditions (Adnan et al. 2017; Zamin et al. 2019). Therefore, developing different crop varieties with climate resilience can provide better food sources to alleviate poverty, especially in Asia and Africa (Varshney et al. 2011). Moreover, the emission of greenhouse gases (GHGs) has significantly increased, and an average rise in annual temperature by 0.8 °C is predicted causing global warming. Surprisingly, these greenhouse gases have been released continuously worldwide for the last 25 years (Sharma and Ravindranath 2019).

In addition, climate change significantly influences all living organisms such as microbes. The rise in the levels of CO_2 in the atmosphere can have unforeseeable effects on agriculture. Increased CO_2 concentrations can enhance the net photosynthetic rate as well as plant growth, but in contrast, it can reduce the quality of crops in terms of nutrition (Irigoyen et al. 2014). Further, the concentration of CO_2 in the atmosphere before the industrial revolution was 28 ppm which has significantly increased up to 397 ppm till now. According to an estimation, this concentration will increase two times at the end of this century. Furthermore, this rise in CO_2 atmospheric level poses severe risks to plants and perturbs plant defense responses against various types of biotic and abiotic stress conditions. For instance, the attack of barley yellow dwarf virus on wheat plants has significantly increased due to the higher levels of CO_2 (Trębicki et al. 2015). Concurrently, the interplay between water deficiency and heat shock conditions also alters CO_2 assimilation, stomatal conductance, and leaf temperature resulting in disturbed photosynthetic rate and plant growth (Feller 2016). The high temperature under water-deficit conditions aggravates plant growth and productivity in many cereal crops (Ihsan et al. 2016; Zandalinas et al. 2018). Additionally, the effect of heat was studied in soybean and maize, and the results showed that the increase in seasonal temperature by 1 °C reduced the crop yield of soybean and maize by 3.1% and 7.4%, respectively (Zhao et al. 2017). In parallel, water scarcity can influence various physiological processes in plants such as pollination, flowering, and grain filling. In contrast, an elevation in humidity level can also increase pest and insect attacks (Munawar et al. 2020).

Moreover, pathogenic attacks of pests, insects, and fungal species are also predicted under changing climatic conditions based on geographical regions. Various *Fusarium* spp. adversely affect important cereal crops, causing yield reduction worldwide (Shabani et al. 2014: Iqbal et al. 2020, 2023). These fungal pathogens cause *Septoria tritici* blotch and *Fusarium* head blight in wheat in China, the UK, and Europe because of changing climate (Fones and Gurr 2015). Climate change has also compelled farmers to deploy climate-resilient agriculture approaches instead of old traditional methods. These practices include growing diverse and stress-tolerant crops, restoring soil fertility, and harvesting rainwater to enhance food security in the agriculture sector (Altieri and Nicholls 2017). Additionally, the use of modern techniques for a climate resilient agriulture can also be improved with the assistance of farm inputs, market risks, and proper checks and controls (Issaka et al. 2016). Therefore, knowledge in plant physiology and molecular mechanisms including genetics will assist scientists in the development of climate-resilient crops. Next-generation breeding is also a possible option using plant germplasm, data management skills, and biotechnological techniques (Taranto et al. 2018). Parallelly, the utilization of omics approaches, genomic editing, *cis*-genesis, and in vitro regeneration could lead to the establishment of second-generation biotechnological products required for sustainable agriculture (Cardi and Neal Stewart 2016). In addition, genome editing facilitates the development of resilient crops against changing climatic conditions through accurate and precise changes in the genome (Courtier-Orgogozo et al. 2017). It is estimated that the world population would be around nine billion by 2030. At the same time, it would be difficult to deal with changing climate for the provision of food resources. Therefore, it is necessary to develop crops that are resilient against environmental conditions. In addition, the integration of molecular plant breeding and genetic editing, as well as engineering approaches, could assist in developing climate-resilient crops.

2 Climate Change-Induced Effects on Agriculture and Food Security

The drastic effects of climate change over time have been reported in the agriculture sector. Crop productivity has been adversely affected as a result of various environmental factors including high temperature, floods, salinity, and drought. On the other side, adaptive measures can be a suitable option by reducing the susceptibility of the natural ecosystem (Klein et al. 2014). Climate change is considered the main driving force influencing agriculture production because of the industrial and urbanization developments (Wheeler and Von Braun 2013). Moreover, developing countries in Africa and Asia are facing this climate challenge seriously due to a lack of technical and financial aid. Some countries in Africa have food shortages due to water scarcity. In addition, wheat production in South Asia will be reduced by up to 50% by 2050 according to the International Water Management Institute (IWMI). It is estimated that this amount accounts for 7% of food production, resulting in food insecurity (de Fraiture et al. 2007; Munawar et al. 2020). Some studies reported that South Asia and sub-Saharan Africa are facing food shortages and are the most vulnerable regions to changing climate (Vermeulen et al. 2012; Bandara and Cai 2014). Pakistan is enlisted in those countries which have a 65% population and are facing food security problems. According to the Food and Agriculture Organization (FAO), some Asian and African countries cannot afford preventive measures to stop climate change and are unable to meet the Millennium Development Goals (MDGs) and zero hunger (FAO 2015).

The world population is rapidly increasing in an uncontrolled manner which consequently shows a fast and high demand for food supply. In addition, the high food prices and food insecurity will further worsen this scenario and cause the failure of the global food supply (Fischer et al. 2014). Therefore, 1.1–1.3% annual production of main crops is unavoidable to deal with the current challenge (Buchanan et al. 2015). The population in India will be around 1.6 billion by 2050 and will require 400 million tonnes of food. Therefore, the sustainable production of food is very crucial, utilizing the same resources and land. At the same time, the drastic effects of climate change could also affect environmental conditions for future food production. Highly water-scarce areas in Europe will face 19–35% water scarcity by 2070 along with reduced water quality and availability (Husaini and Tuteja 2013). Further, climate changes can cause increased temperature, flooding, higher CO_2 levels, more concentrations of O_3 in the troposphere, saline and sodic soils, heavy precipitations, land degradation, and waterlogged conditions, which will eventually affect agricultural crops and their productivity. Furthermore, the diversity and abundance of agricultural pests and pathogens will also be affected because of changing climatic conditions (Abberton et al. 2016).

Greenhouse gases including methane (CH_4), CO_2, nitrous oxide, hydrofluorocarbons, and sulfur hexaoxide reflect solar radiation and increase global warming. Different agricultural practices such as deforestation, grazing, and use of synthetic fertilizers have significantly increased (25%) the production of greenhouse gases.

Further, the cultivation of beneficial crops and the reduction of greenhouse gases should be practiced to mitigate climate change for food security (Wakjira 2018). The production of drought-resistant traits in the agriculture sector can reduce the effects of climate change in drought-prone areas, avoiding desertification. Another study documented that 45% of irrigation requirements will increase by 2080, and 20% of water withdrawals will increase due to the upgradation of the irrigation system (Ali et al. 2017). Parallelly, the Sustainable Development Goals (SDGs) have been introduced worldwide to eradicate poverty, malnutrition, and hunger by 2030. Interestingly, biotechnology offers a possible solution to reduce climate change by implementing various strategies such as carbon sequestration, reduction in the use of synthetic fertilizers, and energy-efficient farming (Wakjira 2018; Munawar et al. 2020). Therefore, transgenic crops can play a critical role in food production under changing climate to alleviate poverty, eradicate hunger by reducing global warming, and maintain agricultural sustainability.

3 Effect of Climate Change on Crop Yield

Climate change has adversely influenced plant physiology through various means. Environmental stresses increased the possibilities of plant stresses due to variations in climatic conditions (Thornton et al. 2014). Climate change can have negative impacts on plants through different types of exposure such as direct, indirect, and socioeconomic. Climate change such as extreme temperature, floods, storms, drought, etc. has drastically enhanced according to the FAO (Raza et al. 2019). According to a study, climate change has significantly reduced crop yield by around 70% since 1982 (Boyer 1982). It is reported that abiotic stress conditions have an adverse impact on crop productivity. This predicts that in the future, many countries will face shortages or drops in major crops because of global warming, water scarcity, and other severe environmental consequences (Tebaldi and Lobell 2018; Bonan and Doney 2018). Various differences in crop vulnerability to climate change were found in Europe depending on the national crop yields survey. Similarly, Northern Europe is facing problems such as the short duration of crop production and low temperatures. However, in Southern Europe, temperature extreme and less rainfall are limiting crop productivity. Further, adverse and severe negative impacts were reported in Hungary, Serbia, Romania, and Bulgaria (Olesen et al. 2011). It is anticipated that the Mediterranean area will have reduced crop yield while North-Western Europe could produce a high crop yield (Olesen and Bindi 2002).

Likewise, in several countries, wheat production is largely influenced by extreme temperatures that decrease crop yield by up to 6% per 1 °C rise in temperature (Asseng et al. 2015). Therefore, the high temperatures and water-deficit conditions are the main reasons for reduced crop yield (Barnabás et al. 2008). Moreover, the activity of the *Rubisco* enzyme is disrupted above 35 °C, and the photosynthesis process is negatively affected (Griffin et al. 2004).

It was reported that both extreme heat and drought could badly affect the crop yield of barley, maize, and sorghum as compared to individual stresses (Wang and Huang 2004). This effect was also confirmed when both stresses (heat and drought) were given to *Leymus chinensis* and resulted in the reduction of photosystem II (Xu and Zhou 2006). The plant reproductive processes such as flowering and inflorescence were also significantly influenced due to extreme temperature and drought events. For instance, a temperature around 30 °C can result in sterility during floral development (Raza et al. 2019). Another research studied the effects of climate change on crop yield and reported significant reductions of about 3.1%, 3.2%, 6%, and 7% in soybean, rice, wheat, and maize, respectively (Zhao et al. 2017). However, the development of climate-smart agriculture through genomic approaches has offered new possibilities to deal with changing climatic conditions (Scheben et al. 2016). Drought stress also has a bad impact on the developmental stages of the wheat crop, especially during grain formation and reproductive levels (Pradhan et al. 2012). Further, wheat crop yield was decreased to 30% during mild drought conditions and 92% during prolonged drought, affecting grain formation as well as flowering (De Oliveira et al. 2013). Furthermore, water-deficit conditions have greatly decreased legume yields. For instance, mashbean yield decreased from 57% to 31% at the time of flowering and 26% during the reproductive phase under drought conditions (Baroowa and Gogoi 2014). Similarly, a 42% reduction in soybean yield was noticed due to drought stress during the grain filling stage (Maleki et al. 2013). Hence, food security is badly affected by climate change, causing disturbance to the agrochemical environment. Climate change can directly influence crop yield, reduce income circulation, and enhance the demand for agricultural products.

4 Conservation Agriculture Under Climate Change

Previously, seeds were sown in the fields by farmers by making furrows using conventional methods like plowing with oxen. Later, the green revolution globally focused on more food production for the growing population by utilizing chemical fertilizers (Timsina 2018). Chemical fertilizers enhanced food production but on the other hand significantly affected environmental quality, e.g., soil degradation (Bhan and Behera 2014). Undoubtedly, the green revolution provided sustainable agriculture production for 50 years to eradicate poverty (Meena and Lal 2018). Climatic changes pose a global problem due to the industrial revolution, environmental pollution, deforestation, and the release of greenhouse gases (Mbow et al. 2017). The higher emissions of greenhouse gases have caused altered rainfall patterns, increased temperature, and raised sea levels resulting in the melting of glaciers (Mbow et al. 2017).

The conservation of agriculture and its management system is a complex process and includes management practices to enhance sustainable agriculture production using agronomic practices based on targeted crops and environmental conditions of the specific region. The main objective of conservation agriculture is to conserve natural resources, reduce soil erosion or degradation, and improve soil fertility without any harmful effects on crop production (Hossain et al. 2021). The environmental problems due to the cultivation of monoculture can be alleviated by crop diversification. Efficient management of different factors such as soil, landscape, crop, water, and nutrient can promote sustainable agriculture production (Bahri et al. 2019). The use of conservation agriculture has been found more effective in increasing crop productivity by 20–120%. In addition, this strategy can reduce the application of fertilizers by preventing runoff, increasing the efficacy of resource use, reducing irrigated water, producing resilient crops against pests and other diseases, and enhancing crop production (Alam et al. 2017a, b). Similarly, reduced tillage can also improve soil health by up to 30% by decreasing soil erosion and water loss in the soil (Gupta and Seth 2007; Alam et al. 2017a, b). In addition to reduced tillage, other tillage forms such as strip tillage, ridge tillage, mulch tillage, and zero tillage have been used in agricultural practices for the conservation of agriculture (Farooq and Siddique 2015). Moreover, the global prospects of agricultural crops regarding the sustainable use of land, less labor work for crop management, and provision of ecosystem services are not uniform (Hossain et al. 2021). Therefore, geographical and socioeconomic factors have a huge impact on sustainable agriculture production. In addition, government support and effective planning can increase the chances of implementation of agricultural practices to reduce the harmful impacts of climate change.

5 Global Climate-Resilient Agricultural Practices

Several agricultural practices or strategies are employed by farmers to mitigate the negative effects of climate change. These practices include modern as well as conventional approaches. The conventional strategies used in Bangladesh, India, and China require more labor (Viswanathan et al. 2012; Altieri and Nicholls 2017). In parallel, smart farming practices such as aerial vehicles (drones) for weed detection and Microsoft's Cortana Intelligence for the selection of planting dates are popular globally (López and Corrales 2017; Lottes et al. 2017). The farmers adopted these climate-resilient agricultural practices regarding water management, crop management, land management, and livelihood management (Fig. 1.1).

5.1 Water Management Practices

Water management is critically important for sustainable agriculture worldwide even under contaminated freshwater resources. Further, the management of irrigation practices such as deficit irrigation, combined use of groundwater and surface water, water reuse, desalination, and use of water harvesting techniques has played a significant role under changing climatic conditions (Viswanathan et al.

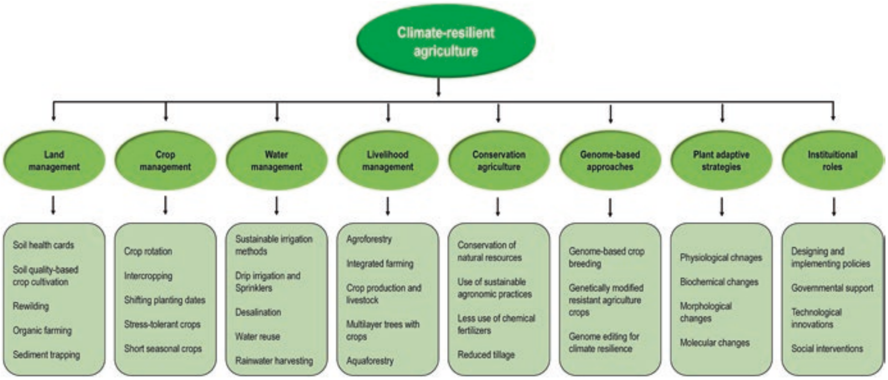

Fig. 1.1 A schematic diagram of various agricultural management strategies used for sustaining climate-resilient agriculture

2020). Therefore, irrigation is considered the most adopted strategy to enhance crops, and the selection of irrigation methods is vital to sustaining water resources (Finger et al. 2011). For instance, micro-irrigation system including sprinkler as well as drip irrigation has become popular in drought-prone areas in India (Viswanathan et al. 2016). In addition, drip irrigation proved to be of utmost significance in Israel, especially in drylands (Tal 2016). Simultaneously, the use of both drip irrigation systems and sprinklers has been adopted across all states in India to mitigate stress conditions caused by climate change (Kumar and Palanisami 2014; Bahinipati and Viswanathan 2019). Another report documented that the adoption of a micro-irrigation system saved 38% water and 58% energy (Kumar and Palanisami 2019).

Desalination is also an efficient approach to deal with water shortage in the agriculture sector (McEvoy and Wilder 2012). For example, wastewater in Vietnam was reutilized to grow rice crops and helped to reduce problems related to water scarcity (Trinh et al. 2013). However, the use of the desalination process for irrigation purposes is more expensive than traditional water bodies. In contrast, desalinated water could be beneficial for economic crops with certain subsidies. Similarly, brackish water can also be a good option in the agriculture sector as compared to marine water (Beltrán and Koo-Oshima 2006). In addition, the use of laser land leveling has also become popular as a water management strategy. Laser leveling is used to level or smoothen the soil surface which can greatly reduce irrigation time and enhance crop yield by up to 7% more than conventional methods (Aryal et al. 2015).

However, another strategy is the intensification of rice which proved to be an effective approach to manage water scarcity and increase rice yield by 25–50%. This approach along with wheat intensification is used for water management in drought-prone areas in Asia (Satyanarayana and Thiyagarajan 2007). Other studies also confirmed that these two intensification methods offer possibilities to enhance crop production with efficient outcomes (Varma

2018; Nayar et al. 2020). Additionally, the harvesting of rainwater is another old method to save water in arid areas. Some studies reported that the collected water from rain can also be used for drinking purposes under extreme water-deficit conditions (Jones and Hunt 2010; Viswanathan et al. 2020). A current report showed that rainwater harvesting and its effective use by constructing ponds or tanks can remarkably increase crop intensity. The existing watersheds can be revived to lessen climatic effects on water sources, especially in drought-affected regions, and can be used by local farmers to increase resilience under worse climate conditions (Patnaik and Das 2017; Patnaik et al. 2019).

5.2 Crop Management Practices

The management practices used for climate-resilient crops include crop rotation, short seasonal crops, different seed varieties resistant to drought conditions, intercropping with legumes, diversification of crops, shifting planting dates, and changing to new crops (Viswanathan et al. 2020). Crop rotation is the cultivation of different crops in the same land in sequence and has been found helpful in reducing different agroecological issues such as a decline in soil quality (Dury et al. 2012). Similarly, another study confirmed the efficiency of crop rotation intensification with an 84% reduction of soil losses without tillage (Deuschle et al. 2019). Moreover, the use of crop rotation of durum wheat as well as sunflower in Spain has significantly increased soil fertility (Pedraza et al. 2015). Therefore, it is essential to use suitable crops to enhance nitrogen levels and increase phytomass production, improving organic matter in the soil (Raphael et al. 2016). In addition to enhanced soil organic matter, this method has also increased carbon sequestration for the maintenance of the carbon cycle. The plantation of new crops with different planting dates also exhibited the adoptive measures in different zones excluding arid regions in Kenya (Bryan et al. 2013). Interestingly, selecting different dates for crop plantation did not affect crop yield and emerged as a practical strategy, especially in the case of wheat and rice in India (Jalota et al. 2012).

Moreover, drought- and herbicide-tolerant crops have also shown the potential to reduce climatic effects and assisted in obtaining climate-resilient crops in Africa (Neate 2013). Similarly in India, one third of rice-growing fields is susceptible to water-deficit stress, and research advancements succeeded in achieving drought-tolerant rice crops (Birthal et al. 2015). In addition, the cultivation of water deficit-tolerant varieties mitigated the stress on existing water sources. Likewise, China also abandoned the cultivation of rice crops because of severe drought and altered crop diversification with cole rice, seedlings, and cotton, as well as cereals (Lei et al. 2016). Nevertheless, a huge shift from staple food rice to other crops because of drought could threaten regional food security. Another adoptive strategy is the use and promotion of genetically engineered crops that are highly resistant to changing climatic conditions. Seeds obtained through genetic modification (GM) have several benefits in agriculture, but their food is greatly challenged (Pray et al. 2011; Saab 2016). Although no such incidents were observed in the consumption of GM food products, many policymakers, researchers, and other civil organizations are suspicious of their use (Key et al. 2008). Further, Bt cotton in India was highly opposed, which resulted in discomfort and suicide among farmers (Thomas and De Tavernier 2017).

5.3 Land Management Practices

According to the United Nations, land management is the utilization of different resources of land such as soil, animals, water, and plants to produce goods for the need of the growing population and concurrently for the maintenance of these resources for the long term to protect environmental health (Sanz et al. 2017). Issuing soil health cards, explaining the detailed description of fertilizer use, and following appropriate crop cultivation on the basis of soil quality are remarkable initiatives taken by the Indian government. In addition, rewilding, organic farming, and sediment trapping have also been identified as natural land management practices (Keesstra et al. 2018). Similarly, organic farming is also another suitable option for sustainable land management practices as compared to traditional farming methods (Andersen et al. 2015). Organic farming can improve soil quality and enhance 22% of net profits (Ramesh et al. 2010). Nonetheless, organic agriculture needs a large land area for the same food produced by other conventional methods. Moreover, this strategy provides fewer environmental benefits as well (Muller et al. 2017).

Kerala (India) has adopted the use of organic vegetables to overcome the climate change problems, which has reduced the transportation costs from other states and the use of chemical fertilizers (Department of Environment and Climate Change 2014). Conservation agriculture is beneficial and environmentally friendly and provides climate-resilient crops. The benefits of using conservation agriculture are the protection of soil cover, reduced tillage, and diversity of crop rotation (Williams et al. 2018). Similarly, another study conducted in Africa showed that the practices used for conservation agriculture including crop growing with parkland trees, green manure, intercropping, soil and water conservation through traditional methods, crop rotation, mulching, and coppicing trees exhibited higher grain yields (Bayala et al. 2012).

Rewilding is also another form of land management commonly found in Europe. This approach includes natural grazing as well as fire regimes in boreal forests and changing flood patterns. Moreover, it is passive management, assisted migration, reprovision of species in a particular area from where species were missing, and recolonization (Sandom et al. 2018). Rewilding is also involved in improving the functions of an ecosystem and supports the ecosystem for its revival. This approach is being practiced in the Netherlands, the

USA, Russia, and Mauritius Island (Lorimer et al. 2015). Besides, sediment trapping has also shown effective outcomes in reducing the adverse impacts of soil erosion and has protected soil cover (Mekonnen et al. 2014). China has also started a new program (grain for green) to lessen soil erosion near river catchments (Neate 2013).

5.4 Livelihood Management Practices

Designing agriculture management strategies against climate change is of utmost significance, especially for developing countries due to their main dependence on agriculture sector. In addition, many farm households, due to climate change, are migrating to big cities for better employment (Alam et al. 2017a, b). Similarly to the case of India, migration because of climate change is considered a survival strategy, and its purpose is to earn money for livelihood (Jha et al. 2018). Agroforestry and integrated farming also offer opportunities for livelihood management practice and are mostly found in Asia, Africa, and America (Singh and Singh 2017). It was documented that approximately 1.2 billion people earn money from agroforestry for their livelihood (FAO 2011). Further, the agroforestry discipline consists of diverse practices such as plantations, improved fallows, gardens, multilayer trees with crops, plants cultivated for soil reclamation and conservation, windbreaks, aqua forestry, and shelterbelts (Nair 1993). Therefore, these integrated approaches are adopted based on their crop production and food security because these activities have a huge potential for climate adoption (Mbow et al. 2014). A study in Vietnam showed that agroforestry has a crucial role in the provision of money, feed, food, and other eco-friendly benefits (Nguyen et al. 2013). At the same time, cocoa agroforestry is practiced in Asia in the form of a multilayer system providing fruits and timber of high quality (Simons and Leakey 2004). The integration of crop production with livelihood practices is a sustainable approach in which livestock can also be managed. It is reported that an integrated approach can support biodiversity and management of food resources using land practices, strengthening the agroecosystem under changing climatic conditions (Singh and Singh 2017).

Animal husbandry and its practice in the future will increase in urban areas for more meat and its other products (Herrero et al. 2010). Farmers are forced by climatic changes to select particular varieties of livestock and their breeds that are suitable to local climates. For example, farmers grow buffaloes, goats, sheep, and chickens for commercial use according to climatic conditions in West Africa, South Africa, and Egypt, respectively (Seo 2010). Similarly, the integration of livestock and crop farming is considered a well-constructed strategy among farmers in Asia (Singh and Singh 2017). For instance, rice-fish farming is a highly recommended practice and far better than monocropping due to resource utilization, productivity, and diversification (Ahmed and Garnett 2011). Further, this integrated farming can improve soil fertility, increase nitrogen and phosphorus levels, and decrease chemical use (fertilizers) resulting in the reduction of greenhouse gases (Giap et al. 2005).

Similarly, rice-duck farming is practiced in China, and a better rice harvest is achieved as ducks can protect the rice plants from harmful insects (Juanwen et al. 2012). Likewise, millet-buffalo integrated farming was promoted and practiced in different states of India, and many farmers obtained benefits from both livestock and crop production (Nagaraj et al. 2013).

The above literature illustrates that various management practices have been used against climate-changing conditions based on water, land, crop, and livestock; however, their success in scalability and applicability varies from region to region. Further, the development of technological interventions such as laser land leveling and salt removal from water has also assisted in achieving climate-resilient crops. However, the success of these adoptive strategies also depends upon the formulated policies, financial and institutional support from the ongoing government, and skillful assistance from the private sector.

6 The Important Part of Policymaking, Innovative Ideas, and Institutional Participation for Sustaining Climate-Resilient Agriculture

Numerous national and international organizations including the FAO are continuously addressing the problems arising from climate change worldwide by designing suitable and functional policies. Asian and African countries are badly influenced by climate change due to their whole dependency on agriculture for livelihood. In addition, the emergence of new climatic events is required to be adjusted through the decision-making process to mitigate environmental problems (Lybbert and McPeak 2012). Nevertheless, farmers are incapable to make decisions because of the lack of sufficient knowledge about farm inputs, remedial steps, and crops. Therefore, the climate change-induced global problems must be addressed by technological innovations and institutional support systems and by designing policies.

Technological interventions can promote climate-resilient agriculture without affecting the farmers and their livelihoods. Further, the development of real-time predictions about the weather can provide irrigation schedules and an exact time for fertilizers and for the selection of appropriate crops (Sidhu et al. 2011). Furthermore, different technological interventions like tensiometer, direct seedling, and laser leveling of land could be useful to improve water efficiency and other inputs at the field level. Moreover, the use of remote-sensing technology will also predict risks and assist in making decisions on investments and on the selection of proper technology (Patt et al. 2010; Trærup 2012). Additionally, social interventions have also been found beneficial in providing facilities for adaptation to changing climatic conditions. Local adaption practices are facilitated in Africa and Tanzania, and social innovations are becoming popular in small-scale communities (Rodima-Taylor 2012). In parallel, the social innovations can promote links via collective actions by the local community and add new horizons for the institutional dynamics to deal with climate change and find out sustainable solutions. Researchers have also recommended some adoption options such as climate-smart villages focusing on agricultural problems by combining institutions and technology. The aim of this approach is to find out and resolve the climate change problems locally which would assist policymakers, farmers, and investors to make prospective strategies for agriculture (Aggarwal et al. 2018). Subsequently, designing and implementing policies regarding the use of sustainable agricultural practices with institutional support and social interventions can significantly promote climate-resilient agriculture.

7 The Role of Biotechnology in Climate-Resilient Agriculture

Climate-resilient agriculture is the main focus of all researchers and other socioeconomic interventions to provide sustainable life under changing climatic conditions. Climate change adversely affects all living organisms, especially plants because we are dependent on them for food and energy. In addition, plants also play a key role in matter fixation to sustain life on Earth. Therefore, climate-resilient crops are essential and need time to prepare, and biotechnology has played a key part in the development of climate-resilient agriculture. Biotechnology provided resilience to agriculture against climate change through genomics, genetic engineering, and genome editing (Fig. 1.1; Munawar et al. 2020).

7.1 Genomics-Based Crop Breeding

Crop breeding is not a new method for the production of climate-resilient crops and has been used by farmers to grow specific and suitable crops according to environmental conditions. However, different crops including wheat, rice, soybean, and maize have been investigated under extreme temperatures (Rejeb et al. 2014). Crop breeding is a time-consuming and complex process against stressors to produce numerous crop varieties. A rise of 1 °C in temperature can reduce the crop production of maize and soybean by 7.4% and 3.1%, respectively (Zhao et al. 2017). On the other hand, weather fluctuations in the UK, China, and Europe are causing diseases in wheat crops such as *Fusarium* head blight. Interestingly, many plants showed enhanced tolerance or resistance to these diseases through plant breeding (Wang et al. 2014). The use of crop breeding helped to produce higher food production and lessen the adverse effects of climate change. In order to adapt to climatic changes, full knowledge of genetic and molecular mechanisms is required to identify climate-resilient traits in plants. Further, next-generation breeding also provides plant populations, germplasm, technological advancement, short-time breeding requirements, and superior alleles for plant breeding (Taranto et al. 2018).

Moreover, population mapping is designed to analyze the variations in traits as well as DNA polymorphisms. Appropriate and sustainable selection of genetic material is done in crops to obtain various germplasm resources for plant breeding which shows resilience to climate change. However, the precision of quantitative trait loci (QTL) as well as mapping might be affected due to the rate and frequency of recombination, size of the population, and inheritance of the specific traits (Cockram and Mackay 2018). QTL mapping is a well-known method used for plant breeding to identify variations in the hereditary material that affect the degree of countable traits (Dhingani et al. 2015). Similarly, a genome-wide association study is investigated to find marker genes based on variations in large DNA nucleotides via population mapping. In addition, the data on the phenotype of each individual is obtained from population genomics to find out the essential phenotype-genotype associations (Hayes 2013). In addition, mutation breeding has also become popular to develop novel alleles, mutant varieties, and genetic diversity in different crops. It is the mutation in the hereditary material that is very crucial from an evolutionary perspective (Munawar et al. 2020).

7.2 Genetic Modifications of Crops Against Climate Change

The field of plant biotechnology has diverse and reliable applications in living systems such as tissue culture, molecular breeding, traditional breeding, and genetic engineering. This technique provides genetic variability to select improved genes for plant development under changing climatic conditions. Plant traits such as tolerance to drought, heat stress, salinity, waterlogging, frost, and disease are of significant importance. In addition, early vigor, efficient water use, and other nutrients such as nitrogen are also promoted to lessen the adverse repercussions of climate change. These genetically modified techniques are beneficial to remove the negative effects of greenhouse gases, carbon sequestration, fertilizer use, and biofuel use (Barrows et al. 2014). Climate-resilient agronomic crops are genetically modified for adoption under changing climates to maintain crop production. For instance, golden rice was achieved through genetic engineering in the last decade through the transformation of carotenoid-related genes in the endosperm of rice (Raney and Pingali 2007). The Environmental Protection Agency in the USA recently approved maize (SmartStax) through genetic engineering containing eight-stacked cry genes. It is estimated to provide pest- and herbicide-tolerant transgenic crop Bt maize (ISAAA 2017).

7.3 Genome Editing of Agricultural Crops

The acquired knowledge from genomic-based breeding, and in vitro tissue culture, has allowed utilizing the second generation of biotechnology dependent on genome editing and *cis*-genesis. The technological advancements led to the development of novel crop products to mitigate the adverse effects of climate change for sustainable agriculture. Genome editing is performed in agricultural crops to protect them from pests, diseases, and biotic/abiotic stresses and to achieve the maximum crop production with minimum costs (Appiano et al. 2015; Courtier-Orgogozo et al. 2017). Genome editing is subcategorized as oligonucleotide-directed mutagenesis (ODM) and site-directed nucleases (SDNs). The former category is a DNA fragment (20–100 nucleotides) which is synthesized chemically and then transferred to targeted sites of plant genome through the bombardment of particles or polyethylene glycol-mediated gene transfer, but the mutation efficacy is very low (Aubert and Kesteloot 1986), while the latter are specific enzymes binding at particular places of DNA segments of 9–40 nucleotides. Further, SDNs function in situ to perform various enzymatic reactions including methylation, acetylation, deamination, and demethylation resulting in the modifications of biological activities via genome editing or specific gene silencing (Puchta 2017). Therefore, different genome-based approaches such as genomic-based plant breeding, genetic engineering, and genome editing could have a crucial part in the improvement of climate-resistant agricultural crops.

8 Recent Advancement in Climate-Resilient Agriculture

The integrated approach of plant molecular breeding, genome editing, and genetic engineering provided new ways to design and improve climate-resilient agricultural crops by utilizing whole-plant genome sequences with the help of functional genomics tools for different crops such as rice, soybean, maize, sorghum, wheat, tomatoes, oranges, and potatoes (Manavalan et al. 2009). A drought-tolerant maize crop (MON 87460) was effectively used to deal with drought conditions in the USA. Moreover, this maize variety was found adaptive and effective under water-deficit conditions and enhanced crop productivity as well. In this perspective, various projects were developed by the maize community to assist the population in Africa (Varshney et al. 2011). Interestingly, this maize crop showed a 20–50% higher yield than other varieties under drought conditions. In addition to this, salt stress tolerance was also achieved in *Arabidopsis thaliana* by overexpressing 40 transcription factors. In parallel, the maize variety showed more stomatal conductance, higher photosynthesis, enhanced chlorophyll content, and increased grain production (Nelson et al. 2009).

Rice plants also achieved drought tolerance through the identification of DEEPER ROOTING 1 (*DRO1*) locus and exhibited higher crop production and nitrogen levels because of the vertical and deeper root system (Arai-Sanoh et al. 2014). Further, Monsanto research workers have designed some bacterial proteins against cold shock (*Csps*) that can be beneficial for various plants as an adaptive strategy. Furthermore, other transgenic plants such as rice and maize with *CspB* introduction have also displayed significant crop production and development under drought conditions (Castiglioni et al. 2008). Currently, an aquaporin encoding gene (*NtAQP1*) in tobacco plants was identified which showed the potential to withstand salt stress in transgenic plants. The same gene was also found responsible for salt tolerance in GM tomato plants and improved water use efficiency (Sinclair et al. 2004). Concurrently, nitrogen fixation dependent on rhizobium was also improved via genetically modified canola. In addition, these plants revealed a higher nitrogen uptake and a lower nitrogen loss in the air resultantly leaching into the soil and through water removal. Intriguingly, biotechnology has also reduced greenhouse gas production. It was achieved through less consumption of fossil fuels, maintenance of soil carbon, and less tillage. It was estimated in 2012 that for the removal of 27 billion kg of CO_2 from the atmosphere, 11.9 million cars might have been removed from roads for 1 year (Wakjira 2018).

Carbon sequestration is the absorption of carbon-bound compounds mainly CO_2 from the atmosphere. Transgenic plants assist in carbon sequestration from the atmosphere. For instance, soybean crops resistant to herbicides in the USA as well as Argentina showed carbon sequestration of about 63.859 million tonnes of CO_2 from the atmosphere (Brimner et al. 2005). In addition, salinity is also another problem that has converted 30% of arable land to barren lands in the last 25 years and will be 50% by 2050 (Valliyodan and Nguyen 2006). In order to deal with this salination issue, GM plants have been formed to tolerate salt stress conditions, low or high temperatures, hyperosmosis, hypoxia, and other environmental pollutants (Liu et al. 2007). The recent breakthrough in technology allows scientists to study OMICS data such as transcriptomics, metabolomics, and proteomics at a subcellular level for developing climate-resilient agricultural crops. For instance, the *SNAC1* gene (NAC transcription factor) has been identified in rice against stress conditions which finally improved rice tolerance against saline and water-deficit conditions. Further, knowledge of the entire plant genome provides new opportunities to find out complex traits for grain quality, yield, disease resistance, and other stresses (Hu et al. 2006; Munawar et al. 2020). Therefore, with the advancement in technology, it is of utmost need to utilize next-generation breeding patterns to improve understanding of bioinformatics, genomics, phenomics, and transcriptomics.

9 Adaptive Strategies in Crops to Extreme Climate Changes

Global warming and extreme temperatures due to climate change are possible threats to all life forms, especially crop species (Espeland and Kettenring 2018). Both drought and heat stresses have significantly influenced the physiochemical processes in plants under field conditions (Pereira 2016). However, plants need an optimum temperature for metabolic functions and normal growth, and temperature fluctuations can adversely affect plant physiology

(Hatfield and Prueger 2015). On the other side, extreme heat events can influence grain production and yield losses, cold conditions can result in sterility, and water-deficit conditions can affect plant morphology (Barlow et al. 2015; Salehi-Lisar and Bakhshayeshan-Agdam 2016). These severe climatic changes can affect plant growth and development and induce various responses such as physiological, biochemical, morphological, and molecular changes (Zandalinas et al. 2018). However, climate change has dual effects (negative and positive) on the agriculture sector and humans as well. Moreover, plant scientists have developed stress-tolerant plants against various stresses (Singh et al. 2018). The main cereal crops such as rice, wheat, and maize are very important due to their daily need for food. Wheat is the most demanding and leading crop that is grown in large areas (Tack et al. 2015). Wheat is obtained around 38.8% of total land used for agriculture providing high protein concentrations such as 15% per gram than rice and maize which together provide 2–3% only (FAO 2017). Despite growing worldwide, its productivity is less compared to rice and maize. A significant reduction (6%) occurs in wheat yield with only a 2 °C rise in temperature (Abhinandan et al. 2018). The filling phase of grains is reduced due to the rise in temperature, and this phase is the major reason for its reduced crop productivity under changing climate (Challinor et al. 2007; Abhinandan et al. 2018). Hence, sustainable agriculture is very important in the current scenario to develop stress-tolerant crops.

10 Conclusions and Future Perspectives

Climate change is a global threat to all life forms, especially agriculture due to the dependency of all living organisms on it. Climate change has severely influenced plant growth and crop yield resulting in economic losses worldwide. Therefore, understanding plant physiology and other biochemical processes under stress conditions is of utmost significance to know about the hidden molecular mechanisms under abiotic stresses. Climatic fluctuations have adverse impacts on agriculture, and it is hard to overcome this global issue. To deal with changing climate conditions, different climate-resilient agricultural practices such as land, livelihood, water, and crop management practices must be followed and implemented to lessen the deleterious repercussions of climate change. Conservation agriculture should be promoted and adopted to sustain climate-resilient agricultural crops. In addition, institutional role and government support play a vital role in designing policies and in implementing them. Further, different biotechnology-based advancements such as genomics, genetic engineering, and genome editing approaches have also shown a huge potential to improve climate-resilient agriculture. Furthermore, a recent breakthrough in climate-resilient agriculture has provided us with better and more reliable means for sustainable crop productivity and food security under different environmental stress conditions. Moreover, different adaptive strategies in crops such as physiological, biochemical, morphological, and molecular changes enable plants to withstand changing climatic conditions. However, more scientific research work is still required to increase implementation efficiencies of different agricultural practices for climate resilience, and novel eco-friendly genetic engineering could offer appropriate and suitable solutions for climate-resilient agriculture.

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Chapter 2
Climate Change and Global Crop Production

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Abstract Climate has a substantial impact on human health, livelihood, food, and infrastructure. However, rapid shifts in climatic conditions threaten the survival of all living creatures. The current abnormalities in precipitation and temperature are leading to nonprofitable agricultural production, food insecurity, and depletion of natural genetic resources. The changing trends towards diversified diets have posed greater challenges for producers in meeting the consumers' demands, necessitating a consistent and reliable food supply. Unfortunately, the current scenario of climatic variation has made it hard to put enough food on the table. Because of flooding, droughts, and salinity stress, a large number of staple crops and their by-products get wasted. Similarly, low production of cash crops also lowers the import–export values and affects the national economy. A few preventive measures could be taken

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to address the challenges of climatic irregularities. Examples include the use of elite genotypes, changing harvest dates, sowing either late or early, and cultivating new crops rather than just the usual ones. It is compulsory to test, validate, and devise a climate-resilient cropping system. In contrast, growers must participate in different activities to determine adoption-related barriers and generate alternative options. These approaches will minimize insect pest infestation, prevent diseases, improve soil fertility, increase water use efficiency, and, above all, help in developing defense mechanisms against climate change. The yields of major crops have been declining, so efforts have been put into converting marginal lands into agricultural lands to compensate for this. However, this practice ultimately degrades the land and threatens the existence of biodiversity in both domestic and wild species. This could affect future attempts to address climate risk. Recently, efforts have been made to improve the operating system at farms by modifying the percentage of pesticide and fertilizer usage, their method of application (foliar/ground), the introduction of the sprinkler irrigation technique, and the use of certified seeds to improve both plant growth and soil fertility. By adhering to these practices, farmers are hoping to be able to deal with climatic variations in a significantly more effective manner. In addition, decision-makers establishing appropriate policies and interventions for climate-smart agricultural production approaches and methods must carefully examine the macroeconomic, social, and ecological interventions. At the same time, policies that encourage unsustainable production and aggravate environmental issues must also be abolished. Moreover, more funding for research, notably action research, is required to deal with forthcoming climate-related threats.

Keywords Abiotic stress · Climate change · Adaptation strategies · Agriculture

1 Introduction

Each passing year exacerbates the irreversible climatic shifts triggered by life-threatening global warming. This transformation does not happen abruptly; instead, it has been an ongoing process of steadily accumulating data on meteorological shifts, encompassing rainfall patterns and extreme temperatures across the planet. (Malhi et al. 2021). The last decades have witnessed notable irregularities in climatic conditions, which are supposed to be either directly or indirectly linked to the activities performed by human beings on Earth. Data have shown that after 1750,

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the percentage of greenhouse gas emission has increased to the higher levels of 150% in the case of methane (CH_4), to 20% for nitrous oxide (N_2O), and to 40% for carbon dioxide (CO_2) (Malhi et al. 2021). At the same time, since 1975, a prominent difference has been observed per decade in the average temperature on the sphere, ranging from 0.15 to 0.20 °C, which is expected to increase twofold in the coming years (Arora et al. 2005). In the agriculture sector, climate changes bring about severe calamities such as water scarcity, temperature rise beyond the threshold level, and frost and salt stress, which cause irreversible damage to plant growth, reduce the overall crop yield, and threaten food security (Malhi et al. 2020). These environmental changes also promote pest attacks and the leaching of soil nutrients, which are detrimental to crop growth (Baul and McDonald 2015). Therefore, scientists should develop climate-smart strategies to avoid the disasters resulting from climatic alterations.

2 Intensification and Diversification of Sustainable Crop Production

According to a report by the Food and Agriculture Organization (FAO), in 2021, globally, almost 828 million people were living under the poverty line and experiencing hunger (FAO 2021). To date, on planet Earth, the total population is around 7.98 billion, which is increasing every second and is predicted to exceed 9.8 billion in 2050, which will double the food consumption and demand by up to 50% (FAO 2021). To deal with this food security problem, efforts should be made to reduce the damages caused by unpredictable weather, which greatly influences traditional farming practices and lowers crop production (IPCC 2014, 2019). Another practice that negatively impacts the conservation of biodiversity and depletion of genetic resources is the conversion of agricultural lands into commercial areas, reducing the percentage of arable lands (Vignola et al. 2015; Zhong et al. 2018: Tan and Li 2019). Lately, diet plan trends have shifted towards diversification instead of simplification, placing a burden on stakeholders to meet the escalating demand for various food items. This change has led to an immediate surge in costs, posing a significant challenge. Moreover, it also jeopardizes the availability of essential resources such as fiber, bio-fuel, and animal-source protein (Garnett et al. 2013; Schiefer et al. 2016: Bryan et al. 2014; Henriksson et al. 2018; Scherer et al. 2018). Hence, to tackle this challenge, it is imperative to prioritize cultivating additional lands while avoiding excessive urbanization. Farmers should consider adopting intercropping and diverse cropping methods, while also making systematic use of available resources (Foley et al. 2011; Hochman et al. 2013; Godfray and Garnett 2014; Loos et al. 2014).

Although short-term economic efficiencies in the agriculture sector can be achieved by expanding agricultural lands, the overall ecology of our environment will be affected in the long run. Moreover, expanding agricultural lands is impossible due to the rapidly increasing human population (Pandey et al. 2001; Pretty et al. 2011;

Bommarco et al. 2013; Newbold et al. 2015). The current food crisis can only be mitigated through effective intensification rather than land expansion (Foresight 2011; Garnett et al. 2013; Lu et al. 2020). Hence, it is necessary to grow more sustainable food crops on the current agricultural lands without compromising on the needs of our future generations and ecological conditions (Lu et al. 2017; Zhong et al. 2017; Cortner et al. 2019).

Previously, chemical inputs were considered the mainstay of agricultural intensification; however, they are now recognized as harmful and unsustainable to our environment (Omer et al. 2010; Pretty et al. 2011; Bommarco et al. 2013; Zhong et al. 2018). The concept of sustainable intensification (SI) is the only viable option to address the global food security issues while conserving our global environment (Sietz et al. 2017; Smith et al. 2017; Weltin et al. 2018; Karlsson and Roos 2019). Intensification without sustainability often leads to severe ecological problems. Sustainable intensification is not just an ordinary food production system but is also a radical reconsideration of food systems not only to enhance human and animal welfare and support rural economies but also to reduce harmful environmental impacts (Agarwal et al. 2016; Adhikari et al. 2018).

3 Adaption Strategies in Agriculture Against Climate Change

It is reported that any sudden change in climatic conditions, such as excessive rainfall during the monsoon season, disturbs the whole ecosystem, damages the infrastructure of the affected area, and threatens human lives. Under such conditions, the agriculture sector suffers greatly by putting food security at risk (IPCC 2014). While modern technology has taken the forefront and resolved numerous agricultural issues, it remains unable to withstand the impact of climatic disasters (Jha and Vi’svavidyalaya 2015; Ahmad et al. 2021a, b, 2022). Globally, especially in developing countries, statistics have shown a paramount reduction in crop yields due to droughts, flooding, temperature variations, and soil erosion (Abid et al. 2019). One of the key strategies suggested is agriculture adaptation, but it cannot serve the purpose alone. A report published by the Intergovernmental Panel on Climate Change (IPCC) defines adaptation as a practice of making amendments to the natural ecosystem and developing a sophisticated mechanism in response to any inevitable climatic aberrations to reduce the fatality rate along with other destructions (IPCC 2014). Moreover, adaptation strategies can be implemented at multiple levels, including local, regional, provincial, and national levels. However, at the local level, as victims of the impacts, it can be challenging to effectively implement adaptation measures (UNFCCC 2010).

Similarly, underdeveloped nations have the most number of human beings suffering from the calamities of global warming because they lack adaptive skills (IFAD 2011). In the agriculture sector, adaptation is a critical factor because of its dependency on the ups and downs of climatic conditions. Therefore, rural residents should prioritize various agricultural interventions for climate change adaptation. These may include embracing integrated crop–livestock management, promoting sustainable forestry, and implementing rehabilitation practices for degraded pastures (OECD 2011). Therefore, it is suggested that the practical implementation of adaptation practices in agriculture will require a dynamic and detailed policy formulation at the national level, which covers solutions to all the related climate change issues (Farooqi et al. 2005; Ahmad et al. 2021c). Policymakers should focus on introducing stress-tolerant germplasm, developing stress-resistant elite cultivars, and training and educating the farming communities, and, so, before planning cultivation schemes, they should also consider adaptation measures (Schlenker and Lobell 2010). Another important factor is each farmer's socioeconomic status, which makes them choose adaption practices accordingly (Deressa 2007; Deressa et al. 2009; Bryan et al. 2013). Similarly, our farming communities do not provide updated information, extension services, financial benefits, and other required resources, which hinders practicing adaptation strategies (Fahad and Wang 2020; Hussain et al. 2020). Otherwise, by practicing these approaches, we could fight the challenge of climate change. Therefore, it is suggested that both public and private sector organizations come forward and take the responsibility for educating the local farming communities (Bryan et al. 2013; Nisar et al. 2022).

3.1 Changing Cropping Practices

A few preventative steps could be taken to address the challenges posed by the irregularities in climate. Examples include the use of elite genotypes, changing harvest dates, sowing either late or early, and cultivating different crops rather than just the usual ones. These approaches will minimize insect pest infestation, prevent diseases, improve soil fertility, increase water use efficiency, and, above all, help in developing defense mechanisms against climate change (Abid et al. 2016a, b; Ali and Erenstein 2017). Most farming communities have realized the importance of genetically engineered crop varieties conferring resistance against disease and pest attacks with improved crop yields. They have started cultivating them instead of using orthodox cultivars (Imran et al. 2018; Ullah et al. 2018; Khan et al. 2021). Previously, farmers were cultivating conventionally released cotton varieties, but, because of severe insect pest attacks, their focus has shifted toward using genetically modified *Bacillus thuringiensis* (*Bt*) cotton. Similarly, wheat growers are now using improved varieties, which show tolerance against heat stress (Abid et al. 2016a, b).

Furthermore, slight amendments in sowing and harvesting dates could play a significant role in coping with changes in climatic conditions. In addition, this is a straightforward and cost-effective strategy (Habib ur Rahman et al. 2018; Abid et al. 2019; Amir et al. 2020; Javed et al. 2020). Due to the current weather oscillations, rice-growing farmers are compelled to adjust the sowing dates of rice according to the rainfall patterns and temperature extremes (Khan et al. 2020). Similarly, studies report that the earlier sowing of sunflowers up to 21 days could reduce the chances of crop production losses caused by climatic variations (Awais et al. 2018). Crop diversification is another important phenomenon to lessen the crop production losses caused by the severity of temperature (Bakhsh and Kamran 2019; Bhatti et al. 2019; Ahmad and Afzal 2020; Shah et al. 2020). At the same time, the intercropping technique is gaining popularity among the farming communities due to its outstanding output in terms of soil fertility enhancement and efficient water use (Shah et al. 2019).

3.2 Changing Farm Management Techniques

Recently, attempts have been made to improve the operating system at farms by modifying the percentage of pesticide and fertilizer usage, their method of application (foliar/ground), the introduction of the sprinkler irrigation technique, and the use of certified seeds to improve both plant growth and soil fertility. With the help of these practices, farmers are hoping to deal with climatic variations in a much better way (Amin et al. 2018; Khalid et al. 2020; Ali and Rose 2021; Shahid et al. 2021). Studies have shown that following the careful use of pesticides and irrigation practices, needful results have been obtained (Salman et al. 2018; Nasir et al. 2020). In the water scarcity scenario, farmers are reported to use smart irrigation practices at the crop sowing time to save water and reduce the effects of temperature fluctuations (Ashraf et al. 2021; Shahid et al. 2021). Similarly, in some cases where rainfall is less than normal, farmers are putting their efforts into proficiently utilizing the available water resources. Moreover, the introduction of advanced irrigation systems such as the "sprinkler irrigation system" has paved the way for farmers to practice adaptation strategies in agriculture (Abid et al. 2016a, b).

3.3 Advanced Land Use Management Measures

The negative effects of climatic variability on crops can be better addressed with effective advanced land use management approaches. A majority of the farmers have adopted the practice of tree plantation to cope with the ill effects of winds, floods, and elevated temperatures (Qazlbash et al. 2021).

However, this practice is not highly common in commercial agricultural farms where farmers anticipate that tree plantation will cause a decline in crop yields (Shah et al. 2019). Moreover, for preserving soil nutrition, most farmers also use organic manure as an adaption strategy to mitigate soil fertility issues. Crops are preserved from harsh weather conditions using different water conservation techniques (Bacha et al. 2018; Sardar et al. 2021). Farmers store water using rainwater harvesting and later use this water to irrigate crops during severe drought (Ali et al. 2020). Similarly, rain water in hilly areas is captured by constructing large dams around the crop fields. The collected rain water later infiltrates the soil and keeps the soil moist to help grow the succeeding crops (Qazlbash et al. 2021).

4 Removing Barriers and Creating a Suitable Environment

Initiatives to enhance sustainable crop productivity usually involves long-term incentives for developing climate change adaption strategies and alleviating various impediments that producers may encounter when embracing climate-smart crop production methods and technologies (Tankha 2020). Automated mitigation strategies might become maladaptive if they do not consider forthcoming environmental conditions and are not guided by previous experiences. For instance, agricultural production using farmland is crucial to human well-being and subsistence. There are merely a few perennial plants that have been tamed, developed, and maintained to supply sufficient food to the entire planet's population. Among the food crops, grains, rice, millets, and soybeans collectively account for two-thirds of all the calories consumed by people. To compensate for the yield declines of major crops, efforts have been taken to convert marginal lands into agricultural lands, which ultimately degrades lands and also threatens the survival of biodiversity in both domestic and wild species. This could affect future attempts to address climate risk (Richard et al. 2022).

It is more convenient to make the changeover to climate-smart farming systems when it is market-driven and intricately intertwined with marketplaces. For crops that play an important role in different crop rotation strategies, local, regional, national, and worldwide markets must be established as components of mitigation and adaptation initiatives. Advancements in market mechanisms, modifications to the infrastructural facilities (roadways, water systems, bulking, computation, warehouses, information and communication systems required to ease access to markets), and investment opportunities in rural areas are all necessary for achieving success in this sector (Raile et al. 2021). Besides technological improvements in infrastructure, the discharge, proliferation, dissemination, allocation, quality assurance, and commercialization of crop seeds are all regulated by laws, regulations, and end users' demands that are essential for the cultivation of climate-smart crops. These laws and policies, which control the growth of crop varieties on national and, increasingly, regional scales, create the crucially necessary conditions for timely access by farmers to the best crop types' seeds and planting supplies, at prices they can afford (Barbon et al. 2022). The potential to fulfill a nation's nutritional requirements in the current scenario of changing weather patterns is offered by climate-smart agriculture (CSA). Environmental issues need to be adequately resolved by the triple-win impact of CSA, which comprises (i) mitigation, (ii) adaptation, and (iii) enhanced productivity. The Sustainable Development Goals are better achieved with these initiatives and aim at enhancing crop production by adapting to climate change harshness (Raile et al. 2021; Waaswa et al. 2021).

Decision-makers establishing appropriate policies and interventions for climate-smart agricultural production approaches and methods must carefully examine the macroeconomic, social, and ecological interventions. However, the implementation of such techniques and initiatives is reliant on investment. At the same time, policies that encourage unsustainable production and aggravate environmental issues must also be abolished (Barbon et al. 2022). Policies on providing market-based incentives, i.e., tax relief, must be reformed to encourage traders and processors to support climate-smart and sustainable agricultural production. In addition, the stakeholders have proposed the creation of a national CSA fund to be made available for the farming communities, which plans to start taking notable local CSA actions. It enables producers to prosper from policies with high initial costs but are economically and environmentally desirable in the long run. Substantial work must encourage the mainstream execution of land acquisition principles while emphasizing regions that require improvement (Ogunyiola et al. 2022).

5 Integrated Research Priorities

More funding for research, notably action research, is required to deal with future climate-related threats. Climate-smart agriculture (CSA) refers to specific cutting-edge agricultural practices and cultivation methods. Such agroforestry systems and water-saving cropping patterns address three crucial twenty-first century issues: ensuring nutrient stability, combating climate change, and ensuring food security (Ogunyiola et al. 2022).

Food products, primarily millets, wheat, and paddy, along with legumes like peanuts and soya, have been the main focus of the most recent research and agricultural modeling studies. Furthermore, extending cropland and incorporating certain less economical biennial and perennial species into intercrops will be essential for safeguarding agroecosystems' sustainability under various climatic conditions (Richard et al. 2022). The scope of crop research should be expanded so that new edible crop species can be added to crop rotation strategies to enhance the climate adaption options for the farming communities. For example, in India, drip irrigation (DI) is quite renowned among farmers, administrators, and policymakers because of its potential to address water and energy shortfalls. However, the primary irrigation mode in India is flood irrigation, and DI has not achieved as much success as expected (Tankha 2020).

Similarly, the theoretical hindrance imposed by traditional breeding programs has been successfully overcome through genetically modified (GM) plants, which exhibits better agronomic, yield, and disease-resistant characteristics. Genetic modification, which provides numerous benefits compared to traditional breeding techniques, primarily entails the implantation or removal of a genome or a gene sequence in a specific plant by employing different biotechnological approaches (Rai 2022). Preserving a diverse array of wild plant genes, traditional landraces, rare animal breeds, and superior offspring of cultivated plants is of utmost importance. Establishing a genetic bank allows for their utilization in creating innovative traits that result in new and appealing plant varieties. Additionally, this initiative fosters commercially viable perennial grains that exhibit resilience to challenges such as drought, storm surges, high salt content, pest infestations, and diseases (Richard et al. 2022).

One of the research goals of climate-smart agricultural systems is to investigate the methods for adjusting crop practices and technologies to site-specific requirements and conditions. Simple assessments of a crop's applicability to and appropriateness at a certain location for a set of circumstances frequently fail to recognize the proper application of numerous climate-smart innovative strategies there. Before recommending any intervention, in-depth research must be conducted to determine the barriers preventing producers from adopting a multi-cropping, climate-smart system. A cropping system that is climate-resilient must be tested, validated, and developed, including seeding and harvesting dates, crop sequencing, and seeding rates. In contrast, growers must participate in different activities to determine the adoption-related barriers and generate alternative options (Waaswa et al. 2021).

Conversely, research institutes relating to agriculture, soil, and water are frequently organized into independent units, each with different objectives. The integrated and effective management of soil, crops, nutrients, and water is greatly hampered due to these fragmented research activities. These will also impede the adoption of climate-smart agricultural techniques. Moreover, integrated research activities also pave the way for producing certain beneficial public entities (Challinor et al. 2022). Research outcomes must be communicated in an eco-friendly manner. A clear "take-home message" and necessary instrumentation must be delivered to policymakers from scientific researchers and development practitioners to prioritize potential strategies and policies. It is advised to use a novel agricultural strategy to encourage farmers to adopt research and make sure that research priorities are determined by experiences at the ground level (Martinez-Baron et al. 2018).

6 Capacity Development for Climate-Smart Crop Production

In relation to climate change associated with anthropogenic climate instability, strategies like CSA aim to assist and reconfigure farming programs to ensure food and nutrition security (Martinez-Baron et al. 2018). Reinforcing the scientific and technological capabilities across many stages, along with the organizational level, in different manners, which creates a supportive environment for modification, is essential for devising and implementing locally customized and effective global climate mitigation and adaption methodologies. The corporate market, notably microenterprises, medium-sized businesses, producers, input suppliers, institutional scholars, and policymakers, belong to the major stakeholder groups. To increase the capabilities of extension agents, farmers, agricultural entrepreneurs, and policymakers, regular updates and upgrades are needed. Upgrading institutional and legal capabilities, especially institutional frameworks, is required under this act (Ogunyiola et al. 2022). The long-term viability of modified agricultural production techniques and the dissemination of information about climate change are crucial, particularly to farmers. Efficiently allocate available resources and mobilize additional ones while formulating strategies to tackle the constraints affecting agricultural systems. Make strategic investments in both climate change mitigation and adaptation measures (Salisu 2022). Diverse and demand-driven extension services are crucial in this regard for empowering the agricultural community to make the necessary changes for the successful production of climate-smart crops. They also assist in reducing the expected anxiety related to changing to a new system and new ways of conducting business. For instance, agricultural education programs, which offer regional forums for cooperation between producers, experts, and investigators, can help build regionally specific plans for coping with climate change. However, these extension services have not proven to be effective in some world areas. Instructions that were previously delivered through traditional means have now been replaced by direct guidance from various organizations, including governmental agencies, farming associations, and funding agencies. This information is disseminated through smartphones, the internet, radio, and other media channels. As a result, private businesses providing agricultural inputs have assumed a more prominent role in society. Numerous growers, especially women farmers, thus fail to obtain development assistance from these extension services. Considering that women farmers play a substantial role in generating food in many regions, it is crucial to examine their capacity development and other requirements (Waaswa et al. 2021).

The implementation of climate-smart food processing methods can also be enhanced by the support of the private sector, which plays a significant role in the manufacturing, delivery, and commercialization of the agricultural machinery. The scarcity of locally produced farm equipment and the unavailability of localized repair and maintenance services are significant barriers to sustainable industrialization and cause difficulties in farming production in most emerging economies (Challinor et al. 2022).

7 Use of Advanced Technology for Enhancing Crop Production in the Changing Climatic Scenario

The current global variations greatly influence agriculture and food security in the environment. The changing weather conditions severely threaten food safety and security. However, reasonable efforts have still not been deployed to cope with this global issue. Thus, various field-oriented approaches are recommended for crops to avoid environmental harshness and survive in the current era of climate change (Raza et al. 2019).

7.1 Biotechnology in Agriculture

Plants undergo various drastic biotic and abiotic stresses during their complete life cycle, which result in severe problems of food insecurity, disturb the natural ecosystem, and impact plants' geographical distribution. It is reported that 40% of water-deficit conditions can reduce the yield of maize and wheat to 40% and 21%, respectively (Daryanto et al. 2016). Overall, abiotic stresses strongly and negatively affect plants' physiological and biochemical mechanisms. Heat stress affects the rate of seed germination, photosynthetic activity, and leads to reduced crop production (Kumar 2013). Similarly, drought and salt stress affect the stomata's closing and interrupt plants' ion concentration and nutrition level (Hu et al. 2007: Younis et al. 2017). However, plants must develop genetic manipulation to increase their tolerance level against stresses (Francini and Sebastiani 2019).

Around the world, agricultural biotechnology has more comprehensive applications in improving plant architecture and quality traits, thus conferring disease and pathogen resistance for enhanced crop production with improved food security. Recently, omics-based approaches have been used to positively exploit genomic information to enhance and improve various crops (Stinchcombe and Hoekstra 2008). In population genetics, numerous traits have been studied using molecular markers across multiple environments to study variations and gene functions (Bevan and Waugh 2007; Keurentjes et al. 2008; Hina et al. 2020; Mahmoud et al. 2021). Nowadays, it has become easy to identify phenotypic variations under multiple environmental conditions with the help of transcriptomic analysis and genetic mapping (Des Marais et al. 2013). Genome mapping is considered one of the best tools to investigate the molecular mechanism conferring abiotic resistance in crops and the evolution of climate-resilient crops with higher yield and biomass production and to enhance quality traits (Roy et al. 2011; Jiang 2013; Kiriga et al. 2016; Leon et al. 2016).

The commencement of high-throughput phenotyping and sequencing approaches is a step forward to cope with the detrimental effects of crop yield losses by understanding and manipulating the mechanism of multiple stress. Marker-assisted selection breeding (MASB) is a valuable tool for the dissection of polygenic and complex traits such as crop yield and biotic and abiotic resistance using DNA markers (Da Silva Dias 2015; Devi et al. 2017; Wani et al. 2018). A wide range of molecular markers are available, which can help identify and differentiate stress-tolerant lines from susceptible ones (Jain 2001; Dogan et al. 2012; Bhutta and Amjad 2015; Saleh 2016). So far, molecular-assisted breeding has been used for developing drought- and salinity-tolerant crop varieties such as *Brassica* (Zhang et al. 2014), maize (Tollefson 2011), *Arabidopsis* (Nakashima et al. 2009), and rice (Fukao and Xiong 2013). In wheat, randomly amplified polymorphic DNA (RAPD) markers were used to identify resistant genotypes against drought stress (Rashed et al. 2010). In rice, two simple sequence repeat (SSR) markers, viz., RM3735 and RM3586, were used to express heat tolerance (Foolad 2005; Zhang et al. 2009; Barakat et al. 2011).

7.1.1 Stress Tolerance via Quantitative Trait Locus Mapping

With the help of quantitative trait locus (QTL) mapping and genome-wide association studies (GWASs), screening and selecting elite cultivars with better adaptability is possible even under abiotic stresses (Collins et al. 2008; Kole et al. 2015).

High-density bin markers and high-throughput sequencing techniques are considered adequate for improving QTL mapping accuracy (Araus and Cairns 2014). Understanding the genetic mechanism underlying complex traits is crucial for developing a strong association between genotypic and phenotypic data (Pikkuhookana and Sillanpää 2014; Zhang et al. 2019; Hina et al. 2020). A wheat variety (Ripper) was developed with the help of QTL mapping, conferring drought resistance with increased grain yield and improved quality (Haley et al. 2007). Elite maize germplasm had a higher yield and drought resistance (Badu-Apraku and Yallou 2009). Similarly, marker-assisted studies were conducted to incorporate drought tolerance in both durum (*Triticum turgidum* L.) and bread wheat (*Triticum aestivum* L.) (Merchuk-Ovnat et al. 2016).

In barley, two double haploid populations, who respond differently under stress conditions, were selected for mapping malt characters. The results proved that marker-assisted selection could be helpful in the improvement of the studied character (Kochevenko et al. 2018). Similarly, a study was conducted to elucidate the gene function linked to grain productivity by studying the physiological response and epistatic mechanism of the identified QTLs, and three major QTLs (*qDTY3.1*, *qDTY6.1*, and *qDTY6.2*) were reported to be linked to increased numbers of grains (Dixit et al., 2017). In wheat, recombinant inbred lines (RILs) were mapped under different abiotic stresses such as drought, flooding, heat, and combined drought and heat conditions. For grain yield, the total phenotypic variation was 19.6%, which was a success in screening elite wheat under stress conditions (Tahmasebi et al. 2016). Three key points in the bread wheat genome (2B, 7D, and 7B) were resistant under severe temperature conditions (Scheben et al. 2016).

7.1.2 Stress Tolerance via Genome-Wide Association Studies

Genome-wide association studies (GWASs) have been extensively used in plants to investigate any target trait and its underlying allelic variation (Manolio 2010). The success of a GWAS is based on a few important factors such as sample size, nature of the question, software tools, design of the GWAS (family- and population-based), statistics modules, and interpretation of the results (Bush and Moore 2012; Uffelmann et al. 2021). Recently, GWASs have been used for the complete understanding of the genetic mechanism responsible for incorporating drought, salt, and flooding stress tolerance in many crops (Kan et al. 2015; Lafarge et al. 2017; Thoen et al. 2017; Wan et al. 2017; Mousavi-Derazmahalleh et al. 2018; Chen et al. 2020; Liu et al. 2020). In soybean, GWASs have been performed to identify the single nucleotide polymorphisms (SNPs) associated with seed flooding tolerance-related traits (germination rate, electrical conductivity, normal seedling rate, shoot and root lengths) across multiple environments (Yu et al. 2019; Zhang et al. 2019). In *Arabidopsis thaliana*, reverse genetics techniques were applied in GWASs to study both proline accumulation under drought conditions at identified specific genomic regions and the underlying the molecular mechanism of the proline accumulation with the help of SNP linkage (Verslues et al. 2014). Similarly, *Aegilops tauschii* possesses multiple genes that regulate the species' abiotic stress resistance (Ashraf 2009). Two different models of GWASs (mixed linear model (MLM) and general linear model (GLM)) were used in this experiment. The germplasm consisting of 373 varieties of different origins was tested using 7185 SNPs to find an association with the phenotype for 13 drought stress-regulating traits (Qin et al. 2016). In another study on *Sorghum bicolor*, 30 and 12 SNPs were reported to be linked to cold stress-related features such as carbohydrate metabolism, expression of anthocyanin, and heat stress-related traits at the seedling stage (Chopra et al. 2017). Similarly, Chen et al. (2017) identified traits associated with heat tolerance at the vegetative growth stage. Their study results showed that 5 SNPs were linked to leaf blotching and 9 to leaf firing, whereas 14 genes were reported to express a response against abiotic stresses (Chen et al. 2017).

7.1.3 Stress Tolerance via Genetic Engineering

DNA recombinant technology is the predominant strategy to manipulate genetic information for crop improvement. The widespread and significant use of biotechnology has been reported to cope with both biotic and abiotic stresses. Studies have shown that numerous transcription factors (TFs) could play a role in developing defense mechanisms against stress resistance in multiple bioengineered crops. These genetically engineered crops depicted a high level of stress resistance when compared with that of controls (Reynolds et al. 2015; Shah et al. 2016; Nejat and Mantri 2017). Plant-specific transcription factors such as the APETALA2/ethylene-responsive element binding protein (AP2/ERFBP) family possess metabolic pathways that generate responses to biotic and abiotic stresses (Riechmann and Meyerowitz 1998: Licausi et al. 2010). The TF family, viz., AP2/ERFBP, is further subdivided into four categories (AP2, dehydration responsive element binding (DREB), ethylene responsive factor (ERF), and related to ABI3/VP1 (RAV)) according to their numbers and affinities. Among them, both ERF and DREB have been reported to play a vital role in regulating drought and cold stress responses in various crops such as maize, barley, soybean, rice, tomato, and *Arabidopsis* (Stockinger et al. 1997; Agarwal et al. 2006; Sharoni et al. 2010; Mizoi et al. 2012). In *Arabidopsis* and rice, DREB1 has been reported to regulate cold stress, whereas DREB2 plays a key role in developing a coping mechanism for drought, extreme temperature, and salt stress (Liu et al. 1998; Sakuma et al. 2002). A study reported the overexpression of DREB1 in genetically engineered *Arabidopsis* plants in improving the tolerance toward chilling, water deficit, and salinity stresses (Gilmour et al. 1998; Jaglo-Ottosen et al. 1998). In addition, DREB1 has also been reported to induce resistance against cold and other stresses in rice, wheat, rye, maize, tobacco, tomato, and rapeseed (Jaglo et al. 2001; Dubouzet et al. 2003; Kasuga et al. 2004; Qin et al. 2004). Another subfamily, ERF, has been reported to regulate the resistance against extreme temperature in plants (Hao et al. 1998; Xu et al. 2008; Dietz et al. 2010). A few ERF TFs are also involved in regulating biosynthetic pathways, which enables them to confer resistance against various biotic and abiotic stresses (Liang et al. 2008). Transgenic rice was developed by overexpressing the *OsDREB2A* gene with better salinity and drought resistance (Mallikarjuna et al. 2011). In another study, the *TaPIE1* gene was introduced into developing transgenic wheat, having resistance against freezing stress and pathogen attacks (Zhu et al. 2014). One of the most important transcription factors, the MYB (myeloblastosis) oncogene family, is widely present in plants and has been reported to regulate various physiological, hormonal, and biochemical biosynthetic pathways and to play a significant role in developing stress tolerance mechanisms in plants (Ambawat et al. 2013; Baldoni et al. 2015; Li et al. 2015). Among the MYB family, a few members, viz., *AtMYB44*, *AtMYB60*, and *AtMYB61*, have been reported to intensify drought resistance in bioengineered *Arabidopsis* through stomatal movement regulation (Cominelli et al. 2005; Jung et al. 2008). In 2009, Seo and his co-workers (2009, 2011) conducted a study in *Arabidopsis* to express the *AtMYB96* gene either by regulating the metabolic pathway of wax or with the help of the ABA signal transduction pathway. In another study, transgenic rice was developed with improved chilling, drought, and salinity resistance by overexpressing the expression of the *OsMYB2* gene (Yang et al. 2012).

Similarly, scientists overexpressed the *TaPIMP1* gene in wheat to build extraordinary drought and pathogen (*Bipolaris sorokiniana*) tolerance with the help of microarray analysis (Zhang et al. 2012). WRKY is one of the large transcription factor families in plants and is considered necessary for stress resistance (Muthamilarasan et al. 2015; Phukan et al. 2016). In rice, the WRKY gene *OsWRKY11* was overexpressed to enhance heat and drought tolerance (Wu et al. 2009). Similarly, Niu et al. (2012) conducted studies to overexpress the function of the *TaWRKY19* gene to generate drought, salinity, and frost stress resistance. In *Arabidopsis*, two genes, viz., *TaWRKY33* and *TaWRKY1*, were incorporated to induce tolerance against heat and water scarcity. These two genes were separated from wheat (He et al. 2016). Another important transcription factor family is the NAC (NAM, ATAF1/2, and CUC2), which is considered significantly important in various biological processes, viz., cell division, flower development, and regulation of plant responses toward different stresses (Nuruzzaman et al. 2013; Banerjee and Roychoudhury 2015). So far, various NAC transcription factors have been reported in many plants, for instance, 151 in rice, 117 in *Arabidopsis*, 152 in maize, and 152 in soybean (Nuruzzaman et al. 2010; Le et al. 2011; Shiriga et al. 2014). In addition, few NAC TFs have shown a direct correlation with stress tolerance; for example, 31 and 40 NAC genes were identified in *Arabidopsis* and rice to combat salinity and drought tolerance, respectively (Jiang and Deyholos 2006: Fang et al. 2008). Similarly, the *SbSNAC1* gene isolated from sorghum was overexpressed in bioengineered *Arabidopsis* to develop resistance against drought (Lu et al. 2013).

7.1.4 Stress Tolerance via Genome Editing Strategies

Although conventional breeding strategies have been used to develop stress tolerance in many crop varieties, due to the detrimental effects of abiotic and biotic stresses, many crops suffer from depletion of genetic resources (Flint-Garcia 2013; Abdelrahman et al. 2017; Abdelrahman et al. 2018a, b). Therefore, more efficient and precise techniques should be practiced for manipulating crop genomes to fight the challenges of drought and salinity along with improved yield (Driedonks et al. 2016; Taranto et al. 2018). Recently, revolutionary gene editing techniques have simplified the process of crop improvement by manipulating the genome sequence through the use of target-specific nucleases (Lu and Zhu 2017; Zong et al. 2017). This advancement offers many novel genetic resources and opportunities for discovering and improving desirable traits and has proved to be remarkable in developing climate-resilient crops (Liu et al. 2013; Dalla Costa et al. 2017; Kamburova et al. 2007; Klap et al. 2017).

In past decades, genome editing has become challenging and has shaken crop improvement strategies. Among them, zinc-finger nucleases (ZFNs) were the first discovered genome editing tools used to generate double-strand breaks (DSBs) at targeted genome sites in many organisms (Lloyd et al. 2005; Beumer et al. 2008; Doyon et al. 2008). In *Arabidopsis*, an endogenous gene, *ABA-INSENSITIVE4*, was inactivated using ZFN, which resulted in the generation of homozygous mutants exhibiting ABA insensitivity. Later, transcription activator-like effector nucleases (TALENs) were added to genome editing techniques that depend on bacterial TALENs (Zhu et al. 2017). However, both complexity and high costs are the main factors restricting the application of ZFNs and TALENs from developing climate-smart crops (Gupta et al. 2019; Razzaq et al. 2022).

After the discovery of clustered regularly interspersed short palindromic repeat (CRISPR)/CRISPR-associated protein 9 (Cas9), these limitations were addressed. They could be used to effectively and precisely develop biotic and abiotic stress-resistant crops. So far, CRISPR has been used to cope with biotic stresses such as diseases and fungal attacks compared to solving the problem of abiotic stresses in multiple crops such as cotton, rice, maize, and wheat (Miao et al. 2013; Char et al. 2017; Gao et al. 2017; Wang et al. 2018). However, in tomato, the "sensitivity gene," viz., *agamous-like 6* (*SlAGL6*), was targeted using the CRISPR/Cas9 system to achieve heat tolerance along with better fruit set under stress conditions (Klap et al. 2017). CRISPR/Cas9 exhibits the required potential and accuracy to rapidly release stress-tolerant crop varieties by focusing on and targeting numerous sensitivity genes in novel and high-yielding sensitive cultivars (Abdelrahman et al. 2018a, b; Zafar et al. 2020).

7.2 Crop Simulation Modeling Applications in Climate Change Research

The potential of crop cultivars in new agronomic areas can be explored with crop simulation models before conducting any time-consuming and expensive field experimentation. Costly and lengthy modeling and agronomic field trials with many experimental treatments can be easily pre-evaluated in a short time using a laptop or a desktop computer (Steduto et al. 2009). These crop simulation models provide valuable information regarding the impact of climatic variations and management practices on the production of alternative crops. This will lead to adding more crops to the cropping systems, thus making our agroecosystem more sustainable (Amanullah et al. 2007; Xiong et al. 2014; Kadiyala et al. 2015). These models provide a better and more affordable approach to exploring how cropland management factors influence agricultural output and the ecosystem (Choruma et al. 2019) and also highlight the optimal management practices for achieving cost-effective crop yields (Yadav et al. 2012).

Crop simulation models can also be used as a support system in making wise decisions regarding assessing the risk and cost-effectiveness of crop and land management strategies in agriculture. Moreover, Zhao et al. (2016) assert that if the simulation models are evaluated using accurately reported field data, then they can offer such conclusions that are sufficiently reliable for formulating sustainable farmland management strategies. Farm management practices, such as irrigation and fertilizer applications, have been refined using these crop simulation models (Khan and Walker 2015). Moreover, these models have also been utilized to test the effectiveness of alternative crop management practices under changing climatic scenarios (Choruma et al. 2019). The development and maintenance of global food security rely heavily on these crop simulation models. They are crucial for economic forecasts, although each system involves modules designed for specific crop cultivation, which usually incorporate knowledge of agronomic and physiological parameters of that particular crop obtained from many years of laboratory and field research (Asseng et al. 2014). The primary food crops include cereals, porridge, corn, and lentils, while also encompassing profitable cash crops like sugarcane, black tea, and cacao beans. These are predicted to be adversely impacted by environmental issues ranging from mild to low (≤3 °C) thresholds of warming (Ramirez-Villegas et al. 2015) if no integration measures are implemented (Challinor et al. 2014; Porter et al. 2014a, b). Findings from regional and local investigations and worldwide meta-analyses of simulation models have demonstrated that adaptation strategies are crucial for limiting any negative outcomes of climate change and effectively capitalizing on any beneficial impacts that might occur (Challinor et al. 2014). Most likely, adaptation measures are the only way to maintain or improve food supply and sustainability to meet the rising demand for food production. According to the latest estimations based on climate models, even moderate adaptations at the farm level might lead to average yield gains of ~7% (Challinor et al. 2014; Porter et al. 2014a, b). This indicates that there might be considerable potential to enhance crop yields if agricultural techniques are modified using these crop models (Ramirez-Villegas et al. 2015).

Through simulated water and nutrient constraints to plant growth, models like APSIM (Agricultural Production System Simulator) or DSSAT (Decision Support System for Agro Technology), based on ecological principles, mimic crop growth and development as a function of soil qualities, meteorological conditions, and management techniques. The APSIM model, which is based on plant, soil, and management modules, typically includes a number of significant crops, trees, pastures, woodlands, and grasslands as well as soil processes like N and P conversion, water balance, erosion, and soil pH. It also typically includes a wide variety of controlled management techniques. APSIM was created in response to a need for solutions that could solve long-term management issues while providing exact projections of crop output in response to the environment, genotype, soil, and management characteristics. Specific high-order processes, such as soil water balance and crop production, serve as modules in the APSIM model. They are related to each other only through a centralized control unit (Schulze and Durand 2016). APSIM has been globally utilized to introduce initiatives to improve agricultural methods under various management systems (Whitbread et al. 2010).

The DSSAT agricultural system model is similar, in that it incorporates functions for genetic, phenological, physiological, and management-based growth and yield. Extremes are possible since the model employs a daily time step. Daily rainfall, maximum and lowest temperatures, and solar radiation all serve as climatic variables, and these are utilized to estimate possible reference evaporation and CO_2 transpiration feedback. These are the main input factors whose variations are expected to fluctuate as the climate changes. Both DSSAT and APSIM models have been utilized to analyze and assess the agronomic potential of various systems, comparing simulated produce of crops grown under varying tillage-based practices and management at specific sites in diverse edaphic and climatic circumstances.

7.3 Statistical Models for Predicting and Enhancing Crop Yields

The effects of climate change on crop plants are being investigated using a variety of statistical crop models (Lobell et al. 2006; Almaraz et al. 2008; Iglesias et al. 2010; Kristensen et al. 2011). To evaluate the dependence of crop output on these significant quickly changing climatic variables, these models typically integrate the quadratic and linear effects of temperature, precipitation, and radiation (Olesen and Bindi 2002).

Regression models are usually utilized to assess the effect of harsh weather conditions on crop production and the probability of distribution of these climatic variables (Song 2016). Functional production models commonly use time series or cross-sectional data to determine the impact of labor, fertilization, rainfall, and temperature on crop yields. Crop yields under changing climatic conditions and the marginal implications of these environmental variables can be precisely quantified using these regression analysis models. Statistical models usually have lower data requirements and are easy to implement compared to some economic or agronomic process-based models (Ward et al. 2014). For example, a basic statistical model only needs data regarding weather and historical yield parameters.

Furthermore, statistical models provide accurate and transparent results compared to the rest. However, the effectiveness of a statistical model is greatly hampered if it does not include the data of the necessary environmental predictors (Lobell and Burke 2010).

Process-based models are occasionally substituted by statistical models, which use previous agricultural output and climate data to validate simplified regression analysis. There are three basic categories of statistical data analysis approaches presented in the literature: those based merely on time series data from a particular point or region (time series methods), those based on both time and space variations (panel strategies), and those based only on space variables (cross-sectional methods). The advantage of using a time series model is that it can also capture the behavior related to a given area. However, cross-sectional and panel methods consider common parameter values for all locations. Moreover, the chances of errors in cross-sectional methods are more because these models omit certain soil and fertilizer input variables that change drastically from area to area (Lobell and Burke 2009).

Transparent assessment and limited reliance on field calibration data are the prime characters of statistical models and the main reason for their success. For instance, if a model does a below-par job of demonstrating crop yield responses to changing climate, this will be visible in a low coefficient of determination (R_2) between modeled and observed quantities as well as in a large confidence interval around model coefficients and predictions (Lobell and Burke 2010).

8 Conclusions

Both the agriculture and the global food security sectors are under constant threat due to the rapidly increasing human population and changing climatic scenarios. Although the scientific community is not certain about the future impacts of climate change yet, it is anticipated that crop production will diminish further due to changing climatic conditions. The negative effects of climate change can be effectively managed using different field and crop adaptation strategies. The majority of the farming communities are currently deploying a score of important adaptation strategies to cope with climate change. These approaches usually include development of climate-resilient crop varieties along with planned agronomic crop management and pest control tactics. The integrated use of these innovative approaches reduces the harmful effects of climatic variations. However, to make effective use of these adaptation strategies, proper investments into capacity development of farmers and policymakers are required. Moreover, to mitigate the vulnerability of the agriculture sector to climate change, outreach of advisory extension services must be enhanced at the farm level. Currently, a significant gap exists between services provided by local bodies and what is needed to be done at the farm level. Moreover, a closer look at the farm level is needed to anticipate the outcome of these adaptation strategies.

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Chapter 3
Crop Responses to Climate Change

Uzma Aslam, Asad Azeem, Aqsa Mumtaz, and Sami Ul-Allah

Abstract Climate change is a leading element for variation in crop responses and correlates mainly with other stresses (abiotic and biotic stresses), which are accountable for poor crop productivity. Many climatic factors affect crop productivity and overall agricultural land in a number of various ways, for instance, rainfall variations, temperature fluctuations, genetic modification of weeds, pests, and an increase in CO_2 concentration. Variation in global climate has fascinated various investigators and scientists with regard to ensuring global food security. According to many published reports, agriculture has become the most vulnerable field negatively affected by climatic variation. Crops responses have become entirely changed in climatic fluctuations, which ultimately lead to poor crop yield. The only single solution to overcoming all the climatic variations and to improving crop productivity is to go for climate-resilient agriculture. The adaptation of climate-resilient agriculture and climate-resilient crop genotypes may lead to global food security. In this chapter, climate change and its impact on crop production, and the possible agronomic, breeding, and genomic strategies for overcoming the negative impacts of climate change in crop production are discussed. This will enhance the knowledge of the reader with regard to food production strategies under the climate change scenario.

Keywords Crop responses · Climatic variation · Genetic engineering · Marker-assisted breeding · Molecular breeding

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1 Introduction

Crop performance and overall plant progressive activities are under the influence of the interaction among environment, crop management practices, and climate change, which ultimately leads to crop yield fluctuation. Positive interaction among climatic variation, genotype, and management practices is essential for better crop responses and breeding as well (Cooper et al. 2020). Srivastava et al. (2016) described climate change as a sea-level upsurge with its associated outcomes, and comprises wilder climate, floods, enhanced occurrence and intensity of storms, hurricanes, poverty, water shortage, amplified fire incidence, malnourishment, and a series of socio-economic and health consequences. Climate change has a collective impact on food production and natural resources and as a result it will exert far-reaching influences on food security. The Food and Agricultural Organization of the United Nations (FAO) documented that there are around 795 million people who are underfed worldwide, with poor nourishment accounting for approximately 45% of deaths in children under the age of 5 every year. An additional 13.5% of the residents in evolving nations are underfed owing to the deficiency of food accessibility; the permanency of food; and/or physical and economic access to food, and, owing to the increase in the global population, these numbers are expected to further increase to 2.4 billion by 2050 (FAO 2015).

Chen and Chen (2016) reported two chief causes of global climate change: greenhouse gases in the inferior levels of Earth's troposphere and Earth's magnetic field changes. Accumulation of greenhouse gases in the subordinate layers of the atmosphere resulted in the Earth's surface temperature rises known as the greenhouse effect. Because of this effect the temperature of the air is higher than it should be, which causes such irretrievable consequences as climate change and global warming. This issue is also linked with deforestation, the production and consumption of industrial goods, globalization, and economic growth.

Across the world, agriculture is the foremost land usage and linked with food production. According to the Food and Agriculture Organization (FAO) 1.2–1.5 billion ha are used for crop cultivation and 3.5 billion ha are being foraged, with an additional 4 billion ha of forest being consumed by humans to varying levels, although, away from the land, worldwide very intensive use of fisheries is made, frequently exceeding the capability. Farming is also a key cultural, economic, and communal activity that offers an inclusive array of ecosystem facilities**.** Agriculture is highly sensitive to global warming in its various forms and locations. For example, the El Niño Southern Oscillation process, with its related cycles of flooding and drought events, has between 15% and 35% of worldwide production of coarse grains, wheat, and oilseeds. Developing nations with mainly rural economies and small agricultural modification levels remain at the greatest threat as they have little flexibility to bumper potentially large variations in their production bases. In Asia, Latin America, and Africa agricultural productivity is likely to decline by as much as 20%. Therefore, farmers have had a negative concept of climate alterations and variability. The literature has supported this on the associations between agriculture and climate change, and perceives that temperate areas will benefit from warming by up to 2 °C compared with the arid and semi-arid regions, which are suffering badly from alterations in climate (Vogel et al. 2007). The linkage between food productivity and climate change has mainly been explored by concentrating on the link between climate variables and agriculture. Along with the assessment of the impacts of climatic variables on food production, it is essential to recognize in what manner the set of approaches executed in the field by the agriculturalists, such as soil preservation measures, shifting crops, and implementing water harvesting technologies in response to extended period of fluctuations, affect crop productivity. Mertz et al. (2009) reported that the combination of poor infrastructure, low productivity, high climatic variability, and economic poverty, influenced farmers' adaptation responses. According to Simunic et al. (2019) climate change negatively affects nature and other resources such as water and agricultural land. Therefore, the objective of this chapter is to advance understanding of the effect of climate change on food security and possible strategies to ensure food security under the climate change scenario.

2 Agriculture and Food Production

The greatest substantial ecological threat of the twenty-first century is climate change. Swinburn et al. (2019) reported that climate alterations, malnourishment, and noncommunicable disorders (NCDs) are three of the most important health concerns of this era, and they share central basic drivers. The impacts of climate change food and nutrition security are also probable to initiate undernourishment and worsen the problem of diet-related NCDs. Climate change is predicted to adversely affect fisheries and agriculture productivity; impair livelihoods and enhance migration; food system instability, the provision of lower-quality humanitarian food support, and volatile and increasing prices of food amongst others (Asch et al. 2018). Change in climate is probably going to have a promising effect on the wheat crop weeds that play a very dynamic role in worldwide food security (Bajwa et al. 2020). In developing nations, rainfall differences have harmful consequences for agriculture. It significantly affects cropland areas as well as a distressing crop yield. According to evidence, cropland is expanding at the rate of 9% in emerging countries over the past few decades because of variations in dryness as growers increase the area to counterbalance yield deficiencies (Zaveri et al. 2020). Climate change has negative effects on food security. In the current scenario, it is a great opportunity to establish an economy on innovation based on energy proficiency; a low-carbon economy is an opportunity to transfer to a novel level of development. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) documented that agriculture in Asia will face rises in temperature, risky climatic incidents, such as floods and droughts, salt intrusion, and soil deprivation because of an upsurge in the sea level. Therefore, worldwide alteration might inevitably cause extreme agricultural losses and threaten global food security (Hijioka et al. 2014). Certain climate changes are advantageous to agriculture, such as increasing CO_2 acting as fertilizers for C3 crops. The atmospheric CO_2 (0.03%) increased global wheat production by 1%, but this advantage is to be wiped out owing to increasing challenges posed by changing climatic conditions and the potential for more frequent and severe extreme weather events. The second benefit of increasing temperature is the altering of development inhibition, which is a spreading constraint at an advanced latitude and altitude. Beside these aids, farmlands in upper-latitude areas will gain an advantage from climate change as the productions of cereals is supposed to improve (Rosenzweig et al. 2014). The chance for novel crops to be cultivated, for instance, tomatoes, cowpeas, and potatoes in areas with low water availability, instead of crops that demand large amounts of water to complete their life cycle.

3 Climate Change and Food Security

Previously, it has been described that dysfunction of the global food system leads to food insecurity (El Bilali 2019), which is beneath the unequalled convergence of numerous pressures such as climate alteration. According to the FAO (2016), besides its influences on agriculture, climate change in all its dimensions will exert adverse effects on food security. Food security is described as "A condition that occurs when entire populations, at all times, have social, physical, and economic access to enough, healthy and nourishing food that meets their dietary requirements and food likings for an energetic and healthy life."

Moreover, the report on the State of Food Security and Nutrition in the World (2019) illustrates that mainly in Africa, Asia, and Latin America more than 820 million individuals were hungry in 2018 (FAO et al. 2019). It is foreseen that Africa will be especially susceptible to climatic transformation and variability allied with food insecurity, biodiversity loss, rise in drought occurrence, and water insufficiency. Climate variations will diminish the productions and harvest of the key staple crops such as wheat (Trnka et al. 2019), rice (Akinbile et al. 2015; van Oort and Zwart 2018) and maize (Freduah et al. 2019) and livestock productivity (Mare et al. 2018). According to its influences on food security and agriculture, climatic alteration is one of the most tenacious challenges facing humanity.

The worldwide community is looking for novel approaches and resolutions to adapt to climatic variations and advance challenges such as food, water, and energy security. The efficient and synchronized management of water, energy, and food is critical for the mitigation and adaptation of climatic modification in the region, as shown in Fig. 3.1.

Fig. 3.1 Aspects that control the susceptibility of food systems to worldwide ecological transformation

3.1 *Climate Change Alters Breeding Targets*

Increasing temperature has a negative effect on climate such as pressure and the changing pattern of water scarcity, novel pests, and diseases. Our principal challenge is to alter our agricultural practices and set up a link to variations in weather pattern such as water deficiency and transportation system because one third of the world's food is produced on irrigated land. In the changing climate, along with the management-based and agronomic methods of improving food production we need improvements in crops' ability to sustain yield and quality with limited water availability, tolerance to salinity, and our main aim is to improve the efficiency of nitrogen use.

3.2 *Impact of Increasing Population on Food Production*

To feed the rising population of the globe our food production with improved quality and reduced inputs would be a great challenge in the shifting climate. The core emphasis of plant breeders should be on species with great potential to enhance yield (food quantity) as well as food quality (improved nutrient content). An additional burden is created by altering climate to enhance our food production in a stable environment.

3.3 Greenhouse Gases

One of the prime political and scientific challenges of the twenty-first century is continuing global climate change caused by the human-instigated rise in greenhouse gases (carbon dioxide, methane, etc.). Owing to the increase in the greenhouse effect the atmospheric CO_2 concentration has exceeded 400 ppm and the progressive rise in the global average temperature, liquid begins to evaporate. Because of the high temperature some researchers fear that in a couple of hundred years, oceans will begin to "dry out." Simultaneously, sea ice and glaciers will soon begin to liquify vigorously. This will cause an unavoidable upsurge in the level of the world oceans; all areas of the earth will be flooded, and our crops will fail, as we already perceive consistent floods in seaside areas.

3.4 Impact on Soil Properties

Climate change will influence the soil owing to alterations in overall rainfall patterns (both the quantity obtained and the dissemination of rain) over the sequence of an average year at numerous sites. Brevik and Burgess (2013) stated that soils are also vital to climate change and food security, because of the ability to warn about food security through its impacts on soil characteristics and processes. Various emerging nations, particularly South Asia and Africa, are at a high risk of food insecurity because the most recent food security problem is low soil fertility, which results from climate change decreasing the soil health (Tan et al. 2010).

3.5 Hunger and Malnutrition

Hunger and malnutrition will increase as climatic variation will have a negative impact on aquatic and terrestrial lives;. Variations also have negative effects on arctic lives, which are already in danger of food insecurity because of the damage to properties and insufficient insurance coverage. They face the probability of enhanced crop collapse and livestock loss.

3.6 Impact on Fishing and Aquaculture

Lakes, seas, streams, oceans, the animals, and plants living in them are influenced by climatic alterations and variations. Globally, about 200 million people depend on aquaculture and fishing and will be affected by climate variation. Some valuable species migrate to other areas where they are less accessible to the fishers; thus, fish resources will decrease, resulting in difficulty for several fishing communities in continuing to earn a livelihood from fish. The rise in sea levels may also result in displacement of coastal communities and migration to new areas to reside and ways to make a earning. Climate change also pressurizes the stability of the food system, as it alters cropping cycles, diminishes crop harvests, there are extreme weather events, reasons to survive and live vanish, income and generate nutrition systems become unstable owing to food shortage, there is increased malnutrition and diseases, and susceptible groups will be badly affected. Food system stability requires an equilibrium between human needs and utilizing natural resources.

4 Adaptations to Climate Change

Climate change is a current phenomenon whereas adaptation to altering stress is a continuous process. Different processes of climatic variation affect diverse parts of the world and these effects will be more intense in the future, particularly on food system.

To lessen the susceptibility of the food system to climatic variations both incremental adaptation (improved resistance to the novel climatic circumstances) and transformative adaptation (by shifting crops or even activities) could happen on scales from farm households to national agencies (Loboguerrero et al. 2018). During such extreme situations, the solitary key is to transit out of agriculture, i.e., in sub-Saharan Africa agriculturalists may be forced to shift to livestock as the prime source of eating, whereas during mild situations (more frequent/more severe) they might need to switch to other crops, i.e., in Nicaragua, climatic challenge may shortly lead growers to move from coffee to other crops, for example, cocoa, and within frequent climatic effects, families can choose to alter breeds and varieties.

4.1 Climate Change Service

Climate change service involves the creation, translation, and communication practice of climate data. Proper information allows cultivators to realize the part of climate versus other drivers in apparent production alterations (Osbahr et al. 2011; Rao et al. 2011) and to cope with climate-associated threats during the agricultural calendar.

4.2 Climate-Smart Agriculture

There is a necessity for a climate-smart method of agriculture to overcome the effects of climate change on crop plants to achieve the objectives of eliminating malnutrition and scarcity by 2030, which is based on the purposes of sustainably increasing variation in climate, food production, and flexibility and a decrease in the release of greenhouse gases. Obsolete farming techniques are regaining global attention as a climate-smart approach due to their renewed relevance. Some prominent features of an outdated agriculture system (crop rotation, traditional organic composting, intercropping, and cover cropping) are the biodiversity conversation, low energy inputs, high efficiency, and climate change moderation (Srivastava et al. 2016). Farmers shifted from traditional agriculture to modern agriculture because of small profits and persistent work. However, modern agriculture has improved food production but has hastened many environmental difficulties such as food insecurity, soil deprivation, climate variation, and ecological contamination (Zhang et al. 2016a). The present situation needs the addition of old to recent agriculture. The three main objectives of a climate-smart agriculture approach: (i) Increasing agrarian yield for a sustained impartial rise in income, growth, and food safety, (ii) growing adaptive size and elasticity to input fluctuations at farm to national stages, and (iii) increasing carbon appropriation and reducing the release of greenhouse gases where the exercise of mixed cropping is combined with the diversity of crops for food security. Minor-scale farmers have reinforced the ancient numerous cropping practices in response to climate inconsistency, but planting both resident hardy varieties and enhanced varieties as a degree of assurance at different times.

4.3 Crop Modeling and Climate Change

Crop modeling may benefit the efficiency of agricultural variation approaches to climate change. Intricate interactions of G (Genotype) × E (Environment) × M (Ma nagement) (Wang et al. 2018) distress the growth, development, and yield of crops and the presence of nonlinearities adds complexity to designing meaningful experimental investigations that sufficiently illustrate the G × E × M space. Crop models offer a unique approach for assessing the merits and effectiveness of various adaptation strategies, as it integrated the biological and physical parameters to simulate the utilization and allocation of available resources. Advancement in crop breeding and genetic engineering is possible by integrating the values of genomics and genetics into crop models that will permit genotype-to-phenotype estimates. Top-down and bottom-up are two methods that may be tried to influence our joint consideration of genetic controls of physical procedures to increase phenotypic estimates.

4.4 Sustainable Crop Production

Major challenges of the twenty-first century are maintainable food production in the period of worldwide environmental difficulties, such as high population rate, variation in climate, and degradation of natural sources such as loss of biodiversity and soil degradation. A suitable cropping system and land on a sustainable basis to confirm food safety is required based on values to limit land degradation and to preserve ordinary resources as well as to improve the safety of food and nutritious over-crop modification. Conservation agriculture could determine the soil degradation, expand crop yield, and progress the socio-economic disorders of minor landholders between numerous of the sustainable cropping systems. Improvement of the conditions of natural sources is possible by conservation agricultural approaches and practices. Conservation agriculture mitigates soil issues, minimizing the soil erosion by maintaining a permanent cover of organic matter on the upper soil surface.

4.5 Low Inputs

Decreasing agricultural contributions, particularly nitrogenous fertilizers, play an important role in the reduction of the detrimental effects of nitrogenous compounds and CO_2 released through agricultural procedures. Worldwide, breeding and agronomic developments have effected a direct rise in the production of food, by a normal degree of 32 m ton year^{-1} of food safety. Rice production of 70% by 2050 is our goal, with regular yearly growth in production of 44 m ton year^{-1}. This is an extraordinary measure of cumulative food production and requires some considerable variations in agronomic procedures and crop development systems. Small-hold farmers can overcome barriers with the establishment of agricultural associations that are related to admittance to ideas, financial facilities, and marketplace involvement, by the distribution of inputs, finances, and training programmes and have been effective in encouraging the usage of maintainable production (Ertani et al. 2015).

5 Plant Breeding and Climate Change

Enhancement of breeding becomes easy by developing new technologies, which is possible by increasing the accessible genetic assortment in breeding germplasm via enlightening genotype and phenotype approaches. If there is better accessibility of these technologies in developing countries, we can get extra productivity and effective food safety. Biotic and abiotic growth of stress-resistant species are ongoing round the world (Zhang et al. 2022). Challenges due to climate change may be managed by the essential breeding approaches to progress adaptation to what will possibly be a briefer crop season by a similar phenology to humidity convenience. There are fewer problems because of highly heritable photoperiod and temperature. Further policies contain maximum access to a set of varieties with diverse development periods to overcome expectable stresses at critical stages during life cycles of a crop plant, ever changing the temperature targets for re-highlighting population breeding and crop development. The stress will be detected in all cases by means of genetic variation sources for resistance to a later stage of abiotic stresses. Genetic variation has two clear novel sources, which are farmers' fields and gene banks

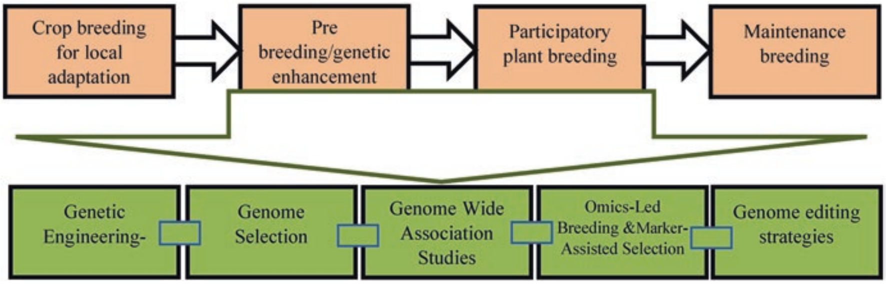

Fig. 3.2 Tools of plant breeding that can be used to combat the effects of climate change

(ICARDA has 120,000 assents of many species containing significant food and fodder crops such as wheat, chickpea, barley, vetch, and lentil and is known as the largest gene bank). Various tools in plant breeding that have been used to tackle adverse impacts of climate changes are shown in Fig. 3.2.

5.1 *Omics-Led Breeding and Marker-Assisted Selection*

Omics methods deliver valuable properties to explain the organic purposes of any genomic material for crop growth and advancement. Observation of diverse molecular markers in populace genomics across various geographical regions empowers the discovery of novel genetic variants. Breeding programs and genomics methods are used together to attain large increases in molecular breeding and to protect germplasms having the desired attribute (Sandhu et al. 2021). Genomics allows the searching of the molecular apparatuses underlying the resistance of abiotic stress. Owing to a change in climate, these methods help in the growth of climate-smart crops, giving a higher yield and greater productivity. Identification of diverse stresses that harmfully disturb the crop production is possibly due to the invention of a high amount sequencing and phenotyping as genomic-led breeding. Moreover, accessible data on ecological excesses, DNA fingerprinting, and quantitative trait loci (QTL) mapping enables the identification of optimal germplasm under abiotic stress conditions. Under biotic and abiotic stresses, molecular plant breeding plays a significant role in the enhancement of crop production. DNA markers have been identified with the development in crop genomics, which are valued for marker-assisted breeding (Jiang 2013).

According to Iquebal et al. (2019), molecular markers may be degraded to discover the exclusive allelic differences in wheat for enhancing the possible to shade- and drought-tolerant varieties. Under diverse conditions of stresses such as flooding, heat, and drought, QTL mapping was performed for a recombinant inbred line population of wheat. A 19.6% variation of grain yield was observed owing to QTL mapping under these stress circumstances (Iquebal et al. 2019).

5.2 Genome-Wide Association Studies for Stress Tolerance

Genome-wide association studies (GWAS) make it easy to consider the whole collection of genetic alternatives in changed crop lines for identifying the allelic variant related to other specific features. Under climatic conditions, GWAS offers assistance in unraveling the genetic factors responsible for genetic diversity. Several genes in *Aegilops tauschii* have been identified for the regulation of abiotic stresses. There is a need for breeders to have significant knowledge in order to understand the genetic structure of *A. tauschii* to recover the drought flexibility. GWAS are helpful to QTLs in response to salinity resistance in plants. Numerous genes that have tolerance to salinity in rice were studied by Chen et al. (2021) by using Infinium high-throughput single-nucleotide polymorphism (SNP) arrays. At the vegetative stage in *Sorghum bicolor*, heat-tolerant characteristics were studied by Chen et al. (2018) such as leaf blotching and leaf dismissal and they found 9 SNPs related to leaf dismissal and 5 SNPs were found for leaf blotching, as identifying the relation between SNPs with genotype and tolerance to heat using GWAS.

5.3 Genome Selection for Crop Enhancement

Kumar et al. (2018) reported an exciting tool that uses marker densities and high-throughput phenotyping to evaluate the elite genotypes, enhancing development of the economical breeding line and polygenic characteristics to improve crops. The successful maker in genome selection was diversity array technology, then SNP, and genotyping by sequencing. Dong et al. (2018) and Crain et al. (2018) developed various genome selection designs for wheat to expose the collections that have improved capacity to adjust to climatic variations, and by utilizing a high-throughput phenomics approach, the 1000 best wheat cultivars for drought and heat stresses were scrutinized.

5.4 Accessing the Genetic Diversity of the Wild Relatives of Crops

Under the discerning pressure of biotic and abiotic stresses, wild plants have subsisted for millions of years. Plants can fight, stand, circumvent highest temperature, flooding or drought, as well as pests and diseases by accumulating genes via natural selection. However, transformation of a plant into being highly productive with inadequate genetic diversity causes the loss of many vital traits and linked genetic material during successive domestication. The genetic resource that is left behind as a remainder is preserved as a weed. Expending with the sequencing of genomes in different crops established the slight germplasm of our modern crops and stressed their susceptibilities to a change in climate (Springer et al. 2018). However, the wild relatives of a crop offer a rich source of genetic material, which helps in the domestication of modern crops.

5.5 New Areas of Biotechnology

There is a need for the implementation of huge-scale resolutions on the insistence of climate change immediately (Merertu and Alemayehu 2019). Green biotechnology, by the alteration in genetic methods, may be a solution for the development of varieties or crop characteristics that have the ability to cultivate in an altering atmosphere and to produce maintainable agriculture by the formation of genetically modified (GM) crops that are intended to counter the climate challenges of an innovative era. Practical usage of living organisms or their subcellular mechanisms was included in methods of biotechnology in agriculture and that newly emerged method now in usage known as genetic modification or genetic engineering, which was used to produce crops that are resilient to different stresses of the environment. In the variation of agriculture to novel certainties of climate and to address these impending problems, modern biotechnology plays a major role by producing seeds that are tolerant of current agriculture environments. According to Ruchir (2017) that genetic modification is the process of manipulating genetic resources in living organisms to produce transgenic organisms or genetically modified organisms using a DNA-recombinant method and the biotechnological technique of gene splicing that allows them to achieve precise functions, which was not possible using conventional breeding methods. This technique is quick and effective to get desired outcomes. Furthermore, over the past two decades the progress of genetic engineering of genes into crops and microorganisms showed resistance to disease, pests, herbicides, tolerance to drought, and the production of nutritional GM crops by reducing the saturated fats and the cumulative unsaturated fatty acids level as well as biocontrol agents (Mohammad and Byong 2014). It is also essential in developing healthy, rich food (golden rice) and cassava lines (UMUCASS 42 and UMUCASS 43), which are rich in vitamin A (Ojuederie and Ogunsola 2017) and making drugs and vaccines in crops. GM crop production played significant role in achieving the requirements of future food security but then can have hazard-related issues.

Moreover, it is mostly rain-fed agriculture land that is affected by climate change (Ghamghami and Beiranvand 2022) in industrially less well-established countries such as Africa. Globally, for the reduction of greenhouse gases using energy-effective farming and for reducing the use of synthetic fertilizers, biotechnological methods play a main role (Gartland and Gartland 2018). Genetically modified crops require less maintenance in comparison to traditional crop cultivation, as they remain unaffected by the fluctuations in input availability that can impact the equipment used by conventional growers. As a result of this simple yet effective application of GM crops in agricultural leads growers to minimize fuel consumption owing to the simple and active application of GM crops, it became easier to operate on an agricultural farm at extensive scale. Despite this, there are some countries that have shown doubts or hesitancy toward the suitability and acceptance of modern technology, which have an even greater effect on food insecurity and climate change. In order to address the challenges posed by climate change, to enhance the yield of cash crops, and to ensure food security, it becomes imperative to consider the utilization of surplus resources to educate the public on the benefits of biotechnology. Typically, it may be overwhelmed in an alteration in social attitudes and norms, as the main purpose of green biotechnology is to improve production and exploit the productive size of global incomes.

5.6 Genetic Engineering

Normal plants show less tolerance to variations in climate than transgenic plants (Shah et al. 2016). *AP2/ERFBP* group is identified as plant-specific transcription factors, and is accountable for various plant growth pathways and plays roles in abiotic and biotic stress responses (Licausi et al. 2010). Different transgenic crops against abiotic stress have been developed by inserting *DREB1* purified from rice, rye, wheat, oilseed rape, and maize. Many GM crops have been developed, as shown in Table 3.1.

6 Challenges of Climate Change

Agriculture is tremendously vulnerable to climatic modification. Variations in climate cause the plant physiology to decline by several means. The chances of several stresses on plants are increasing with the climate variability and ecological excesses. Direct, indirect, and socio-economic factors are the causes of declines in crop production due to climate alteration, as shown in Fig. 3.3.

All major crop production and agricultural cultivation practices are affected by climate variability. Agriculture production is affected by three processes as was demonstrated recently that deterioration occurs in crop flexibility, for example, in the case of wheat crops in Europe. According to future predictions of the IPCC (2018) that variability in climate and its influences on agriculture will make it challenging for breeders to develop climate resilient crop genotypes. Changes in rainfall pattern and temperature are associated with the spread and growth of pathogens. Many examples showed the relation among climate variability, crop growth, pests, and their natural foes (Heeb et al. 2019).

Worldwide decline in production (10–25%) of three crops, rice, wheat, and maize, per degree worldwide means global warming because the rise in temperature quickens the metabolic rate of insects and their feeding rate also increases (Deutsch et al. 2018). Growth of the insect population depends on the temperature, for instance, pollinators (bumblebees) are influenced by the variation in climate, as

Table 3.1 Genes extracted from various crops to develop genetically modified crops

Gene	Extracted from	Inserted in	Role	References
ZmMYB30	Maize	Over-expressed in *Arabidopsis*	Salinity resistance	Chen et al. (2017)
ZmDREB2A	Maize	Over-expressed in *Arabidopsis*	Drought resistance	Qin et al. (2007)
GmDREB2	Soybean	Over-expressed in plants	Salt and drought resistance	Chen et al. (2007)
MdMYB121	Apple	Apple and tomato	Drought and salt tolerance	Cao et al. (2013)
GmMYB76	Soybean	*Arabidopsis*	Salinity and freeze resistance	Liao et al. (2008)
sDREB1	Wheat, rye, maize, rice, and oilseed rape	Rapeseed, rice, tomato, and tobacco	Various abiotic stresses resistance	Qin et al. (2004)
MdSIMYB1	Apple	Tobacco and apple	Resistance against cold, salinity, and drought stresses	Wang et al. (2014)
Ls-miR156	*Lactuca sativa*	*Arabidopsis thaliana*	Late/delayed flowering	Huo et al. (2016)
Gma-miR172a	*Glycine max*	*Arabidopsis thaliana*	Early-flowering phenotype	Wang et al. (2016)
Gma-miR172c	*Glycine max*	*Arabidopsis thaliana*	Enhanced salt and drought tolerance, but increased ABA sensitivity	Li et al. (2016)
Osa-miR319a	*Oryza sativa*	*Agrostis stolonifera*	Increases salt and drought tolerance	Zhou and Luo (2014)
Ath-miR395d	*Arabidopsis thaliana*	*Brassica napus*	Modifies leaf morphology and delays the conversion between the juvenile to the adult phase of vegetative development	Huang et al. (2010)
Sp-miR396a-5p	*Solanum peruvianum*	*Nicotiana tabacum*	Increases susceptibility to *Phytophthora nicotianae* along with cold, salt, and drought tolerance	Chen et al. (2015)
Ptr-miR396b	*Poncirus trifoliata*	*Citrus× limon*	Cold tolerance	Zhang et al. (2016b)
Ath-miR399d	*Arabidopsis thaliana*	*Solanum lycopersicum*	Tolerance to phosphorus deficiency and cold	Gao et al. (2015)

revealed by the move in the range of bumblebee species (Kerr et al. 2015). Climate change is also altering the resistance pattern of different weeds and recent evolution is proving their higher resistance against herbicides. Several pathogens, insects, and weeds have been recognized in various regions as a growth of their geographical series.

High temperature, drought, and their combination on growth-associated characteristics have been extensively examined as many studies revealed the harmful effect of drought and heat stress on cereal growth, development, and reproduction,

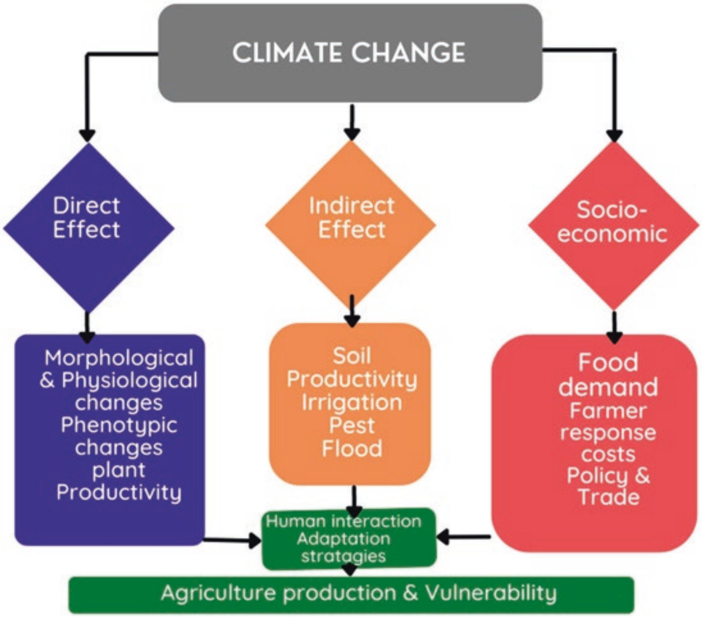

Fig. 3.3 Direct and indirect effects of climate change on crop response

and also their yield (Hlavácová et al. 2018). Yield is also barely decreased by the combination of drought and salt stress (Ahmad et al. 2018). According to Zhao et al. (2017) the decline in production of maize (3.1%) and soybean (7.4%) is due to a rise of 1 °C in the regular temperature. A rise in atmospheric CO_2 has an incompatible impact on crops, as it regulates a rise in the growth and photosynthesis of the plant as well as its harmful impact on the nutritious value of crops and their health rank (Irigoyen et al. 2014), such as a rise in yellow dwarf virus of barely has been detected in wheat owing to a high CO_2 concentration (Trebicki et al. 2015). There are many challenges in the process of breeding crop varieties due to ecological stresses, as the influences of stresses on crops are mutable and intricate, particularly when crops are subject to numerous pressures (Trebicki et al. 2015). Plant responses are different according to the specific combination of pressures, on the strength of every strain, and on the growing stage of the plant. To meet the challenges of climate variability, strategies are needed to grow climate-resilient genotypes and accelerate the number of genetic gains. The main objectives for the next generation of breeding should be consideration of the genomic, physical, and molecular mechanisms that permit crops to acclimatize and respond to climatic variability and also identify the adapted characteristics to variable environmental conditions caused by climate change.

Crop varieties in which the need for the application of fertilizers is less due to nutrient use efficiency, thereby declining release of N_2O, as well as fodder increasing the nourishment value of foraging livestock, which leads to the creation of less CH_4. There is a need to breed cultivars with high nutritious value to meet the consumers' demand for health awareness in diets. Plant breeding contains genetic engineering, which offers ways to acclimatize to the associated stresses of climate variability. Transgenically grown crops would also play a role in climate alteration which put an extra burden on crop productivity by affecting yield factors in crop plants. Thus, genetic engineering will provide the expansion of cultivars adapted to climate alteration. In recent years, various stresses were identified, responded and their signal transduction in plants were covered by the advanced molecular techniques, thus contributing resources for manufacturing some of the functional and regulatory genes to improve plant performance under stress.

7 Conclusion and Prospects

Globally, major crops are facing adverse effects from fluctuating temperature owing to climatic variation, which results in reductions in crop yields. Crop management, genotype, and climate change are crucial aspects in maintaining better crop yields. Breeding programs and genetic modification play vital roles in minimizing the impacts of climate alteration on crops. Various breeding approaches in collaboration with genome editing are working to address climate change effects on crops. CRISPR/Cas9 is one of the emerging gene editing techniques for crop improvement against various stresses under climatic change.

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Chapter 4
Impact of Climate Change on Vegetable Production

Bornita Bose and Harshata Pal

Abstract Vegetables, as a major source of nutrients, such as vitamins, proteins, minerals, and fibers, have been a staple part of a well-balanced human diet regimen since time immemorial. The cultivation and production of vegetables initially began as a result of subsistence agriculture practiced by farmers to meet basic dietary requirements. With the gradual outburst in population, the need for food no longer stayed limited to fewer households and rather expanded globally. This also marked the beginning of the exploitation of nature for human needs. One of the adverse effects of human exploitation has been observed in the form of climate change, which is slowly proving to be detrimental to farming, including vegetable and fruit cultivation. Climate change has devastating consequences, such as global warming, changes in seasonal patterns, droughts, stressful biotic and abiotic conditions, salinity, and other physiological and biochemical changes that are, in turn, putting vegetable crops at risk. For instance, the rapidly elevating levels of greenhouse gases like methane (CH_4), carbon dioxide (CO_2), and chlorofluorocarbons (CFCs) and the accumulating sulfur and nitrogen oxides in the atmosphere have led to deterioration of the quality of crops and reproductive growth, extremely low crop yield, and, sometimes, failed agriculture, hampered plant–pathogen interactions, disturbance in the ripening period, and much more. In addition, notably, these climatic variables negatively impact the health-beneficial qualities provided by naturally synthesized secondary metabolites such as alkaloids, phenolics, fatty acids, and terpenoids that are found in vegetable crops. Most of the vegetables consumed by humans are climate-specific as well as climate-sensitive, and any small or significant alteration in the atmosphere can cause an imbalance in vegetable production, thus decreasing its salability and economic value in the market and bringing about a major financial loss to the farmer. Agriculture has become one of the major targets of climate change

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among many others, henceforth making it an environmental, economic, political, and global issue requiring immediate attention. This chapter comprehensively discusses the disturbances caused in vegetable production due to the adverse effects of the environmental factors associated with climate change and also emphasizes the pressing importance of developing effective measures to maintain the yield and quality of vegetables even when exposed to harsh environmental conditions (global warming, high temperatures, low temperatures, frosting, excessive greenhouse gas emissions, air pollutants, droughts, salinity, high CO_2), thereby preventing the current global food crisis from escalating and causing havoc in the society.

Keywords Vegetable production · Climate change · High temperature · Low temperature · eCO_2 · Drought · Salinity

1 Introduction

Climate change has become a matter of concern and is a much-discussed hot topic in the modern world. According to the reports collated by National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) and published in 2020, it can be surely confirmed that the last decade between 2010 and 2019 has been the hottest ever recorded since 140 years when climate recording began, with 2019 ranking as the second hottest year, leading to a substantial increase in relative humidity, precipitation, and temperature accompanied by a notable change in the gaseous composition of the earth's atmosphere, including greenhouse gases like methane (CH_4), carbon dioxide (CO_2), and chlorofluorocarbons (CFCs) and oxides of sulfur and nitrogen. Natural variabilities along with anthropogenic activities like deforestation, industrialization, urbanization, mining, fossil fuel incineration, and many other human activities can be held accountable for such drastic changes in climate, thereby bringing about the most prevailing consequence of climate change termed the "greenhouse effect" or "global warming" (Prasad and Chakravorty 2015). This might raise questions regarding the connection between climate change and agriculture with a specific emphasis on vegetable production. Vegetables are seasonal crops and are highly climate-sensitive. Based on their ability to tolerate frost, vegetables can be broadly categorized into two major groups – winter-season vegetables and summer-season vegetables.

- On one hand, winter-season vegetables, also referred to as temperate or cool-season crops, owing to their tolerability to frost, thrive in optimum average temperatures within the range of 15–18 °C. These can be further subdivided into hardy or tolerant winter vegetables and semihardy or semi-tolerant vegetables. Examples include:
    (i) Tolerant or hardy vegetables – chive, spinach, leek, broccoli, pea, turnip, brussels sprouts, garlic, parsley, cabbage, knol khol, rhubarb, kale, asparagus, radish, onion, and collard.

(ii) Semi-tolerant or semihardy vegetables – globe artichoke, Chinese cabbage, potato, leaf beet, carrot, lettuce, celery, and parsnip.

- On the other hand, summer-season vegetables, also known as nonhardy or warm vegetables, are frost-intolerant and can grow best in a temperature range of 20–27 °C. These can be classified into two subgroups –

(i) Sensitive or tender vegetables – snap beans, sweet corn, tomato, and chili.
(ii) Extremely sensitive or extremely tender vegetables – tapioca, sweet potato, eggplant, cucurbits, amaranth, lima bean, yam, chili, okra, cowpea, cluster bean, bell pepper, and *Colocasia* (Dhaliwal 2007).

Cultivation of qualitative and quantitative vegetables is greatly dependent on climate (as shown in Fig. 4.1) and thereof any alteration in seasonal patterns, limitations in soil moisture, and/or changes in atmospheric gaseous composition, glacial melting, or temperature can result in the sensitivity of vegetables to extremities, with a distinct impact on various biochemical and physiological processes, including disturbed enzymatic activities and metabolic pathways, depreciation of photosynthesis, declined pollination rate and fruit set, thermal injuries caused to tissues, and many more with destructive effects and disturbance of the interactional balance between plants (host) and specific pathogens (parasite) (Ayyogari et al. 2014). As much as climate change is important for agriculture, it also makes crops vulnerable to the adverse impacts of climate change and sensitive to natural adversities. For instance, crops grown in temperate regions are susceptible to damage from frost and temperatures lower than that of the optimum range, during the onset and at the end of the harvesting and growing season as they can cause the development of bolts in

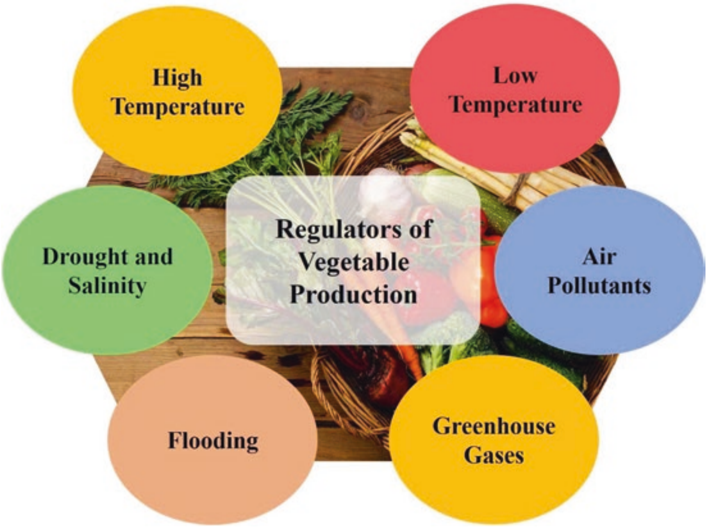

Fig. 4.1 A schematic diagram portraying environmental factors involved in climate change affecting vegetable production

some crop species like carrots and onions. Likewise, warm-season vegetables face several negative effects due to higher temperatures exceeding their ability to cope. Young vegetable seedlings can form a "heat canker" on exposure of the hypocotyl to the heated soil surface where the hypocotyl cells begin to die due to high temperatures. High temperatures often give rise to high humidity, which causes hindrance in the translocation path of calcium ions to the newly developing tissues and results in the occurrence of lettuce tipburns and celery "black heart"' At high temperatures, lettuce seeds undergo dormancy or lettuce itself may develop premature flower stalks, also referred to as bolts. The occurrence of bolts is also evident in spinach. High temperatures also induce more production of male flowers as compared to female flowers, predominantly in cucumbers (McDonald and Warland 2020). These radical changes in the quality of vegetables as a result of extreme climatic variations make it hard for farmers to sell their products in the market, and, more critically, it can eventually pose a threat to global food security.

Since agriculture and climate change are correlated processes, it has been estimated by the Intergovernmental Panel on Climate Change (IPCC 2009) that a temperature rise, occurrence of floods, desertification, droughts, and other weather changes can hugely affect agriculture, particularly in developing countries (Abou-Hussein 2012). Not to mention, India is one such developing country that stands second in order after China in vegetable production with an average twofold increase in the last two decades. Climate change is expected to delay the summer monsoon in South Asian countries accompanied by monsoon failure. This most often than not leads to a shortage of water supply, especially in regions prone to drought, including Andhra Pradesh, Rajasthan, northern Karnataka, Gujarat, eastern and northern parts of Maharashtra, and Orissa along with eminent crop losses in parts of Tamil Nadu, Karnataka, and Andhra Pradesh due to heavy rainfall during harvesting and insufficient rainfall during sowing. Climate change not only affects crops during preharvest or sowing but also severely impacts the postharvest quality of vegetables (Prasad and Chakravorty 2015). Seldom are there chances of heavy rainfalls that can sometimes result in floods, thereby washing out the nutrient-rich upper soil in contact with plant roots and interfering with the interactive strength between plant-soil and plant-specific pathogens. Such climatic stresses are the primary reason for the great loss of agriculture where plants go out of their way to protect themselves from such adversities. In the following few sections, we will be discussing the impacts of different elements of climate change on modern agriculture with a focus on vegetable production on a global scale.

2 Effects of Environmental Changes on Vegetable Production

2.1 Global Warming (High Temperatures)

Theoretically and practically well-known facts associated with global warming inform us that the rapidly elevating levels of greenhouse gases, including CO_2, hydrochlorofluorocarbons (HCFCs), nitrous oxide (NO), methane, ozone (O_3), and hydrofluorocarbons (HFCs), cater to the entrapment of heat radiating from the sun, leading to a potential increase in the temperature of the earth's atmosphere and thus to a universal phenomenon known as "global warming." Any vegetable crop has certain specified growth parameters in terms of environmental (abiotic) and biotic factors for producing an adequate yield per year. However, unnecessary fluctuations in temperature have been observed to influence the vital temperature-dependent metabolic, biochemical, and physiological activities of vegetable crops, including plant growth, fertilization of gametes, fruit size and weight, fruit set and its quality, flower shedding, pollen viability, and seed germination (Spaldon et al. 2015), by inducing stress in the surrounding crop environment. Due to the diverse range of variations in vegetable crops worldwide, and their varied adaptation abilities, it is extremely difficult to study the environmental effects on each vegetable species. It has been noted that high temperatures prove fruitful for some vegetables, whereas in others, it creates immense stress (Abou-Hussein 2012). In other words, temperature plays a limiting role in vegetable yield. Tropical crops are more accustomed to growth under higher temperatures, and any alteration in the predefined temperature causes temperature stress (Prasad and Chakravorty 2015). The most prominent example of such crops is tomatoes, whose green fruits if and when exposed to such extreme temperatures become sunburned while its ripened fruits undergo scalding (Abou-Hussein 2012). Tomatoes are acclimatized to the 25–30 °C temperature range during the photoperiod and to approximately 20 °C during nighttime, and even a slight alteration of 2–4 °C can hamper gamete development along with causing hindrance to seeded fruit formation from pollinated flowers (Spaldon et al. 2015). In addition, it can also be responsible for compromised fruit quality and deteriorated fruit set, which is evident from a few symptomatic occurrences during and post reproduction, like viability, dropping of buds, poor production of pollen grains, ovule abortion, abnormal development of flowers, reduced availability of carbohydrate residues, and many more. High temperatures are also associated with the developmental disorders seen in anthers, such as absence or lack of stomium opening, insignificant pollen formation, and endothecial and epidermal irregularities during the pre-anthesis period. For instance, pepper showcases no effect on stamen or pistil viability during the pre-anthesis stage; however, the post-pollination period is characterized by fruit set inhibition, indicating that fertilization is sensitive to high temperature. Along with this, high temperature also has a prominent effect on photosynthesis, resulting in an apparent decline in productivity (Bhardwaj 2012). High temperatures, in combination with long days, induce bolting (formation of seed heads prematurely) and poor quality of heads in spinach, lettuce, and celery (Prasad and Chakravorty 2015). Lettuce, in particular, also harbors accumulated bitter compounds along with notable tipburns and leaf chlorosis at day and night temperatures of 17–28/3–12 °C, respectively. In comparison to beans adaptable to 21/16 °C, common beans subjected to day/night temperatures above 27/22 °C produce small seeds at the time of seed development (Christopoulos and Ouzounidou 2021). It may further negatively affect the reproduction and survivability of some predators and parasites in vegetables such as the presence of *Trichogramma.* Such negative consequences faced by crops as a result of such temperature fluctuations reduce their market value and economic importance. In contrast, higher temperatures may prove fruitful for the leafy vegetables of colder regions as they extend the cropping season and provide an opportunity for elevated seed germination (Abou-Hussein 2012). Global warming can also speed up the rate of vegetable development, which, on one side, can be desirable for photoassimilation and short crop duration, while, on the other side, it may be responsible for declined yield on exceeding the temperature threshold (Bisbis et al. 2018). Hence, conclusions drawn regarding the effects of high temperature on vegetable cultivation cannot be considered as either entirely positive or entirely negative, as indicated in Table 4.1.

2.2 Low Temperature

Among the numerous restraining environmental stress factors, low temperature is one such deleterious factor that accounts for serious agricultural losses and damage to vegetable production. Low-temperature stress can be induced by either chilling (<20 °C) or freezing (<0 °C), both of which have differential effects on vegetables. Chilling per se triggers abated biochemical reactions that normally include enzymatic activities and membrane translocation. On the other hand, freezing results in the formation of ice crystals, thus disrupting the cell membrane’s integrity or causing its complete rupture. Being sensitive and intolerant to cold stress, vegetables undergo acute biochemical, metabolic, physiological, and morphological alterations characterized by a few phenotypic symptoms such as chlorosis and wilting (leaf yellowing), withering, affected tillering, reduction in leaf expansion, changed cytoplasmic viscosity, and, under the worst conditions, necrosis (death of tissues), leading to plant death. It also triggers photosynthetic impairment and hampers protein assembly, particularly, pollen sterility, ovule abortion, stunted seedlings, distortion in the pollen tubes, flower dropping, and declined fruit set during the anthesis period, thus impacting the overall growth, quality, and yield. Low-temperature stress negatively impacts the cellular metabolic aspects of a chilling-sensitive crop. Interestingly, research findings show that lower temperatures are responsible for influencing the higher production of female flowers, whereas higher temperatures are recorded to favor male flower production. In addition, freezing or chilling temperatures cause hindrance to seed germination as few seeds irregularly germinate, whereas others, for example, beans, do not. Cold stress can particularly have a detrimental outcome on tropical or warm-climate vegetables and, to some extent, on temperate region crops. These summer vegetables are intolerant to chilling temperatures between 0 and 15 °C and can face losses concerning reproduction and vegetative growth and seed germination (Atayee and Noori 2020). Crops grown in tropical climates are expected to experience frost injury in comparison to the ones grown in colder climates and have the capacity to survive a little freezing, but not too much. Likewise, temperate climate crops are quite sensitive to chilling temperatures and, therefore, can suffer from delayed maturation or direct damage, leading to complete or reduced crop failure. At times, when there is a slight drop in the normal temperature, crops sensitive to chilling temperature do not suffer any visible side effects

Table 4.1 Varied effects of temperature on numerous vegetable crops

Vegetable crops	Temperature	Effects	References
Tomato	High	Green fruits get sunburned Ripened fruits undergo scalding Hampering of gamete development Hindrance to seeded fruit formation	Abou-Hussein (2012)
		Dropped levels of macronutrients (Ca, Mg, K) Decreased contents of antioxidants, lycopene, and carotene	Christopoulos and Ouzounidou (2021)
	Low (around 10–15 °C)	Signs of frost injury Reduced seed germination Slow pollen tube growth	Atayee and Noori (2020)
Pepper	High	Fruit set inhibition during the post-pollination period	Abou-Hussein (2012)
Celery	High	Bolting	Prasad and Chakravorty (2015)
Spinach	High	Bolting	Abou-Hussein (2012)
Lettuce	High	Bolting Enhancement of antioxidants and tocopherol concentration Tipburn	Christopoulos and Ouzounidou (2021)
	Low	Loss in thee potential for survivability	Prasad and Chakravorty (2015)
Broccoli	Intermediate (~25 °C)	Uneven heads Oversized flower buds Yellow discoloration Tipburn	Bisbis et al. (2018)
Chinese cabbage cultivars	High	Slightly enhanced proline content Increased permeability of the cell membrane	Prasad and Chakravorty (2015)
Grapes	High (above 30 °C)	Reduced weight and berry size Deteriorated grape quality in terms of taste and appearance Decrease in acidity Elevation in sugar concentrations Modification in aromatic compounds influencing the wine industry	Christopoulos and Ouzounidou (2021)
Carrot	Intermediate (around 15.5–21.1 °C)	Accumulation of antioxidants (sesquiterpenes and monoterpenes) and essential oil components Accumulation of carotene, responsible for orange root coloration	Bisbis et al. (2018)

(continued)

Table 4.1 (continued)

Vegetable crops	Temperature	Effects	References
Soybean	Low (around 10–15 °C)	Signs of frost injury	Lynch (1990)
Cauliflower	Temperature (15–25 °C) with high humidity	Good yield	Atayee and Noori (2020)
Onion	High (at or above 40 °C)	Reduction in bulb size, declined yield	Atayee and Noori (2020)
Potato	High	Deterioration in tuber yield by 10–20%	Atayee and Noori (2020)
	Low	Reduced tuber yield as a consequence of frost damage by 10–50%	
Button mushroom	Temperature above 20 °C	Hampering of cultivation increased occurrence of diseases	Atayee and Noori (2020)
Muskmelon	High temperature (around 27–30 °C), low humidity, and sunshine	Proper ripening, High sugar content	Kumar and Reddy (2021)
	Low	Chances of frost injury, growth reduction	
Watermelon	High (around 24–27 °C)	Production of superior quality fruits during ripening as well as maturity stage	Kumar and Reddy (2021)
	Low	Chances of frost injury, growth reduction	
Cucumber	High (around 18–24 °C)	Enhanced fruit growth, reproductive increased growth rate, rapid seed germination	Markovskaya et al. (2007)
	Low (around 17.5 °C)	Impaired fruit development	Marcelis and Hofman-Eijer (1993)
		Declined seed germination	Markovskaya et al. (2007)
White asparagus	Higher than optimum	Early head opening Purple discoloration Presence of more fibers Poor quality and reduced yield	Bisbis et al. (2018)
	Heat and drought stress	Disturbed calcium metabolism Shoot tip wilting	
Bush bean	High (around 25–30 °C)	Accelerated flower expression	Bisbis et al. (2018)
Common bean cultivars	High (around 27–32 °C)	Development of abnormal anther and pollen grains Increased flower abscission Poor fertilization of ovules Lower yield	Bisbis et al. (2018)

themselves; however, the productivity rate is reduced by 50%. One exceptional leafy vegetable that loses its potential for survivability at around 0 °C temperature, despite having its origin in a temperate zone, is lettuce (Prasad and Chakravorty 2015). Moreover, cold stress induces fluidity by causing alteration in the lipid composition of biomembranes and promotes proline accumulation (Atayee and Noori 2020). Hence, it can be said that cold temperature (chilling and freezing) stress plays a crucial role in determining the varied distribution of vegetable crops across the globe, which, in turn, ensures sustainability regarding agriculture and food availability.

2.3 Drought and Salinity

Being succulent and composing 90% water, vegetables are extremely sensitive to droughts and salinity (salt stress), which are the concomitant impacts of global warming. Drought can be defined as a period of persistently prolonged dry weather and lower precipitation than the normal range, caused due to a shortage in the water supply, which leads to severe hydrological imbalance. It is marked by the absence or presence of minimal rainfall that severely damages agriculture and any living conditions. Generally, a drought is accompanied by elevated levels of solutes in the soil, resulting in a phenomenon known as salinity that pressurizes plants to drain out (reverse osmosis) water into the environment. As a result, there is a significant increase in plant solute concentration and lowered water potential, which disrupts cellular membranes and inhibits metabolic processes (e.g., respiration, photosynthesis). Under intense dry conditions, vegetables experience electrolyte leakage, deteriorated vegetative growth, decreased chlorophyll content, and declined relative water content (RWC) in leaves. Water unavailability also results in poor fruit quality and yield. Such conditions also mark high evapotranspiration, creating high salt stress around the crop roots that hinders the water uptake pathway of plants from the soil. Therefore, water can be specified as the most crucial factor that can prevent drastic fluctuations in vegetable production and procure a good quality vegetable yield. A drought greatly poses a threat to water availability, which is reflected through several physiological variables, namely, osmotic adjustment (OA), water use efficiency (WUE), relative water content (RWC), maximum photosystem II (PSII) quantum yield (F_v/F_m), the integrity of cell membranes, and the water potential of leaves. Speaking of which, it can also be added that drought stress restricts the conversion of light energy into chemical-bound energy, which results in the accumulation of excess light. As a result, photoinhibition is most likely to occur, which, in turn, slows down photosynthetic activity, thereby signifying reduced maximum PSII quantum yield (F_v/F_m) (Giordano et al. 2021). Salinity, to a great extent, varies with season and region. For instance, its intensity is higher during the dry season in comparison to that of the rainy season due to prevailing freshwater flush, and, in terms of region, it takes a heavy toll on coastal agriculture. Coastal regions, in particular, are hit by natural disasters such as tsunamis that increase soil salinity, subsequently followed by osmotic stress, groundwater contamination, and generation of high salt-containing irrigation water. Exposure of coastal vegetable crops to such saline conditions leads to crop cultivation failures, agricultural loss, and affected soil fertility. Salt stress is inflicted on sensitive plants by means of water deficiency, the initial altered concentration ratio of K^+/Na^+ ions, and their detrimental accumulation around the crops. Furthermore, it can be reciprocated through wilting, leaf abscission, respiratory changes, epinasty and leaf curling, turgor loss, reduced photosynthesis, a decline in growth, cellular integrity loss, necrosis, potential plant death, retarded plant development, impairment of seed germination, reduction in nodule formation, and poor crop yield. The United States Department of Agriculture (USDA) categorizes onion, eggplant, tomato, cucumber, and pepper as highly to moderately saline-sensitive vegetable crops (Bhardwaj 2012). Additionally, salt stress imposes barriers to the growth of a few vegetable species such as peas, pepper, tomato, and celery (Prasad and Chakravorty 2015). Likewise, crops like pumpkins, cucumbers, snap beans, lima beans, tomatoes, squashes, peppers, peas, melons, and sweet corn are adversely affected by droughts, majorly during the flowering stage but also during the fruit development and seed germination stages. The need for sustainable agriculture has been imperative for a long time, especially when it seemed like the production of staple vegetables was threatened by the stressful conditions of the surrounding environment. To understand the in-depth effects of environmental stress, particularly salt stress and droughts, elaborate studies have been conducted on several vegetable crops, as mentioned in Table 4.2.

2.4 Flooding

Flooding is another abiotic stress recognized by the Food and Agriculture Organization (FAO) and the International Institute for Applied Statistical Research, which is responsible for huge crop loss. Vegetable crops are widely grown during the wet and dry seasons in the tropics where they are highly susceptible to the effects of excessive moisture or flooding, resulting in annual lower yields. Flood symptoms are strongly associated with increasing temperatures supported by heavy rain, which undoubtedly creates excessive moisture in the environment, thereby clogging the root zone and further affecting oxygen availability for aerobic processes. Tomato, for example, induces the excessive synthesis and accumulation of the ethylene precursor, 1-aminocyclopropane-1-carboxylic acid (ACC), as a result of lower oxygen levels under flooding conditions (Bhardwaj 2012). Excessive rainfall or flooding often leads to waterlogging, which, in turn, generates hypoxic conditions around the plant rhizosphere. This can severely impair the morphological and physiological performance of terrestrial plants in addition to changes in leaf respiration, chlorophyll content, and photosynthetic assimilation in leaves. Reports have also suggested that flooding induces the accumulation of starch and photosynthates in the leaves of sunflowers while simultaneously depleting carbohydrate levels in the roots, thereby indicating deteriorated phloem transport. As a defense

Table 4.2 Vegetable cultivation impacted by drought and salinity conditions

Stress factor	Affected crop	Impact	References
Drought	Wheat	Mostly affected during the flowering stage and grain-filling stage Inhibited growth and reduced yield Disturbed metabolic processes like photosynthesis Decreased nutrient assimilation	Hasanuzzaman et al. (2018)
Drought and salinity	Cucumber	Restricted growth Poor texture and quality Biochemistry and photosynthesis are affected	Christopoulos and Ouzounidou (2021)
Salinity	Bean	Stunted growth Inhibition of the photosynthetic activity Alteration in stomata conductivity Reduced size and number Lowered water potential Deteriorated transpiration	Ayyogari et al. (2014)
Salinity	Cucurbits	Decrease in total chlorophyll content Reduction in relative water content Decreased fresh and dry weight	Ayyogari et al. (2014)
Salinity	Chili pepper	Reduced leaf area and net assimilation Increase in the leaf area ratio Insufficient dry matter production Relative growth rate is hampered Delayed fruit ripening Retarded flowering	Julien et al. (2019)
Salinity	Potato	Reduced tuber yield	Ayyogari et al. (2014)
Salinity and heat	Potato	Salt accumulation is damaged Reduced leaf area index Effected canopy functioning Failed recovery of vegetative growth	Ayyogari et al. (2014)
Salinity	Cabbage	Shortened root and shoot length Decreased rate and percentage of germination Reduced weight of fresh roots and shoots	Ayyogari et al. (2014)
Salinity	Broccoli sprouts	Notable elevation in sulforaphane, antioxidant, glucoraphanin, and myrosinase activities Observed increase in phenolic content Decreased concentration of ascorbic acid	Šamec et al. (2021)
Drought	Leafy vegetables (spinach, amaranth, palak)	Reduced water content Poor yield	Ayyogari et al. (2014)

(continued)

Table 4.2 (continued)

Stress factor	Affected crop	Impact	References
Drought	Potato	Sprouting of tubers	Ayyogari et al. (2014)
Drought	Okra and onion	Inhibited seed germination	Ayyogari et al. (2014)
Salinity	Pea	Enhanced stomatal density	Ayyogari et al. (2014)
Salinity	Eggplant	Reduced NO_3^- uptake Elevated Cl^- uptake and accumulation	Ayyogari et al. (2014)
Salinity	Spinach	Reduced intercellular spaces	Ayyogari et al. (2014)
Moderate salinity	Rapeseed sprouts	Observed increase in antioxidant activity and phenolic content	Šamec et al. (2021)
Moderate salinity	Radish sprouts	Increase in myrosinase, total phenol, total glucosinolates, and glucoraphasatin activities has been recorded	Šamec et al. (2021)
Low-to-moderate salinity	Kale sprouts	Elevated total phenolic acid content	Šamec et al. (2021)

mechanism or response to flooding stress, various plant species have strategized potential anatomical, physiological, and morphological adaptations, with the primary being adventitious roots, hypertrophied lenticels, aerenchyma, and suberized epidermis. Adventitious roots help plants combat their incapability to take up inorganic nutrients by absorbing air and nutrients from the environment. These crops endure waterlogging in unique ways and maintain the annual crop yield. Specifically, tomato is an exceptional vegetable crop that exhibits vigorous growth of adventitious roots accompanied by reports on adventitious root growth in beans, cucumber, zucchini, Italian ryegrass, and barley. Similarly, dicotyledonous plants such as tomatoes and soybean usually develop a taproot system; however, they tend to grow adventitious roots that not only extend into the soil but also toward the soil surface during flooding (Patel et al. 2014).

3 Impact of Other Stress Factors on the Production of Vegetables

3.1 Air Pollutants

Other essentially climate change-correlated stress factors, particularly air pollutants, vastly reduce crop yield by directly impacting plant tissues and their interactions with pathogens. Such pollutants are SO_2, O_3, acid rain consisting of sulfur and nitrogen dioxides, and ultraviolet (UV) radiations. Different concentrations of O_3

and SO_2 induce varied effects on vegetables, for instance, 50–100 ppb stimulates fungal invasion, penetration, and parasitic nematode reproduction in plants with simultaneous egg hatching and spore germination (Khan 2012). On the contrary, 200–300 ppb O_3 and SO_2 have been demonstrated to influence pathogenic fungal invasion, followed by their sporulation in plants, and inhibit germination, thereby increasing the severity of plant pathogenic diseases under stressful conditions. Several anthropogenic activities have led to ever-increasing levels of sulfur and nitrogen dioxides, which, in turn, degrade the ozone layer and allow harmful UV rays to penetrate the earth's atmosphere, thus contaminating the environment and inhibiting healthy plant growth. As a consequence of exposure to UV-B rays, vegetable crops like tomatoes suffer a decline in photosynthetic rate, dry weight, plant height, and leaf area along with inhibited growth. French beans exhibit phenotypical symptoms, including bronzing and glazing along with increased susceptibility to viral infections (Prasad and Chakravorty 2015). An elevation in the concentration of ozone hampers sugar and starch composition, reduces root growth and biomass production, and mediates leafy vegetable chlorosis, and, as a result, postharvest quality is declined, which majorly affects sweet potatoes and carrots (Leisner 2020).

3.2 Greenhouse Gases

Greenhouse gases are inseparable from the topic of climate change, and, hence, a discussion on their effect on vegetable production is of significance. One such major greenhouse gas that forms one of the elemental components of life is CO_2, which has a direct effect on plants and serves as a molecular link between the biosphere and the atmosphere. Not only this, but it also harbors the ability to regulate crucial physiological processes, including respiration, transpiration, and photosynthesis. Few stipulate that exposing vegetable crops to elevated CO_2 (eCO_2) levels, owing to anthropogenic activities, can exceptionally elevate crop yield by stimulating photosynthetic rate and increasing leaf area and the efficiency of water uptake. Examples include an increase in the length and number of roots in sweet potatoes during propagation. Moreover, eCO_2 generally enhances the efficacy of nutrient uptake; however, evidence shows a decline in kohlrabi (Abou-Hussein 2012). A CO_2 concentration of 1000 ppm in the leaves of red lettuce was demonstrated to increase caffeic acids, sugars, and flavonoids, whereas the same CO_2 concentration has been noted to negatively impact nutritional parameters, including amino acids (methionine, leucine, threonine, isoleucine, tyrosine, lysine, and phenylalanine), vitamin C, essential fatty acids (linolenic and linoleic acids), proteins, and minerals (zinc, Zn; iron, Fe; magnesium, Mg; manganese, Mn; and calcium, Ca). At 800–1000 ppm CO_2, vitamin C levels in the stems and leaves of Chinese cabbage, celery, and lettuce were increased. Likewise, total chlorophyll and phenolic content as well as antioxidant activity were enhanced in spinach and lettuce at 700 ppm CO_2. Despite all the advantages offered by CO_2, a noteworthy elevation in the level of atmospheric CO_2 beyond the threshold limit can pose serious threats to vegetable production, for instance, eCO_2-stimulated deterioration in the levels of macronutrients (potassium, K; nitrogen, N; and potassium, P), proteins, and organic acids (oxalic, malic, and citric acids) in tomato fruits (Christopoulos and Ouzounidou 2021). Moreover, it induces an elevation in sugar content (reducing sugars, glucose, and fructose) that lower tuber quality increases acrylamide production, and browning, and regulates susceptibility to diseases and tuber malfunctioning in potatoes along with a significant drop in calcium, protein, and potassium levels (Leisner 2020).

4 Conclusions and Future Perspectives

Climate change is a gradual phenomenon that has only been visually pertinent when its substantial effects could be noticed on agricultural practices and crop production. Although we are aware of a few causes of climate change, a lot remains unknown to us, but the undesirable impacts of the very same on agriculture have the potential to disturb the generic balance between nature and living beings. From theoretical and practical knowledge, it can be deduced that climate greatly controls agricultural patterns and even a slight alteration can completely hamper the annual cropping per se. As a consequence, greater reflection will be evident in the global food demands. With the limited availability of literature and resources, few adaptive measures have been developed by scientists focusing on plant stress physiology research, but the highlight is the fact that these measure depend on specific countries. For instance, farmers belonging to underdeveloped and developing countries have to make do with the sparse agricultural options available and adapt to climate changes through innovative tools to maintain the yield and quality of their crops. With regard to this, the utilization of water through efficient management systems marks one of the essential steps toward adaptation. Along with this, cultivating advanced cropping practices like the use of shelters, raised beds, and mulching can help protect against flooding and high temperatures, and grafting techniques can eliminate the susceptibility of vegetable crops to soil-borne diseases, which enables the development of resistant crops. Harnessing genome sequencing of numerous vegetable crops can help identify genes having the capability to confer stress-tolerant and stress-responsive phenotypes, in addition to using new farm techniques like resource conserving technologies (RCTs) and modified crop and pest management practices. However, most importantly, educating farmers regarding indigenous practices and imparting technical knowledge along with spreading awareness about the serious threats posed to the farming communities and global food security by disastrous climate change can unite people from every social level toward developing immediate measures and utilizing the available resources most beneficially, thereby favoring vegetable production even under the most undesirable climatic conditions.

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Chapter 5
Impacts of Climate Change on Fruit Physiology and Quality

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Abstract The world is currently experiencing a faster rate of warming than ever before, resulting in climate change that affects natural vegetation and ecosystems. Changing phenological aspects and both the quantity and quality of global fruit production are affecting farmers' incomes and food security. Fruit and nut species may survive in the wintertime in their native environments due to dormancy. Climate change also affects winter chilling, thus reducing fruit production and quality since most temperate fruit and nut species require exposure to chilling conditions for their proper development. Various strategies, including cultivar selection, defoliation, microclimatic modulation, color shedding, and usage of dormancy-triggering drugs, have been explored to bypass dormancy limitations. Rising temperatures accelerate fruit tree maturity, leading to earlier harvests. Higher temperatures and CO_2 levels produce fruits and vegetables with higher ascorbic acid and phenols. Climate change shortens the vegetative and reproductive phases. Higher temperatures reduce the vegetative phase of most fruit crops, thus shortening their blooming period. Changes in the blooming seasons might introduce new insect pests. Global warming and

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unpredictable moisture levels will affect future food production despite increased carbon dioxide levels. Carbon dioxide has a smaller impact on most substances as opposed to temperature. Faced with these kinds of challenges to world fruit production, mitigation and adaptation strategies relating to strategic scientific evaluation should be developed.

Keywords Climate change · Dormancy · Nutrition · Fruits · Food security · Global warming · Productivity

1 Introduction

Climate change is described by the United Nations Framework Convention on Climate Change (UNFCCC) as "a change that is attributed directly or indirectly to human activity which alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods" (Rogelj et al. 2017). Climate change intensifies temperatures, increases precipitation, and thus increases the probability of severe occurrences, including frosty spells, cold waves, floods, and droughts (Pereira et al. 2021). Climate change affects plant development, blooming, ripening, and fruit quality. Extremely irregular precipitation patterns and unanticipated warm temperatures, as a result of climate change, may affect agricultural yield (Wagner et al. 2021). Temperature increases impact flavonoid concentration, sugars, hardness, antioxidant activity, and organic acids. In one study, it was discovered that an elevation in carbon dioxide in the atmosphere reduced potato sugar content and caused tuber deformity and disease (Arumugam and Rabert 2022). Some nations' banana crops were harmed by rising temperatures and changing rainfall patterns. Water stress and excessive temperatures during blooming affect ovule and pollen viability, fruit development, and production. The sterility of papaya stigma and stamen is induced by high temperatures, which trigger flower loss and sex changes in female and hermaphrodite flowers (Hirpo and Gebeyehu 2019). During blooming, low temperatures cause flower drop in mango, guava, litchi, and other fruits. Vital pollinating organisms, including moths, bees, and butterflies, are diminishing in number, geographic range, and pollination activities due to climate change. Rising temperatures during the development of fruits increase the occurrence of physiological problems such as mango spongy tissue and black tip, fruit fracturing, citrus granulation, etc. (Raj 2021). Climate change affects agricultural pests as well. Warm and moist circumstances facilitate fruit fly infestation in guava, carambola, citrus, etc. (Haokip et al. 2020). Such conditions are also suitable for sucking pests, mildew, blight, etc. Maintaining consistent production requires developing new cultivars with an increased yield potential and resilience to different stressors (water shortages, flooding, saltiness).

Breeding strategies should enhance the heat resistance of essential tropical and subtropical fruit crops (Khan et al. 2018).

Earth has gone through glacial and interglacial eras over the previous million years. According to the Vostok and Dome C ice drilling operations in Antarctica, carbon dioxide levels rose from 180 to 280 ppm during the interglacial era (Yan et al. 2019). Carbon dioxide levels were 280 ppm before industrialization and have now risen to 400 ppm. According to predictions, carbon dioxide levels will exceed 700 ppm and the temperature will rise by 1.8–4.0 °C (Chen and Chen 2020) in the near future.

In the coming decades, environmental changes will continue to threaten food security, healthcare, and well-being (Dhimal et al. 2021). Changing climate, increased ground-level ozone, variations in water resources, CO_2 fertilization, soil deterioration, deforestation, and alteration in land use may directly affect agricultural productivity (Du Preez et al. 2020). Variability in pests, diseases, and pollinator numbers and dispersion might potentially have an indirect influence on agriculture. Without effective and broad adaptation and mitigation methods, global nutritional indemnity might be compromised (Kerr 2017).

Climate change, notably in the form of rising global temperatures and CO_2 concentration, more climatic variability, and more severe weather situations, can also lead to several alterations in global and regional economies (Bruhwiler et al. 2021). Climate change has been mostly linked to increasing human emission of greenhouse gases (GHGs) ever since the preindustrial period, particularly deforestation and fossil fuel depletion. This affects both human and natural systems, especially agriculture, which uses 37.5% of the planet's surface (Fawzy et al. 2020). Changing climate has altered agricultural productivity, which affects food supplies, crop pricing, and farmer earnings. According to research, climate change also affects agricultural quality (Praveen and Sharma 2019). Nutritional value, phytochemical content, health-beneficial qualities, sensory features, and safety all define the quality of a crop (Kyriacou and Rouphael 2018). Evaluating the impact of climate change on the properties of a crop is especially crucial for fruits, the properties of which are controlled by the availability and amount of certain phytochemicals and nutrients like minerals, amino acids, vitamins, and carbohydrates. The nutritional quality of fruits reduces the severity of diet-related chronic illnesses by providing minerals, vitamins, and phytochemicals (Yahia et al. 2019). Nutrition (Tables 5.1 and 5.2) is one of the biggest health concerns at present, and the total worldwide mortality caused by poor consumption of fruits and vegetables is estimated to be 2.635 million deaths yearly. Vegetables and fruits reduce the risk of degenerative illnesses, congenital heart defects (CHDs), obesity, cataract, and diabetes (Yahia et al. 2019).

The health benefits of fruits come from their nutrients and phytochemicals. Phytochemicals defend plant tissues against climatic factors, pests, and diseases. Polyphenols are the most researched class of compounds due to their ubiquity (thousands in number) and benefits to human nutrition as anti-inflammatory and antioxidant agents (R Dias et al. 2017; Abdullahi and Hamza 2020). Red and purple fruits contain anthocyanins (flavonoids) and protect from neurological disorders, cardiovascular diseases (CVDs), diabetes, and cancers. Every fruit contains

Table 5.1 Countries that generate a large amount of fresh fruits

Total top 25 countries		34,435,548 tones	
Rank	Countries	Tones	Percentage (%) of the top 25 countries
1.	India	10,755,000	31.25
2.	China	3,056,082	8.87
3.	Vietnam	2,803,489	8.14
4.	Pakistan	2,547,440	7.40
5.	Iran	1,682,769	4.89
6.	Myanmar	1,448,652	4.21
7.	Indonesia	1,337,349	3.88
8.	Nigeria	1,144,551	3.32
9.	New Guinea	1,136,054	3.30
10.	Thailand	948,785	2.76
11.	Colombia	806,346	2.34
12.	Saudi Arabia	770,015	2.24
13.	Bangladesh	661,823	1.92
14.	Dorn. Republic	618,763	1.80
15.	North Korea	561,848	1.63
16.	Mexico	553,062	1.6196
17.	Turkey	525,741	1.53
18.	Egypt	517,371	1.50
19.	South Sudan	425,461	1.24
20.	Sudan	425,000	1.23
21.	Nepal	397,653	1.15
22.	Niger	386,261	1.12
23.	Costa Rica	385,345	1.12
24.	Uzbekistan	279,570	0.81
25.	Philippines	261,118	0.76

Data compiled by the authors from FAOSTAT (2019)

phytochemicals and minerals with antioxidant, antifungal, antimutagenic, and antimicrobial activities. Due to its interactions with vitamin C and phytochemical makeup, the antioxidant properties of one apple are equivalent to the amount of 1500 mg of vitamin C. (Begum et al. 2019; Walia et al. 2019). This chapter reviews the impacts of climate change on fruit crops. We begin by discussing climate change and farming. Next, we evaluate the consequences of and the ways to mitigate the impacts of climate change on the nutritional value of fruits and also provide suggestions for future research.

Table 5.2 Nutrients that are affected by climate change

Nutrient	Relevance to human nutrition	Source
Vitamin C	In the human body, vitamin C acts as an electron donor. Electron donation has antioxidant effects, so vitamin C is critical to disease prevention. Additionally, inadequate vitamin C consumption can potentially cause scurvy.	World Health (2005)
Carbohydrates	Carbohydrates are humans' primary energy source. Fruits provide carbohydrates in the forms of fibers and sugars. Carbohydrates are especially healthy when consumed in whole fruits because they provide a slow release of energy in the body. Additionally, adequate fiber intake can reduce the risk of colorectal cancer.	Reynolds et al. (2019)
Calcium (C22)	Calcium plays a vital role in providing strength to the human bones, and inadequate calcium consumption can lead to bone loss and osteoporosis. Additionally, calcium is involved in most metabolic processes, including neural conduction, muscle contraction, and blood clotting	World Health (2005)
Magnesium (Mg)	In all, 50–60% of the human body's Mg^{2+} is located on the surface of the bones. The remainder is found in the muscles and soft tissues, where it helps maintain the electrical potential of cell membranes in the muscles and the nervous system	World Health (2005)
Iron (Fe)	Most of the iron in human bodies is found in the form of hemoglobin. Hemoglobin is a protein structure that transports oxygen from the lungs to the remainder of the body. Iron deficiency is the most common nutritional deficiency worldwide. Severe iron deficiency causes anemia, a condition in which oxygen delivery to the tissues is diminished	World Health (2005)
Anthocyanins	Anthocyanins are a subclass of flavonoids commonly found in red to blue pigmented plants. They act as antioxidants in the human body. Over time, their consumption is correlated with a decreased risk for many cancers and chronic diseases.	Dangles and Fenger (2018)
Flavonoids	Flavonoids are a class of phenolic compounds that are commonly found in the skins of fruits. They act as antioxidants, and their sustained consumption over time is correlated with a decreased risk for many cancers and chronic diseases	Hoensch and Oertel (2015)
Antioxidants	Antioxidants reduce the negative effects of reactive oxygen species in the body. They are also critical to cell membrane stability. Many of the nutrients listed in this table function as antioxidants	World Health (2005)
Potassium (K)	Potassium is an essential player in the maintenance of total body fluid and electrolyte balance. Potassium consumption at or above the daily recommended values can help protect against heart diseases and high blood pressure.	World Health (2012a)
Sodium (Na)	Sodium is the main ion present in the extracellular fluid in the body. It is a critical component in cell signaling. However, excessive consumption of sodium (primarily from processed food) is associated with increases blood pressure and heart diseases.	World Health (2012b)

(continued)

Table 5.2 (continued)

Nutrient	Relevance to human nutrition	Source
Phenolic compounds	Phenolic compounds are a type of secondary metabolites commonly found in food plants and closely linked to their nutritional quality. They act as antioxidants, and, over time, their consumption is linked to a decreased risk for many cancers and chronic diseases	Lin et al. (2016)
Proteins	Proteins are essential to human development, muscular function, and mental function. They are made up of combinations of amino acids. Both quality and quantity are important when it comes to proteins. Uncooked whole foods are good sources of high-quality bioavailable proteins.	Green et al. (2022)
Tannins	Tannins are a type of phenolic acids that are typically found in immature plants and create an astringent taste. They can bind to dietary proteins during digestion, making them harder to digest. Therefore, overconsumption of tannins can have a negative effect on nutrition.	Soares et al. (2020)
Sugars	Sugars are one of the common carbohydrates found in fruits. “Free sugars” or sugars that have been refined to some extent and their consumption are correlated with obesity, diabetes, and other noncommunicable diseases. However, the sugars that are found in whole fruits are nutritious carbohydrates, which will be slowly absorbed by the body to provide energy. Their consumption is associated with lower body weights and can improve gut health.	World Health (2015)

2 Fruit Crops

Perennial fruit crop orchards need big expenditures; climatic unpredictability may affect crop performance from year to year, thus also affecting farmers’ incomes and their willingness to continue maintaining such farmland (Wolfe et al. 2018; Pathak et al. 2018). Farmers would stop planting these crops after incurring many years of losses. In Himachal Pradesh, rising temperatures, lengthy periods of dryness throughout summers, and less snowfall during winters have left major apple-growing regions unsuitable, pushing farmers to migrate to other more economical products (Johnson et al. 2019). Temperature influences blooming, and the proportion of hermaphrodite flowers is higher in late developing panicles, which is interrelated with elevated warmth. Guava and mango are damaged by cold and hot waves (Nath 2021). Latency in monsoon, prolonged drought, and unexpected rainfall during the water deficit season can lead to the promotion of blooming, while higher temperatures during flowering and fruit development are common occurrences in citrus crops. Higher temperatures (31–32 °C) promote banana plant maturation, minimizing the formation of bunches. High temperatures (more than 38 °C) and intense sunlight cause sunburn in unprotected fruits (Lima et al. 2021; Kaur 2022). High heat and dryness can trigger clump choking. During the vegetative stage, soil moisture shortage promotes poor clump development and fewer and smaller tips. Water deficiency generates underfilled tips and uncommercial bunches and also lowers bunch mass and elongation. Stunted bananas are flooded for more than

48 hours (Pegg et al. 2019). Originally from temperate places, grape has adapted to tropical climates via a cycle of two pruning resulting in one crop. As a result of the changing climate, growing degree days (GDDs) vary, thus hastening phenological phenomena (Lahav et al. 2019).

Climate changes influence agribusiness, and, as such, strategic approaches must be devised to protect global agricultural production. In the last 100 years, Japan's temperature has risen by 1.2 °C. In Japan, cultivars and fruit-growing technologies have improved greatly within the last 100 years, making it impossible to compare present-day agricultural production to that of 100 years ago (Raina et al. 2016). Since the 1970s, Japan's average temperature has undergone significant changes, particularly noticeable since the 1980s. Since 1990, the average temperature is 0.7 °C greater than what it used to be in 1970 and 1989. Fruit trees are especially sensitive to climate change since perennial crops are less resilient. Global warming also affects Japanese fruit crop yields (Coello-Camba and Agustí 2017).

Climate change is a lifelong variation in climate caused by human activities, which modifies the global atmosphere. The 1990s have been the hottest decade of the century, and the hottest year was 1998 (Baldi 2017). An increase in temperature is ascribed to a disconcerting increase in the air's concentrations of nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons (CFCs) caused by industrialization (Jogdand 2020). In 2100, carbon dioxide levels might be 100% greater than those in the preindustrial epoch. This agroclimatic indicator is unlikely to stay steady for the reason that with the end of the twenty-first century, the world's temperature is estimated to hike to 6 °C compared to preindustrial conditions (Defrance et al. 2020). Atmospheric gases, airflow, temperature, light, water, moisture, nutrient cycling, and rhizosphere conditions define an orchard's climate. Regarding plant development, dryness, temperature, ultraviolet (UV) rays, etc., are all stressors for a crop. Climatic conditions may determine the physiological stages; for example, photosynthesis relies on temperature, radiation, CO_2, moisture, and nutrients (Lakso 2018; Ferrante and Mariani 2018). Growing a crop in an ecophysiologically inappropriate area raises the production costs and diminishes financial prosperity. Growing conditions at a specific location determine the plant size, length of the morphological and physiological stages, harvest timing, and quantity (Dang et al. 2021).

3 Biological Foundation of Plant Climate Adaption

Plants' ability to adjust to both indirect and direct climate changes impacts conservation threats, environmental and agricultural viability, and food production. Dealing with intensifying changing climate, it is vital to study how life-forms and societies adjust to their new circumstances. Several species have moved to higher latitudes and upslope to colder places (Lavorel et al. 2019; Sattar et al. 2021). These alterations have caused regional loss of biodiversity and population reductions at hotter area borders and range expansions into formerly colder poleward latitudes

Fig. 5.1 The key features of plants regarding climate adaptations (Anderson and Song 2020)

and upslope elevations. Several species currently appear and reproduce earlier in the year due to reduced winter season, early growing seasons, and protracted water shortages (Spence and Tingley 2020).

In order to exist, cold-climate fruit trees become dormant in winter. Dormancy requires precise parameters, including moderate temperatures and durations. Choosing the correct tree cultivar for a climatic zone is vital for excellent crop output. Dormancy allows fruit trees to withstand cold in their native settings (Studd et al. 2021). During this time, physical expansion ceases and most physiological functions slow down. Plants detect temperatures throughout the season and adjust their physiology accordingly (Fig. 5.1; Anderson and Song 2020). Early blossoming and harvest reflect altered dormancy mechanisms (Whitehouse et al. 2020).

4 Effects of Climate Change on Fruits

4.1 Climate Change

Climate change will affect agriculture in both indirect and direct ways. Variations in temperature, water resources, and climatic parameters will affect crop production. Temperature increases cause accelerated crop growth, shortened periods, and reduced outputs (Dixit et al. 2022). Temperature influences respiration and

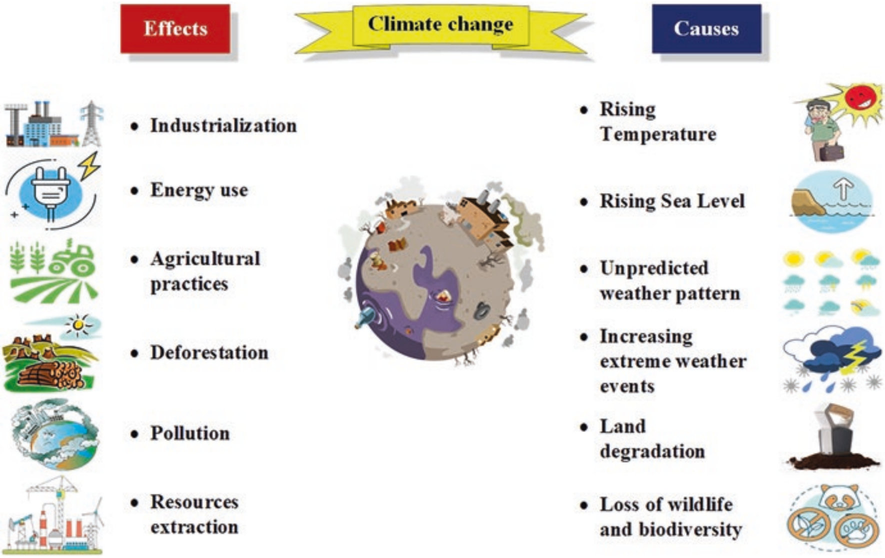

Fig. 5.2 The main causes and impacts of climate change (Evincism 2022)

photosynthesis. Maize, sorghum, and sugarcane (C_4) have a higher photosynthetic optimal temperature than do fruits, vegetables, and cereal crops (C_3) (Jobe et al. 2020).

Rising CO_2 levels in the environment may stimulate photosynthesis in C_3 crops and water use efficiency (WUE) in C_4 and C_3 plants, thus enhancing the development of plants. Diminished canopy transpiration or variations in metabolite or enzyme concentration may diminish protein, vitamin, and mineral concentrations in the consumable section of the crops (Raj et al. 2021). Almost all C_3 crops are sensitive to climate change. Fruits and vegetables have been less researched than have principal harvests in recent years (Rasul 2021).

Moreover, in addition to direct impacts, rising temperatures also affect the harvests of vegetables and fruits due to reduced farmer work efficiency, leading to a decrease in agricultural output (Tudi et al. 2021). Several fruit and vegetable crops demand substantial labor contributions, particularly for cultivation and harvesting, and, thus, extreme heat can adversely damage this industry. Directly and indirectly, climate change influences numerous environmental variables (Lemi and Hailu 2019). Warmer temperatures enhance ground-level ozone creation, which inhibits plant photosynthesis and development. Climate change affects all life-forms, and a decline in pollinator numbers might affect agricultural productivity (Sage 2020). Climate change may also exacerbate agricultural losses from pests, diseases, weeds, and fungi (Fig. 5.2; Evincism 2022). Between 1960 and 2012, hundreds of diseases and pests migrated 2.7 km year^{-1} toward the poles.

4.2 Global Warming

High heat and dryness may reduce agricultural and animal output, especially milk yields. Rain-fed areas may need irrigation, causing greater expenses and groundwater tension. Changing regular rainfall patterns, heavy storms, and floods may hinder cultivation and harvesting (Steiner et al. 2018). An ideal growing temperature may be that of higher-latitudes regions, where soil and nutrients are more favorable to crops, thus making lower-latitude locations the least profitable. If winters are not cold enough, then plant pests and insects may persist and flourish. As humidity and temperature fluctuate, additional pests may enter every zone, for example, lower-latitude pests may transfer to higher-latitude regions (Larson et al. 2019; Tian and Benton 2020).

4.3 Biodiversity Loss

In locations where wild vegetables and fruits make up a large part of the diet, biodiversity loss might affect food supply. Field-grown crops and cattle rely on environmental resources, including pollinators, pest predation, and soil micro- and macroorganisms (Falahzadah et al. 2020).

Within the last several years, pathogens, insecticides, and habitats have harmed pollinators. Several fruit and vegetable plants are pollinator-dependent, and, therefore, the complete demise of pollinators might lower world fruit production by 23%, vegetables by 16%, and nuts and seeds by 22%, with significant health consequences (Majewska and Altizer 2020; Hristov et al. 2020).

Complex ecosystem processes make it impossible to estimate the proportion of biodiversity required for agricultural output. Achieving a high degree of biodiversity boosts agroecosystems' tolerance to their changing environment (Jiao et al. 2022). Diversifying agroecosystems, increasing crop genetic variety, integrating livestock and crop output, and managing soil organic matter all lessen environmental change susceptibility. Diversifying crops decreases diseases and pest and weed invasions and improves tolerance to climatic instability and fluctuations (Jabran et al. 2020). High-diversity crops in low-income areas are more susceptible to storms and water deficiency. Small-scale farmers in tropical areas are sensitive to climatic unpredictability, especially irregular rainfall (Aguilera et al. 2020). To cope, they depend on biodiversification, for instance, growing a high-pitched variety of plants every year, notably multiple kinds of identical plants, utilizing water stress-resilient plant types, rotating crop sites, and planting trees to provide shelter and preserve moisture (Peltonen-Sainio and Jauhiainen 2019).

4.4 Impact on Phenology

Physiological time shifts, i.e., phenology is a major climate change phenomenon. The initiation of flowering in fruits of temperate regions is strongly regulated by low-temperature. Genetic makeup, light cycle, and temperature all work together to determine blooming (Ben Michael et al. 2020). Wolfe et al. found a 2–8-day acceleration in spring phenology for woody perennials in northeast United Stated from 1965 to 2001 (Hall et al. 2016). Comparable phenological changes with an increasing temperature tendency have been observed for several other high- and mid-latitude locations. Cox's Orange Pippin, Apple Boskoop, and Golden Delicious have all bloomed 10 days sooner in the past 20 years than in the preceding 30 years, less than the 14 days recorded for Germany (Haokip et al. 2020). Variations in tree blooming timings reveal that dormancy breakdown mechanisms are starting to shift, presumably because of climate change (Kijowska-Oberc et al. 2020).

4.5 Impact on Pollination

Changing climate might disrupt each element of an agroecosystem, including insect pollination. Climate change has reduced pollinator populations. Extreme temperatures inhibit fertilization and fruit development. Improper chilling may affect the crop yields of cross-pollinated fruits like walnuts and pistachios (Grubisic et al. 2018; Quigley et al. 2019). Optimal pollination and fertilization temperatures for temperate fruits, including cherry, apple, plum, and pear, are 20–25 °C. Freezing temperatures and damp or misty circumstances restricted sour cherry pollination in the United States (Distefano et al. 2018; Beltrán et al. 2019).

4.6 Impact on Patterns of Blooming

According to Vedwan and Rhoades, climatic variations impact flowering, holding, fruit productivity, and apple quality in India's Western Himalayas. Elevated temperatures from January to March (winter and spring) contribute to early blossoming, which overlaps with spring frost, resulting in frostbite to apple blossoming (Guo et al. 2019). In temperate climates, frost may also harm crops. Spring frosts may damage apples and other temperate produce. During the flowering phase, a small instance with temperatures minus zero might harm or destroy flower buds. Mild frosts reduce the quality of the fruit; extreme frosts jeopardize the production (Pardee et al. 2018).

4.7 Impact on Pest and Disease Incidence

Changing climate might affect the growth of pathogens, host tolerance, and host–pathogen relationships (Kreiter 2018). Climate change might support shifts in population expansion rates, geographical range of species' habitats, elevation in the number of generations, overwintering, elongation of reproductive cycles, crop–pest phenology synchronization, insect interspecific interactions, and migratory pest invasions. Besides having a direct influence on apple output, changing climate has worsened diseases and insect outbreaks, causing yield reductions (Raza et al. 2019; Garrett et al. 2021).

4.8 Impact on Dormancy and Chilling Requirement

Dormancy protects plants' delicate tissues from harsh weather. Extreme weather events might modify the adaptation of several temperate fruit crops and cause major production issues (Nautiyal et al. 2020). Most fruit and nut plants particularly need winter chilling for economic production. Mild winters cause aberrant bud break and growth in temperate fruit plants. Warming may alter temperate tree fruits' winter chilling, thus creating additional varieties or genotypes (Andersen 2018). Changing crop sizes and maturation phases at the harvesting level impact both productivity and fruit development. Melting Himalayan ice caps will lessen the cooling impact needed for the blossoming of cherry, apple, etc.. Limited regions with acceptable chilling rates are present now for pears, cherries, and apples, and computational estimates forecast that none of these will exist by the mid-century (Delgado et al. 2021; Hajinia et al. 2021).

4.9 Impact on Fruit and Postharvest Quality

Temperature increases of 0.7–1.0 °C may alter the region acceptable for Dashehari and Alphonso mango cultivation (Tirkey et al. 2022). A 0.2 °C temperature increase may dramatically reduce guava's red-colored patches. Direct daylight of 35 °C results in 2.5 times harder mandarins than does shade (20 °C). In rising temperatures, cell wall activity of enzymes decreases, thus delaying ripeness (Chonpracha 2019; Cosme et al. 2022).

Change in temperature may directly influence photosynthesis in plants, and an increase in the world's temperature can be predicted to come up with a substantial effect on the postharvest value by affecting sugar production, antioxidant chemicals, organic acids, hardness, and peel color. High-temperature-grown grapes contain more sugar and less tartaric acid (Srivastava 2019; Hameed et al. 2020; Pathak et al. 2021).

4.10 Ozone Layer Reduction and Repossession

The stratospheric ozone layer, which protects the planet from UV rays, has been declining because of man-made emissions of CFCs and nitrous oxides, but new data show regeneration because of decreasing CFC exposures. Antarctica's ozone hole increases annually, although that of the Arctic's varies greatly (Molina 2020). Clouds, elevation, surface reflection, and stratospheric distance all affect plant sensitivity to UV-B radiations. Because of natural fluctuations in these variables, the consequence of ozone layer maintenance is not yet identified in UV-B observations. UV-B rays damage plant membranes, proteins, DNA, and RNA (Kuttippurath and Nair 2017; Wilka et al. 2021). A meta-analysis of the impact of UV-B rays on productivity has indicated that several fruits, like strawberries and sea buckthorn, and herbaceous plants, like carrots, tomatoes, beans, spinach, gourds, radishes, and cucumbers, exhibit a more massive loss in productivity than do woody plants (Fuentes et al. 2022; Eleftheratos et al. 2022).

4.11 Diminution of Nonrenewable Reserves

Reduction of nonrenewable sources involves lower accessibility of minerals needed for fossil energy, fertilizers, or infrastructures and degradation of irrigation aquifers. A limited supply of these inputs might affect agricultural output unless other approaches are used, for example, sustainable power or biological fertilization (Rahman et al. 2022).

Currently, commercially usable phosphate resources will run out in 50–100 years. Thus, biowaste and sewage sludge recycling may become economically sustainable. Modern farming utilizes biofuels to produce chemical fertilizers, operate agricultural machines, and much more (Blengini et al. 2019). Decline of fossil fuel reserves or incapability to utilize them due to climate change may threaten agricultural productivity until sources of renewable energy are enhanced. This will be a greater concern in modern agricultural systems than in small–scale farming that primarily depends on physical labor (Chen et al. 2020; Kalair et al. 2021).

Decline of freshwater supplies may affect agricultural productivity, particularly in locations where groundwater contributes to irrigational needs (Corwin 2021). Variations in rainfall, river degradation, and increasing water consumption deplete groundwater (Jiang et al. 2019). Climate change models predict precipitation rises in high-latitude regions and in few portions of the tropics and also declines in certain tropical and lower mid-latitude zones (Mankin et al. 2019). Small-hold farmers in dry, Asian, semiarid tropics and African mega-deltas are especially subjected to water fluctuations (Rahman et al. 2019). Global food trading diminishes groundwater in supplying regions. Irrigation water is primarily utilized for principal food crops, especially wheat, and not more than 10% is devoted to vegetables and fruits that reflects the number of acres required for these crops (Adhikari et al. 2018; Benbrook et al. 2021).

4.12 Water Quality

Water quality affects crop quantity and quality. In recent years, water quality variations linked to environmental alteration have imposed restrictions on the farming industry, and these patterns are predicted to persist (Jayasiri et al. 2022).

Saltwater contaminates irrigation water. Crops have different salt thresholds. Saltwater intrusion reduces crop production but has variable effects on quality. Salt content decreases the worth of many fruit crops. Salinity may enhance sugar concentration in carrots and asparagus and soluble solids in tomatoes and watermelons (Zhu et al. 2022).

Changing climate may worsen saltwater challenges, which affect health via water and nutrition. In climate-vulnerable coastal locations like Bangladesh, growers face extra difficulty when they switch from saltwater irrigation supplies to deeper groundwater levels, which include significant arsenic concentrations. Arsenic may persist on a crop's exterior after plucking and threaten the health of consumers. Variable patterns of precipitation and water shortages may raise salt levels in inland freshwater ecosystems, thus impacting irrigation and the quality of drinking water (El Behairy et al. 2021).

Polluted irrigation water reduces agricultural quality and yield. More than 10% of the world's population eats food watered with wastewater discharges or feces-contaminated surface water. Most of these individuals reside in poor, arid, and semi-arid nations. Rising water shortages, growing populations, and realization of wastewater's fertility benefits are pushing the use of polluted water for agriculture. Pathogen-contaminated municipal wastewater used for watering and postharvest operations are associated with food-borne sickness. This is a concern with uncooked vegetables and fruits (Manikandan et al. 2022).

High quantities of chloride, salt, and boron in irrigation water may harm crops and diminish productivity if absorbed by plants. Industrial and agricultural causes contribute to toxicity levels in water, along with the discharge of dangerous chemicals in agricultural watersheds and the pumping of irrigation water (Machado and Serralheiro 2017). Usually, agricultural sources of water have chemical amounts below toxicity levels, but most fruit and vegetable crops have limited boron resistance, so even low amounts may harm them. Perennial crops are more vulnerable to irrigation water poisoning. Lastly, excessive nutrients in irrigation water, particularly nitrogen, threaten water quality (Vetrimurugan et al. 2017).

This is frequently the consequence of overfertilizing farmland, which pollutes irrigation water and marine environments. Increased nitrogen contents postpone maturation in sensitive crops, including avocado, apricot, and citrus (Erkan and Dogan 2019; Wurtsbaugh et al. 2019). This reduces harvestable green crops and might alter fruit quality metrics like sugar concentration. It might also induce bigger growth of crops, making them more susceptible to lodging in tropical storms (Tyagi et al. 2017).

4.13 Land Use

Over the past 40 years, soil degradation and pollution have degraded about a third of the agricultural lands worldwide. Rapid urbanization, rising sea levels, production of renewable energy, for example, solar cells on farmland, and bioenergy, and certain other nonfood crops also cause agricultural land degradation (Lavorel 2019; Corlett 2020). Rising meat consumption and feeding supply have led to the conversion of woodlands to farmland. The proportion of worldwide farmland has stayed unchanged for centuries. Habitat loss accelerates numerous environmental problems, including changing climate and biodiversity loss, and indirectly may have adverse consequences on agricultural production, e.g., via deficit of wild foods (Prăvălie 2021). Soil degradation includes erosion, compaction, desertification, salinization, and invasive plants. Organic matter in soil is critical to long-term sustainability (Liebig and Toledo 2019). Industrial agricultural techniques, including monocropping, little use of natural manure, and crop waste disposal, are some of the primary causes of depletion of organic matter in the soil (Sanaullah et al. 2020).

Acidic rainfall or nitrogen fertilizers may acidify fields. Acidic raindrops come from the interaction of molecules of water with nitrogen oxide or sulfur dioxide in the surrounding air, typically from human sources like power production and various industries. Acidification of soil reduces the availability of nutrients and hinders the growth and development of plants, unless in alkaline soils (Cheng 2018; Brusseau et al. 2019). Limestone and calibrated fertilizers reduce acidification-related damage to crops. Phytotoxicity is the hazardous impact of phytotoxins, allelochemicals, trace metals, salinity on plants, and pesticides. Soil contaminated with harmful metals like cadmium and aluminum harms agricultural production and health and the environment. Metals induce oxidative stress, thus reducing biomass production (Yaashikaa et al. 2022).

5 Climate Change Effects on Few of the Most Consumed Fruit Crops in the World

Climate change affects the nutritive and phytochemical content of apples worldwide. Apple producers in India's Himalayan states have reported losses in productivity, fruit quality, and fruit size and hikes in pests and diseases (Kour et al. 2022). Apple growers adapt to climate changes by altering apple cultivars or plantings. In the last 50 years, climate change has affected five apple-producing areas in China. Climate change has influenced distinct climate parameters in each location, with varied consequences on apple quality. In two places, rising temperatures and lower sun radiation enhanced apple anthocyanin content, vitamin C levels, and the sugar–acid ratio (Stewart and Ahmed 2020). Certain places in China have worse apple quality because of temperature changes beyond the appropriate limits, sunlight durations under the permissible limits, and moisture rates below or above the optimum value (Rissman et al. 2020). Despite higher temperatures, radiation from the sun, and precipitation in apple-growing areas of Japan during the last 40 years, dissolved solid content has steadily risen. An increased soluble solid concentration suggests a higher amount of sugar, which improves the taste for humans (Champ and Kundu-Champ 2019). In Slovenia, increasing sun radiation and temperatures boosted apple phenolic levels, suggesting nutrient value. Prolonged durations of warm temperatures and sunlight exposure cause sunburn in apples, which reduces productivity. Climate change has increased the sunburn rates, which may reduce agricultural production (Munné-Bosch and Vincent 2019; Morales-Quintana et al. 2020).

German research has revealed that using hail netting to shelter apples from sunlight increased soluble solid content, anthocyanins, and vitamin C levels. Apple trees covered with white-red or white hail netting decreased temperatures and sun radiation while boosting moisture without affecting nutrition (Vuković et al. 2022). Colored hail netting lowered temperature and sun exposure despite increased moisture, resulting in economically substandard apples assessed on soluble solid content, anthocyanin, and vitamin C levels. Based on the conclusions, climate change factors improve the nutritive value of apples up to a particular level (Bowling et al. 2020). When temperatures, sun radiation, and moisture exceed this barrier, apple quality declines. Increasing temperatures may assist one apple-producing area now, but they might hurt the same region in the coming years if they remain elevated. Apple-producing areas must use climate-resilient measures to reduce yield losses and maintain nutritive value, such as utilizing white hail netting to avoid sunburn (Unterberger et al. 2018; Stewart and Ahmed 2020).

Most studies on climate's influence on the nutritive value of grapes focus on phenolic components like flavanols and anthocyanins. These antioxidant molecules also affect wine taste. Climate change's impact on grape nutrients varies by geography. Several experimental and observational investigations have linked temperature to phenol, flavanol, and anthocyanin content (Spinardi et al. 2019). Several studies show that high temperatures reduce phenolic, anthocyanin, and flavanol concentrations. Since the temperature in summer is generally higher than ideal for anthocyanin formation in grapes, winter grapes in China probably have greater phenolic component concentrations and antioxidant qualities (Cheng et al. 2019; Mansour et al. 2022). Our analysis demonstrates that when global temperatures rise, grapes' antioxidant qualities may gradually rise to a certain limit. Grape antioxidants may be affected by high temperatures. Solar exposure affects grape nutrients. Radiation from the sun affects phytochemical characteristics more than temperature and also increases cinnamic acids, flavanols, and flavanonols (Flemming et al. 2021). In another analysis, boosting grapes' sunlight and UV exposure enhanced wine's soluble solid content, anthocyanins, tannins, and phenols (Shah and Smith 2020). In comparison, similar findings have revealed that the number of ultraviolet rays affected the quantities of anthocyanin metabolites in grapes, suggesting that radiation regulates anthocyanin biosynthesis (Samkumar et al. 2021).

Shifting sun radiation levels may affect the antioxidant qualities of grapes while various varieties and areas may observe varied results. Climate change-related water stress affects grape nutrients (Ali et al. 2020; Christopoulos and Ouzounidou 2021). Most research show that water shortage during growing increases the flavanol and anthocyanin content of grapes. Water deficiency timing may alter which anthocyanins are impacted. Temperature and sun radiation may affect the nutritional content of grapes more than drought conditions (Kizildeniz et al. 2018). This may illustrate how an investigation discovered a connection between ripening rainfall and phenolic content (Drappier et al. 2019). More precipitation is also connected with elevated temperatures and solar rays, which might boost phenolic content. Numerous analyses have mimicked climate change's impact on grapes (Bonada et al. 2020). Elevated CO_2, temperatures, and moisture decreased the anthocyanin and acid levels of grapes. In another investigation, elevated CO_2, temperature, and drought conditions reduced the anthocyanin level. In predictions, climate warming lowered grape nutrients (Arrizabalaga-Arriazu et al. 2020, 2021).

Soil nutrients, temperature, air, and water availability may impact banana harvests. Many studies have explored how climate affects banana nutrients. There seems to be an indication that a rise in the mean daily temperature decreases the average mass of banana fruits and decreases and increases particular nutrients, especially fructose, glucose, phosphorus, calcium, and magnesium (El Barnossi et al. 2021). Whereas a gain in micronutrients may imply a good influence on human nutrition, a drop in carbohydrate content might have detrimental implications in countries where bananas constitute a primary carbohydrate (Alikhani-Koupaei et al. 2018). Several tropical and subtropical people eat bananas regularly. Bananas constitute 25% of the daily calorie intake in rural Uganda, Rwanda, and Cameroon. Climatic effects on banana yields, sugars, and carbohydrates might harm human nutrition (Gupta et al. 2019).

As water shortages continue to increase, watermelon nutrition may decline. Water deficiency boosts watermelon's magnesium potassium and potassium levels. Although drought-grown watermelons may be more nutritive, water deficiency decreases production and may leave them lesser delicious. Watermelon's soluble solid content affects its flavor (Acharya et al. 2020; Naseer et al. 2021). There are contradictory data on whether dryness reduces soluble solids or has little influence. Water deprivation increases the protein content in watermelon leaves. This impact has only been seen in leaves, but it may transfer to fruits and improve watermelon's nutrients (Devi et al. 2020). Rising temperatures may alter the nutritional value of melons. Another team of researchers have observed that lowering daytime temperatures and increased overnight temperatures may boost the dissolved solid content of watermelons (Acharya et al. 2020).

Rising global temperatures may interact with drought conditions and other variables to affect dissolved solid content. Temperature influences watermelon nutrients along with soluble solids. Watermelons cultivated under 35 °C have more phenolic compounds, reflecting nutritional benefits (Huh et al. 2020). Additional studies have demonstrated that watermelon leaf micronutrients increase with temperature. It is uncertain whether enhanced micronutrients will also happen in fruits; however, watermelon micronutrient content may rise as temperature rises. Due to climatic stresses (high temperatures, drought stress), watermelons might contain greater vitamins and proteins but less phenolic substances. Sugar levels might also affect watermelon taste (Basirat and Mousavi 2022).

According to research on the effects of temperature on oranges, climate change might affect oranges' nutritive value. As the global temperature rises, orange fruit size might also rise at the costs of vitamin C and phenolic chemicals (Habibi et al. 2020). As carbon dioxide levels rise in the coming decade, orange production, volume, and content of vitamin C might improve (Aziz et al. 2018). If salt stress rises because of climate change-related reduced moisture, then oranges' leaves and branches and roots' nutrient content may fluctuate, affecting fruit micronutrient makeup. Rising temperatures, environmental carbon dioxide, and salt stress may all influence oranges' nutritional value in the coming years. Some climatic conditions are economically productive, whereas others are not (Alae-Carew et al. 2020).

6 Adaptation and Mitigation Choices

Farmers and civilizations can acclimatize to climate changes in various ways. These techniques might vary from small to significant network-wide alterations (Raza et al. 2019). The food and agricultural industries may evolve to boost elevated crop yields with minimal environmental impacts. Rising food supplies do not really promise that food will be evenly distributed, and, thus, additional measures are needed to increase everyone's access to high-quality balanced food (Fig. 5.3; Lal 2010).

Farmers may adjust to changes in the environment by modifying crop cultivars, planting schedules, irrigation techniques, and manure application or by adopting substantial changes to the system, such as shifting the type of crop, modifying agricultural systems, or migrating to other farmland (Asfaw et al. 2019). Several climate-resilient agricultural techniques also reduce greenhouse gas (GHG) emissions. Bioengineering and targeted farming may enhance agribusiness. Novel plant biotechnology approaches may produce drought-tolerant or micronutrient-rich crop cultivars (Msungu et al. 2022). Smart agricultural techniques combine Geographic Information System (GIS), Global Positioning System (GPS), and remote detection to spot changes in farms and assist growers locate pesticides and fertilizers where they are maximum required. Slight unmanned aerial systems are widely employed for field scanning to proactively discover problematic areas (Msungu et al. 2022). Robots are increasingly used in agriculture, notably for tasks like weeding, fertilizing, and collecting vegetables and fruits. They may displace human labor as a response to climate change, notably in locations where excessive daytime temperatures render fieldwork impractical (Aslan et al. 2022).

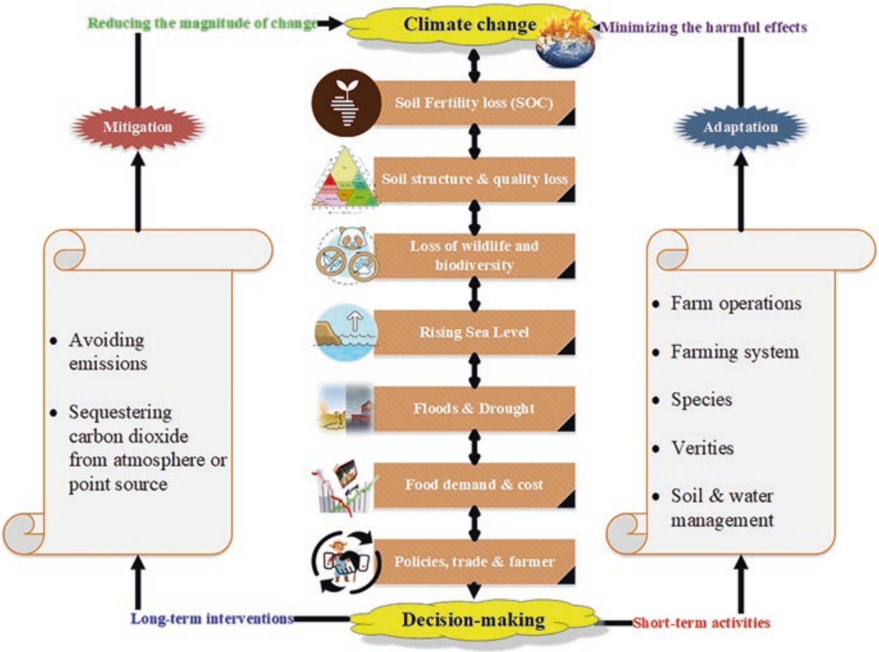

Fig. 5.3 Mitigation and adaptation options for climate change (Lal 2010)

Novel technologies can solve systemic problems. Indoor farming and cellular agriculture reduce environmental impacts on food production. Vertical indoor farming, for example, skyscrapers, decrease area and transportation demands by moving production nearer to city areas (Benke and Tomkins 2017). Several indoor farming systems require energy-intensive artificial lighting; however, light-emitting diode (LED) lamp innovation may increase energy efficiency in the coming years (Engler and Krarti 2021).

Postprimary or post-farm processes require mitigation and adaptation. Severe climate and hydrological disasters, including flooding, severe thunderstorms, and land sliding, may hinder food delivery (Saco et al. 2021; Jakob 2022). Diversifying supply networks and increasing local output may strengthen the world's food networks. This might also force food consumers and businesses to adapt to seasonally buying patterns. Depending primarily on domestic producers is risky because of adverse environmental and hydrological disasters (Kent et al. 2022).

Consumers may impact the viability of the food supply chain through their consumption pattern and food habits. As a result of environmental variations, the accessibility and pricing of popular fruits and vegetables may fluctuate (Fróna et al. 2019). Therefore, customers may need to pick various fruits and vegetables at different times by becoming habituated to more varieties. Buying locally made goods may boost local manufacturing (Stuart 2021).

7 Approaches

7.1 Heat Treatment

Temperature is a major variable in the phonological cycle of fruit trees in temperate climate. Rising temperatures boost metabolic responses, which extend the development period and affect plant phonology (Chowdhury et al. 2021). In certain plants, heat-shock proteins (HSPs) rise with chilling. Tamura et al. (1998) observed that nine HSPs formed in trees subjected to a short-term high temperature (45 °C for 4 hours) and triggered bud rupture in Japanese pear (Nijisseik) floral buds (Haokip et al. 2020). When pear plants were exposed to 45 °C water for 3 hours, bud rupture was triggered. Chandler (1960) found that apple trees' buds rupture after being subjected to 44–46 °C for 6 hours in July, October, and November (Gupta et al. 2021).

7.2 Evaporative Cooling

Bud rupture can be accelerated by evaporatively chilling buds during endodormancy. Evaporative cooling reduces bud temperatures in mild winters, raising the number of chilling hours needed for bud rupture (Parkes et al. 2020; El-Yazal 2021). The flowering of "Sungold" nectarines and "Flordagold" peaches was advanced by 7 days by evaporatively chilling (Rai et al. 2015). Intermittent overhead sprinklers like Dormex improved bud break and production, according to Allan et al. (2004) Uzun and Caglar (2001) postponed pistachio flowering by evaporatively chilling fruit buds. Israel uses overhead watering to chill buds during the day's warmest periods (Haokip et al. 2020).

7.3 Low-Chill Cultivars

This is the best remedy for inadequate chilling. Breeding low-chill varieties is challenging. Current biotechnology is needed to trace the genetic determinism of chilling to speed up the breeding procedure and produce optimal varieties for all essential fruits (Boudichevskaia et al. 2020; Gogorcena et al. 2020). A fresh orchard must reevaluate fruit types based on climate change. Low-chilling varieties of peach, apple, plum, and pear were introduced and adapted in North Indian plains and lower hills (Table 5.3; Nautiyal et al. 2020).

Table 5.3 Low-chill cultivars

Fruit crop	Low-chill cultivars	Chilling requirement	References
Apple	Maya, Anna, Parlin's Beauty, Tropical Beauty, Michel, Tamma, Schlomit, Vered, and Neomin	<800	Nautiyal et al. (2020)
Peach and nectarine	Sungold red nectarines, Flordasun, Floredared, Shan-e-Punjab, Sharbati, and Saharanpur Prabhat	<500	Chauhan et al. (2022)
Pear	Kieffer, Gola, Punjab, Pasternak (sand pear), and Le Conte	<150	Singh et al. (2020)
Plum	Jamuni, Santa rose, Aloo Bukhara, Alucha purple, Satluj purple, Titron, and Kala Amritsari	–	Bhatt and Tyagi (2021)
Grapes	Grape vines: *Vitis vinifera* and *Vitis labrusca*	–	Londo and Johnson (2014)
Apricot	Shipley's early Ambroise, New castle, Chaubattia Alankar, and Kaisha	–	Rai et al. (2015)
Mango	Nam Dok Mai, Nungklangwun, Rad, Kaew, Tongdum, and Okrong	<15	Pinsirodom et al. (2018)
Blood orange	Sanguinello, Sanguine, Tarocco, and Moro	<5	Habibi et al. (2021)

7.4 Dormancy Avoidance

Approaches that inhibit plants from reaching dormancy enable bud rupture without chilling. Griesbach (2002) noted that defoliating trees after harvest can induce dormancy. Luedeling (2016) said that defoliating trees allow them to restart their yearly harvest cycle without chilling, allowing India and Kenya to produce temperate fruits (Gupta et al. 2021; Yilmaz et al. 2021). Bud ruptures of Japanese plum, pear, apple, and apricot may be prevented through artificial means by desiccation, manual defoliation, renewed watering, and rest breaking therapies. Zinc sulfate and copper sulfate or urea enhance peach and apple bud sprouting. Delayed pruning and watering affected peach bud rupture in Mexico (Haokip et al. 2020).

7.5 Rest Breaking by Chemical Application

Inadequate winter chilling causes tardy and irregular flowering and foliation in deciduous nut and fruit plants. Substances like cyanamide or Dinitro-ortho-cresol (DNOC) oil may break the resting. DNOC oil and hydrogen cyanamide treatments led to 3- and 4-week prior bud break in "Granny Smith" apples. Mineral oil (4%) with Dinitro-butyl-phenol (DNBP) (0.12%) enhanced lateral bud break rate by 40% in apple trees handled using Petri dishes (Choudhary et al. 2022).

7.6 Temperate Fruit Tree Chilling Requirements

When tree varieties are chosen and grown in orchards, they must survive for many years. Tree crop farmers must adjust quickly to climate changes. Even commercially grown fruits may perform badly owing to climate changes. Insufficient chilling has resulted in the development of cultural, technological, and chemical methods (Dudley et al. 2020; Čirjak et al. 2022).

8 Future Research

Future study is needed to determine the impacts of climate change on valuable fruit crops in exotic locations throughout the globe and to discover solutions to prevent climatic consequences (Gruda 2019; Ausseil et al. 2019). Future studies may assist in determining how climatic change affects the nutritive content of fruits that sustain farmers' incomes and foods (Leisner 2020). Climate change's detrimental impacts on fruit nutrition must be measured, monitored, and mitigated. Collecting research on climate change's influence on fruit nutrition for a broad range of plants will help in the understanding of variations over time, including unique climatic problems that particular crops will experience in various places (Authority et al. 2020). Considering climate problems for various crops in different places helps identify administration techniques to reduce fruit production concerns. Researchers have shown that shielding apple groves using hail netting reduces apples' surface temperature and the quantity of ultraviolet light they experience (Vuković et al. 2022). In locations where climate change may increase temperatures and ultraviolet rays, hail netting can minimize sunburn damage, enhance taste, and increase apples' consumer acceptability (Ali et al. 2021).

Mulching vineyards is another management option that arose from our literature study. Australian viticulturists use mulch to generate soil carbon and hold moisture. Southeastern Australian researchers have found that spreading decomposed mulch in vineyards reduces evaporation and soil warmth, thus increasing soil water content. Growers protect their crops from climate change by mulching and putting up hail netting (Romero et al. 2022). Future studies should uncover numerous alternative fruit crop management practices that may maintain a steady supply of healthy fruits. Agricultural heterogeneity, planting trees and preserving natural vegetation, regulation of organic matter in soils and carbon capture and storage, management of water resources, disease and pest control, and relocation and shifting farming systems to more appropriate places are all ways to reduce climate risk in fruit-producing systems (Bavougian and Read 2018; Singh et al. 2022). Additional study is required to examine these management options for minimizing the climate crisis on crop yield. Research is required to discover climate-tolerant fruit varieties in diverse geographic locations and agricultural practices. Such study should identify crop productivity and quality standards for various fruit varieties (Woomer et al. 2019).

9 Conclusions

Global warming affects many elements of Earth's existence. Several climatic forecasts estimate a rise in temperature by around 1.4–6.4 °C by 2100 and a rise in carbon dioxide to 850 ppm. This will affect fruit development. Early blossoming and harvesting are signs of this. Global warming's negative effects include lack of winter chilling and altered bioactive chemical concentration. If the temperature increase pattern continues, then new methods need to be considered. Utilization of appropriate varieties, pesticides, and shelters are currently accessible techniques.

Changing climate influences fruit crop winter chilling, physiological problems, pollinator malfunction, and phenology. Climate change and variable weather patterns will affect future agricultural production, leading to increased carbon dioxide. At present, there is insufficient evidence on the effects of insects and pathogens in a swinging climatic condition, which could sometimes affect future food supply. Changing climate reduces fruit quality and yield. Climate change will reduce plant variety and geographical adaptability. As global warming is considered unavoidable, attempts should therefore be made to regulate the chilling needs of temperate fruit crops by different techniques. Faced with these kinds of challenges to world fruit production, mitigation and adaptation strategies based on scientific appraisal must be established.

This chapter focuses on evaluating several stress factors and the associated interplay, not just one. The emphasis on vegetables and fruits underscores the necessity for greater study on this nutritionally essential food category, since most research studies have focused on basic plants and animal supply foodstuffs. This chapter has identified various environmental challenges that might conceivably have severe health and nutrition impacts until adaptation and mitigation techniques are applied. Producers and impoverished consumers in underdeveloped nations, where adaptability opportunities are inadequate, might suffer from a variety of significant hazards. This approach helps generate future research to evaluate the health and nutrition outcomes of environmental changes on various groups of people and the viability of alternate adaptation and mitigation methods with diverse timescales.

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Chapter 6
Effects of Climate Change on Medicinal Plants and Their Active Constituents

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Abstract Climate change is increasingly being recognized as one of the most serious threats to humanity and all other forms of life on Earth. Global climate change has been blamed for changes in seasonal patterns, weather events, temperature ranges, and other related phenomena. Medicinal and aromatic plants (MAPs), like all living members of the biosphere, are vulnerable to the effects of climate change. Climate change information on MAPs is increasingly being recognized as one of the challenges to humanity and all other life-forms on Earth. Due to their significance in conventional medical systems and as beneficial plants for the economy, the impact of climate change on MAPs could be particularly devastating. Although it is unclear how climate change may affect MAPs in the future, there are certain potential dangers that merit discussion based on the research that is currently available. The main effects of climate change on medicinal plants are changes in geographical limits, changes in crop yields, and impacts on the production system. The goal of this chapter is to better understand the issue of climate change's impact on the medicinal and aromatic plant sector by understanding its impact on plant phenology (sowing, germination, growth metabolism, flowering, and harvest time), growth parameters, and active constituents of MAPs in order to improve adaptation strategies and management of the MAP sector in the context of climate change for sustainable development.

Keywords Climate change · Medicinal plants · Plant phenology · Active constituents

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1 Introduction

One of the greatest challenges to humans and all other forms of life on Earth is climate change, which is increasingly understood to be a concern. On a worldwide scale, reports have linked seasonal patterns, weather variations, temperature ranges, and other related phenomena to global climate change (Aryal 2015). Since Earth's temperature has risen to 0.74 °C and is expected to rise from 1.8 to 4 °C by 2100, the world is becoming hotter by the day (Solomon et al. 2007). The Intergovernmental Panel on Climate Change predicted a 4.2 °C rise in global average temperature by the end of the twenty-first century (Solomon et al. 2007; Faravani et al. 2011). Climate change is occurring as a result of increased urbanization, fuel consumption, and high carbon dioxide (CO_2) emissions, which are trapped in the atmosphere and cause global warming (Ahmad et al. 2010). Not only is climate change a significant worldwide environmental issue but it also poses a specific threat to developing countries.

Several climate changes have been observed. In the previous 30 years, the average global surface temperature has increased by 0.2 °C every decade (Hansen et al. 2006). The water cycle has also undergone changes. Due to the system's thermal inertia and the lengthy period necessary to return to a lower equilibrium, changes are likely to persist even if greenhouse gas concentrations stabilize (Solomon et al. 2007). Climate change and global warming increase the risk of mass extinction of biodiversity beyond the capacity of species to adapt (Lindzen 1990; Das 2010). There is a need to identify with the pattern of climate change, which is one of the most serious global environmental challenges, and to understand and assess various types of impacts (Cavaliere 2009). In addition to being a serious environmental issue worldwide, climate change is also a big concern for developing nations. Climate change is "unequivocal" (Solomon et al. 2007).

2 Definition of Climate Change

A change in the statistical characteristics of the climate system over extended periods of time is the broadest definition of climate change, regardless of the source (Wikipedia 2012). As a result, fluctuations lasting less than a few decades, such as El Nio, do not represent climate change. On a broad scale, the rate at which energy is received from the Sun and lost to space determines Earth's equilibrium temperature and climate. Winds, ocean currents, and other mechanisms distribute this energy around the world, thus influencing the climates of various regions (Buba 2004).

The main factors for understanding the spatial and transient differences in climate within a geographical range, in addition to their interactions with other factors, are the activities related to climate change and the management of natural resources, such as environmental planning, land-use planning, watershed managing, and protective ordering (de Zuviría and Canziani 2011).

3 Causes of Climate Change

Climate change has two major causes: anthropogenic and natural (Tamuno 2009). Anthropogenic causes are those human activities that change the chemical composition of the atmosphere by increasing the volume of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), and so on. The natural causes of climate change are based on:

(a) Terrestrial (Earth) causes, influenced by shifts in the following: distribution of land and water surface, the planet's topography, atmospheric chemistry, and the cryosphere
(b) Astronomical causes (Milankovitch hypothesis), which are influenced by variations in the equinox precession, eccentricity of Earth's orbit, and obliquity of the ecliptic plane
(c) Variations in solar radiation output and solar radiation absorption outside Earth's atmosphere have an impact on extraterrestrial causes. In a ratio of roughly 60:40, the combined effects of anthropogenic and natural causes were responsible for climate change.

4 Factors Affecting Global Climate Change

Elevated levels of CO_2 and ozone (O_3), which are greenhouse gases that significantly contribute to global climate change, are one of the factors affecting the climate change. Additionally, ultraviolet (UV) radiation and temperature, which are also directly impacted by these greenhouse gases, have an impact on the world's climate. Increased UV light has been linked to ozone depletion brought on by chlorofluorocarbons, hydrofluorocarbons, and other harmful chemicals released by various industries, which break down stratospheric O_3 molecules. While the majority of greenhouse gas increases, such as CO_2, have been blamed for global warming, this is not the only factor (Solomon et al. 2007).

5 Medicinal Plants and Climate Change

Due to their use for preventive or therapeutic purposes, or as a source of raw materials for the pharmaceutical industry, some plants are called "medicinal plants," and this term refers to many plant species, which belong to various plant families. A part of such a plant or the whole plant may be used for medicinal purposes. Such plants are spread across all habitats and in all climatic zones. Reports indicate that around 50,000–70,000 plant species are used in traditional or modern medicine worldwide (Batugal et al. 2004). Although many species are still unidentified, several may be potential sources of new pharmaceutical entities. The contribution of medicinal plants to healthcare is obvious; these provide livelihoods to tribal and rural people and are also used as raw materials in various industries. A massive amount of medicinal plants are collected from the wild, which is specially concerning for the climate change regime. Medicinal plants play an important role in mitigating human sufferings cause by diseases, ailments, and disorders and are vulnerable to climate change. This endangers some medicinal plants, especially those that are endemic to geographical regions or ecosystems, thus making them particularly susceptible to universal climate change. Furthermore, such global climate change issues will almost certainly pose a more prominent or immediate threat, with the potential to exert increasing pressures on medicinal plant species. Due to their importance in conventional medication delivery systems and as plants with a high economic value, medicinal plants are particularly vulnerable to the effects of global climate change (Sharma et al. 2020).

Climate change information on medicinal plants is increasingly being recognized as one of the challenges to humanity and all other life-forms on Earth (Cavaliere 2009). Medicinal and aromatic plants (MAPs), like all living members of the biosphere, are vulnerable to the effects of climate change. The life cycles and distributions of the world's flora, including wild MAPs, are changing because of climate change (Aryal 2015). Due to their significance in conventional medical systems and as beneficial plants for the economy, the impact of climate change on MAPs could be particularly devastating.

Although the future consequences of climate change are not fully understood, present data indicate that these phenomena have an impact on MAPs and that there are certain potential dangers that should be taken into account and discussed (Aryal 2015). The major costs of climate change on medicinal plants include shifts in their geographical range, adjustments to crop yields, and effects on the production system. Some notable studies on the effects of climate change on plant ecology and growth are shown in Table 6.1.

This aim of this chapter is to understand the impact of climate change on the distribution, prevalence, plant phenology, growth parameters, and active constituents of medicinal plants in order to improve MAP adaptation strategies and their management in the context of climate change for sustainable development. The impact of climate change on medicinal plants is discussed under the following headings:

- Effect of climate change on plant distribution and extinction
- Effect of climate change on plant phenology
- Effect of climate change on yield and plant growth parameters
- Effect of climate change on plant secondary metabolite production

Table 6.1 Some notable studies on the effects of climate change on plant ecology and growth

Study type	Study region	Plant species or ecosystem	Effect/concern	References
Food agriculture	Various (12 regions)	Multiple food crops	Southeast (SE) Asian and southern African regions are particularly prone to negative impacts.	Lobell et al. (2008)
	Global	Multiple food crops	The effects of climate change will differ between regions. Developing countries are less adaptable and will be the most severely affected. It is likely that SE Asia and sub-Saharan Africa will have a greater dependency on imports.	Schmidhuber and Tubiello (2007)
	Global, although with greater emphasis on the tropical and subtropical regions	Staple foods (corn, wheat, rice, and other primary food crops)	Increasing temperatures and declining precipitation will result in substantial impacts on global food security. Adaptions of agricultural methods are required (crops grown, use of technology, etc.), particularly in developing regions	Brown and Funk (2008)
	Global	Multiple food crops	The productivity of both irrigated and rain-fed agriculture is expected to decrease due to decreasing precipitation. Adaptive measures to improve land and water management practices will be required to boost resilience to climate change	Turral et al. (2011)
	Global	Multiple food crops	Agricultural production is highly vulnerable to climate change. Even low-end (2 °C) predictions will have major implications on production. The authors highlight possible adaptive measures, including new farming systems, targeted technologies, and institutional change	Vermeulen et al. (2012)

(continued)

Table 6.1 (continued)

Study type	Study region	Plant species or ecosystem	Effect/concern	References
	Global	Multiple food crops, although with a focus on *Fusarium* spp. and *Microdochium* spp.	This study is interesting as it examines the facets of climate change that are neglected in most other studies. As well as examining the direct effects of changes in temperature and precipitation, this study also examines the effects of climate change on the incidence and management of plant pathogens. The authors have highlighted the increase in *Fusarium* spp. head blight disease in recent years and link this to climate change. Thus, climate change may also indirectly affect agricultural production by increasing plant pathogens and thus agricultural losses	Chakraborty and Newton (2011)
	Ethiopia	Multiple food crops	Climate change is already significantly impacting agriculture in the semiarid regions of Ethiopia where low-tech subsistence farming is normal. However, the authors demonstrate that climate change is driving adaption by farmers and that farms that have adapted have substantially increased agricultural productivity	Di Falco et al. (2011)
	Tanzania	The study models the effects on nine major agricultural crops, although the report focuses on maize	Climate change is likely to adversely affect agricultural production in Tanzania. Indeed, in a dry model scenario, crop production is likely to drop by more than 10% compared to a no-climate-change model. However, a wet change model predicts that some regions of Tanzania may receive increased rainfall. This is likely to increase productivity in these areas, although localized flooding in some locations could result in increased crop destruction	Arndt et al. (2012)

Forestry	Europe	Boreal, temperate, Mediterranean climate zones and alpine region forests	Increased atmospheric CO_2 content and warmer temperatures are expected to increase forest growth in northern and western Europe in the short term. Long-term effects (increasing droughts and disturbance risks) will outweigh much of these positive effects. The risk of droughts increases from west to east. Droughts and fire risks are expected to have especially serious implications in Mediterranean regions. Boreal and temperate region forests have greater adaptive capacity, so the effects of climate change are expected to be less severe in these regions	Lindner et al. (2010)
	Global	Natural forest ecosystems	Globally, many forested ecosystems are already responding to climate change, and, recently, higher-than-average tree mortality rates have been noted, even in areas that are not considered water-limited. Furthermore, climate models predict higher future tree die-off in response to global warming and droughts	Allen et al. (2010)
	Global	Natural forest ecosystems	This study has reviewed the recent reports on forest production levels. In contrast to the Allen et al. (2010) study above, the authors of this study noted that 37 of the 49 studies reviewed reported increased forestry production levels and only 5 studies reported negative production trends. The authors correlate these positive trends with positive effects of CO_2 levels and N deposition	Boisvenue and Running (2006)
	Amazon	Rain forests	Evaporation and condensation over the Amazonian forests drives global atmospheric circulation and has downstream effects on precipitation across South America and across the northern hemisphere. There has been a general drying of the northern Amazonian forests since the mid-1970s, and climate models predict further drying, including in southern regions of the Amazonian forests. Together with ongoing deforestation, these climate changes are predicted to have significant effects on Amazonian forest growth, and, by extension, further exacerbate global climate change	Malhi et al. (2008)

(continued)

Table 6.1 (continued)

Study type	Study region	Plant species or ecosystem	Effect/concern	References
	United States	Natural forest ecosystems	Most studies on the effects of climate change on forests focus on the direct effects of increased temperatures and changed precipitation patterns. However, these factors also affect various disturbance regimes (fire, competition with introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, and landslides). This study reports that these indirect effects of climate change will also have significant effects on forest survival	Dale et al. (2001)
	Western North America	Pine forests	Mountain pine beetles are native North American insects, which, in large-scale outbreaks, kill large numbers of trees in pine forests. Climate change has been linked to outbreaks of pine beetles in an order of magnitude greater than previously recorded outbreaks. Thus, climate change may induce forestry loses through increases in forest pests.	Kurz et al. (2008)
Medicinal and aromatic plants (MAPs)	Indian Himalayan region	Alpine ecosystems	Currently, most reports on the conservation of MAPs focus on overharvesting due to increased demand. However, endemic plant species in the alpine regions such as this are particularly vulnerable to climate change, and a high risk of extinctions is predicted under current climatic trends	Gairola et al. (2010)
	Pakistan	Several members of the Asclepiad plant family with medicinal properties	The authors used Maxent modeling to predict the habitat gains for *Pentatropis spiralis* in southern Punjab and Balochistan regions but loss of habitat in southeastern Sindh. Furthermore, *Vincetoxicum arnottianum* and *Tylophora hirsuta* are predicted to gain habitats in the alpine regions of northern Pakistan, although *T. hirsuta* is likely to lose most of its other habitats in those regions	Khanum et al. (2013)

6 Effect of Climate Change on Plant Distribution and Extinction

Both biodiversity and ecosystems are already being forced by climate change to adapt to changing habitats, altered life cycles, and the emergence of novel physical traits. There are few studies on how climate change affects medicinal plants. The reaction of different plants to climate change will be varied, with some continuing in their geographical zone and others adapting to their new climatic conditions. Other species will relocate to higher latitudes or elevations. Some medicinal plant species may become extinct, which is a cause for concern (Keutgen et al. 1997). As a result of climate change, some species are being forced to move to new ranges, such as the poles or to higher elevations. Some MAPs are at risk because they are endemic to places or ecosystems that are particularly vulnerable to climate change (Faravani et al. 2011).

Factors influencing species distributions interact in complex ways, so simple correlations with temperature changes are not always observed. Rather than being gradual or monotonic, range shifts are frequently episodic (Walther et al. 2002; Parmesan and Yohe 2003). According to the results of the moderate climate change scenario, future land use patterns and climate change will be harmful to German flora (Cavaliere 2009). As the climate warms, the species that are not currently recorded in Germany may migrate, potentially disrupting the existing species pools. There are many unknowns surrounding how potential climate change may impact plant species distributions, especially the degree to which farmed crops may be impacted. It is unclear what types or degrees of range shifts might occur. Even while it seems like agricultural crops can adapt to climate change better than natural ecosystems, other locations might become far less productive. A recent research from Botanic Gardens Conservation International has stated that as temperature ranges and rainfall availability vary, adjustments to crop distribution patterns will be necessary. More appropriate cropland is anticipated to be added in several regions of the world, while in others, particularly in emerging African and South Asian countries, major losses in food output are anticipated (Cavaliere 2009; Nelson et al. 2010). The data in Table 6.2 summarize the impact of severe weather conditions on plant distribution.

Climate change-induced range shifts in wild plants may endanger the survival of some species. Every ecosystem supports a diverse range of species with varying degrees of migratory potential. Species that rapidly and aggressively migrate are at one extreme of the spectrum, whereas specialized species with little mobility are at the other (Nelson et al. 2010). Natural and man-made migration barriers may also threaten the survival of some species experiencing climate-induced range shifts.

Severe weather has already affected medicinal plants on every continent with growing evidence that extreme weather events like storms, droughts, and floods have increased in frequency and severity globally in recent years (Graham et al. 2011). Future warming is anticipated to make these events more frequent and more severe, with detrimental effects on ecosystems, infrastructure, and human health.

Table 6.2 Impact of severe weather conditions on plant distribution

Species	Location(s)	Climate change factor	Distribution change	References
Various trees	Sweden	Increased temperatures	Distribution shifts to higher altitudes	Kullman (2001)
Pinus peuce	Bulgaria	Increased temperatures	Distribution shifts to higher altitudes	Meshinev et al. (2000)
Nothofagus menziesii, *Nothofagus solandri*, *Nothofagus fusca*, and *Prumnopitys ferruginea*	New Zealand	Increased temperatures	Distribution shifts to higher altitudes	Wardle and Coleman (1992)
Betula nana, *Salix* spp., *Alnus crispa*, and *Picea glauca*	Alaska	Increased temperatures	Introduction of several shrub species into areas where they previously did not occur	Sturm et al. (2001)
Multiple plant species	European Alps	Increased temperatures	There is a shift toward higher elevations of 1–4 m per decade	Grabherr et al. (1994)
Multiple plant species	Antarctica	Increased temperatures and increases in water availability	Various distribution changes	Kennedy (1995)
Multiple plant species	Amazonia, Europe, South Africa	Mid-range climate warming	The study models climate change events and predicts multiple extinction events of plant species endemic to these regions. The extinction events are particularly high in South Africa (a region with high levels of biodiversity and endemism)	Thomas et al. (2004)
In all, 171 plant species occurring across the elevation range 1–2600 m above sea level	Global	Increased temperatures	The study reported a general upward shift in the optimal elevation of all species of 29 meters on average per decade. Grasses and species restricted to mountainous habitats had substantially great shifts to higher altitudes than the average	Lenoir et al. (2008)
In all, 1350 European plant species	Europe	Multiple climate change events	Niche-based modeling was used to predict changes to European plant diversity. The study predicts that more than half of the species examined would be vulnerable or threatened by 2080. The study also predicted high levels of species loss across different regions, with the degree of loss correlated with temperature increases and moisture levels	Thuiller et al. (2005)

Extreme weather conditions have a history of interfering with harvesters' and cultivators' capacity to grow and/or collect medicinal plant species, as mentioned in recent reports (Huber and Gulledge 2011).

In Europe, the cultivation process of medicinal plants, from sowing to harvesting, is being affected by extreme weather conditions. Some medicinal plants, like chamomile, have been unable to successfully reseed in the fall in Germany and Poland due to the extremely dry soil conditions brought on by the recent abnormally hot summers. In addition, no fennel (*Foeniculum vulgare*, Apiaceae) seed yield was observed in Bulgaria in 2007 due to drought conditions in that nation during spring (Cavaliere 2009). The impact of climate change and insufficient rainfall is severe in Africa because irrigation is only used to grow a small portion of therapeutic plants. The cost of medicinal plants has already grown dramatically in several places as a result of rising collecting costs and decreasing yields. African farmers may gradually turn away from rain-fed agriculture and wild harvesting practices in favor of irrigation, where it is feasible, and output may shift to the tropics, which are more humid (Cavaliere 2009).

A growing body of research and evidence has revealed that specific kinds of extreme weather events are occurring more frequently and with higher force globally (Drine 2011). The detrimental impacts of recent storms, droughts, and floods on herbal crops have shown the threat that more extreme weather may pose to the supply and availability of MAPs, even though specific weather events cannot be attributed to climate change (Cavaliere 2009).

7 Effect of Climate Changes on Threats to Medicinal Plants Species

Around the world, medicinal plants are being impacted by climate change, which might result in the loss of certain important species. The information featured in HerbalGram, which summarizes the results, observations, and views of several researchers and conservationists working with medicinal plants, is the basis for this conclusion (Cavaliere 2008, 2009). Due to their immense significance in conventional medicine and practicality from a financial standpoint, the prospective effects of climate change on MAPs may be extremely severe. Although the long-term implications of climate change are not yet clear, they will affect MAPs and could eventually pose a far bigger hazard. The livelihoods of numerous individuals may be significantly impacted by the disappearance of some MAPs. Although the issue of rising temperatures and interrupted seasonal events is similarly difficult to comprehend, early efforts may unquestionably stop the loss of biodiversity. Climate change has a significant impact on medicinal plants, both cultivated and wild. The need of the hour is a focused research approach, particularly on the accumulation of secondary metabolites with health implications (Harish et al. 2012). Endangered plant species are believed to be more susceptible to the effects of climate change and may even go extinct because of their narrow geographical distribution.

High-altitude plant life cycles and distributions are significantly impacted by climate change, according to research from other parts of the world. As a result, a better understanding of the factors causing such changes necessitates intensive and continuous field measurements at representative sites. Furthermore, more research on the habitat range and secondary chemical production efficiency of threatened Himalayan medicinal plants under climate warming scenarios is required for developing conservation strategies as well as agro-technologies for cultivation. These investigations are crucial as well because changes in the induction of plant chemicals might have major ecological effects (Bidart-Bouzat and Imeh-Nathaniel 2008).

8 Effect of Climate Change on Plant Phenology

The study of periodic events in plant life cycles, as influenced by the environment, is known as phenology (especially seasonal variations in temperature and precipitation). The timing of phenological events like flowering is frequently linked to environmental variables like temperature. Thus, it is anticipated that shifting surroundings would result in altered life cycle events, which have already been seen in several plant species (Parmesan and Yohe 2003). These modifications could affect plant competitiveness or bring about asynchrony between species. For instance, British plants' flowering cycles have changed, causing annual plants to bloom before perennials and insect-pollinated plants to bloom before wind-pollinated plants, which might have negative ecological effects (Fitter and Fitter 2002).

Changes in the timing of such cycles provide some of the most compelling evidence that global climate change is affecting species and ecosystems because plant life cycles correlate with seasonal signals (Cleland et al. 2007). Important phonological events for medicinal plants adapted to climate change include

(i) Bud burst and leaf unfolding
(ii) Autumn or dry season leaf drop
(iii) Flowering and fruit setting
(iv) As global warming intensifies, the linked processes of winter hardening and breaking, the start of spring, and the duration of the growth season will be impacted (Sparks and Menzel 2007).

The timing of phenophases is believed to be strongly genetically controlled, resulting in regionally adapted ecotypes influenced by:

I Temperature: Temperature has a strong influence on leaf unfolding and bud burst.
II Frost: After flowering or bud burst, trees may undergo reproductive failure and limited growth for that season if late-season frosts occur (Selås et al. 2002).
III Chilling: Periods of chilling, which may involve super cooling and desiccation of the cell protoplasm, may be necessary to induce complete winter dormancy.
IV Photoperiod: In latitudinal adapted tree ecotypes, photoperiod initiates dormancy adaptation.

V Evapotranspiration: Higher surface temperatures and possibly lower summer precipitation

VI Droughts: A seasonal drought that reduces growth during the growing season (Selås et al. 2002)

It is expected that the patterns of reproductive phenology would shift at the community level as a result of climate change since plant blooming and fruiting phenology are both sensitive to environmental signals like temperature and moisture. In a well-controlled warming experiment, Sherry et al. (2007) discovered that early-flowering grass and herb species blossomed sooner and late-summer flowering species flowered later. The community's staggered progression of flowering and fruiting in the middle of the growth season was disrupted by the warmth-induced differentiation of flowering and fruiting toward the two ends of the growing season (Faravani et al. 2011).

The timing of a species' activity, or phenology, offers some of the most convincing evidence that species and ecosystems are being impacted by global environmental change since plant species are well-suited to their seasonal environment (Cleland et al. 2007). Studies have also demonstrated that plant species have started to adjust to recent climate changes through altered species ranges, in addition to shifting phenology (Parmesan 2006).

Harish et al. (2012) reported that the major phonological events for medicinal plants that have adapted to climate change include bud burst and leaf unfolding, blooming and fruit setting, fall or dry season leaf drop, and the related processes of winter hardening and breaking. The start of spring and the duration of the growing season will be impacted as global warming continues. In temperate and boreal zones, trees now have a longer growing season. The data clearly show that early flowering, in the majority of cases, indicates a shorter vegetative period, which may have a considerable impact on productivity. Numerous studies have demonstrated that plant species that typically flower in early spring are being accelerated by warming to a greater extent than are other plant species, which can be unresponsive or can experience delayed phenological events (Cleland et al. 2007). Studies have also demonstrated that plant species have recently started to adapt to climate changes through altered species ranges, in addition to shifting phenology (Parmesan 2006).

According to recent studies on medicinal plants, many of these plants, such as cranberry (*Vaccinium macrocarpon*, Ericaceae), feverfew (*Tanacetum parthenium*, Asteraceae), St. John's wort (*Hypericum perforatum*, Clusiaceae), and wormwood (*Artemisia absinthium*, Asteraceae) are now in bloom more than a week earlier than they were 150 years ago (Nickens 2007). Additionally, peppermint (*Mentha* x *piperita*, Lamiaceae) blooms 10 days sooner today than it did 150 years ago (Nickens 2007). Contrarily, according to statistics from Nature's Calendar, numerous UK plants have begun to bloom earlier, including the commonly used medicinal plants hawthorn (*Crataegus monogyna* and *C. laevigata*, Rosaceae) and horse chestnut (*Aesculus hippocastanum*, Hippocastanaceae) (Nickens 2007).

The timing of development is influenced by temperature, both independently and in combination with other cues like photoperiod, and, therefore, changes in the global climate may have a considerable effect on plant phenology (Bernier 1988; Partanen et al. 1998).

In the same ecosystem, phenological diversity among plant species can lessen competition for pollinators and other resources. Climate change may have an impact on some MAPs' chemical makeup and eventual survival. It is crucial to preserve genetic diversity because it is possible that plants may do so in order to survive as their environment changes (Aryal 2015). Compared to cultivated plants, wild plants seem to be more prone to phenological shifts (Cleland et al. 2007). Since many MAPs are obtained through wild harvesting, this may have had an impact on their yield and quality. In addition, some notable studies on the effect of climate change on plant phenology are summarized in Table 6.3.

9 Effect of Climate Change on Plant Growth Parameters

9.1 Effect of CO_2 on Plant Growth Parameters

One of the most restricting elements in photosynthesis is CO_2. Agriculturists have been intrigued by the prospect of enhancing photosynthesis in plants through CO_2 enrichment for an extremely long time (Ibrahim and Jaafar 2011a, b). It has been demonstrated that CO_2 enrichment increases plant growth, development, and yield of agricultural crops and that this response depends on the CO_2 concentration and exposure time (Bailey 1995). Under glasshouse conditions, higher CO_2 concentrations promote vegetative growth, biomass expansion, carbohydrate accumulation, fruit production, and quality in plants (Chen et al. 1997). Crops grown in environments with higher levels of CO_2 exhibit better plant growth and adaptation. The improvement of photosynthetic capacity is one of CO_2 enrichment's greatest benefits, especially in harsh climates. This is the most noticeable in the vegetative growth of young plants (Brevoort 1998; Jaafar 2006). The data in Table 6.4 provide an overview of the responses of some plant species to changes in CO_2 levels, as reported from various studies.

According to Tisserat (2002), compared to high CO_2 levels and ambient air, ultrahigh CO_2 levels (3000 l CO_2/liter of air) increased the fresh weight of the leaves, roots, and shoots of *Mentha spicata* L., *Thymus vulgaris* L., and *Mentha aquatica* L., respectively. However, the fresh weight and leaf and root counts of the shoots of thyme (*Thymus vulgaris* L.), peppermint (*Mentha piperita*), spearmint (*Mentha spicata*), and lemon basil (*Ocimum basilicum* L.) increased as compared to cultures grown on the same medium in ambient air. Save et al. (2007) studied the formation, concentration, and content of secondary metabolites of *Hypericum perforatum* and *Echinacea purpurea* in Mediterranean habitats under greenhouse conditions. In environments with higher CO_2 levels, *Hypericum* plants' leaf dry weight increased by 33%. Additionally, there was a difference in the distribution of biomass, roots, and stems. After 7 months, *Echinacea* plants exposed to high CO_2

Table 6.3 Some notable studies on the effect of climate change on plant phenology

Plant species	Study region	Climatic event	Phenological effect	References
In all, 385 British plant species	United Kingdom	Increased temperatures	Annual plants are flowering substantially earlier than perennial plants. Insect-pollinated plants are flowering earlier than are wind-pollinated species. This is already affecting species distribution and biodiversity	Fitter and Fitter (2002)
Multiple plant species	Germany	Increased temperatures	Increased temperatures induce multiple phenological changes, including changes to the timing of leaf emergence, leaf opening, start and end of flowering, fruiting or heading, time of ripening, etc. In general, the correlation between temperature changes and phenological changes was stronger in perennial plants than in annual species	Estrella et al. (2007), Sparks and Menzel (2007)
Picea abiesa (L.) Karst.	Norway	Changes in seasonal temperatures and durations as well as rainfall effects	Increased summer temperatures and decreased precipitation resulted in decreased growth in individual *P. abiesa* tree widths but increased seed production and dispersal	Selås et al. (2002)
Multiple plant species	China, although the study examined experimental temperature increases rather than environmental climate change events	Increased temperatures and timing of precipitation	Warmer temperatures had variable effects on flowering and fruiting phenology in different species. Increased temperatures induced early-flowering species to flower substantially earlier than normal, yet resulted in delays in flowering in later flowering species The temperature-induced divergence in between flowering and fruiting toward the two ends of the growing season resulted in a production gap in the middle of the season. Variation in the timing of precipitation events did not significantly affect phenology	Sherry et al. (2007), Faravani et al. (2011)

(continued)

Table 6.3 (continued)

Plant species	Study region	Climatic event	Phenological effect	References
Multiple plant species	Global	Multiple climate change events	The study reported that plant species, which normally flower in early spring, are flowering substantially earlier, whereas species active later in the growing season can be unresponsive or can experience delayed phenological events	Cleland et al. (2007)
Artemisia absinthium, *Tanacetum parthenium*, *Vaccinium macrocarpon*, *Mentha piperita*, *Hypericum perforatum*, *Crataegus* spp., and *Aesculus hippocastanum*	United Kingdom	Increased temperatures	Many medicinal plants, including wormwood, feverfew, St. John's wort, and peppermint, now flower substantially earlier than they did 150 years ago. Indeed, peppermint flowers 10 days earlier than it did previously	Nickens (2007)
Multiple plant species	Various regions, although the study emphasizes the changes in the Arctic and alpine species	Increased temperatures	Phenological variation between plant species in the same ecosystem can reduce competition for pollinators and other resources. Climate change could affect the chemical composition and ultimately the survival of some MAPs	Cavaliere (2009)

levels produced 79%, 339%, 546%, and 57% more dry weight of leaves, flowers, stems, and roots, respectively (Save et al. 2007).

With increased (685–820 ppm) and ambient (430–480 ppm) CO_2 concentrations in a controlled greenhouse setting, another study on broccoli (*Brassica oleracea* var. italica Plenck) was conducted. According to the findings, increased CO_2 concentration caused the fresh weight of the broccoli heads to increase by about 7% (Schonhof et al. 2007). The Halia Bentong and Halia Bara varieties of *Zingiber officinale* were exposed to various CO_2 concentrations (400 and 800 ppm). At 800 ppm CO_2, high rates of photosynthesis were seen in both Halia Bara and Halia Bentong (Ghasemzadeh and Jaafar 2011).

Another study on the growth of the wild poppy (*Papaver setigerum*) revealed that elevated CO_2 levels significantly increased leaf area and above-ground biomass. This study used experimental CO_2 values of 300, 400, 500, and 600 ppm (Ziska

Table 6.4 Some notable studies on the effect of carbon dioxide (CO_2) levels on plant secondary metabolite production

Plant species	Climate change parameter	Phytochemical change	References
Triticum aestivum	Elevated CO_2 levels and varied levels of irrigation	Elevated CO_2 levels induce increased production of flavonoids and total nonstructural carbohydrates in wheat	Estiarte et al. (1999)
Hypericum perforatum and *Echinacea purpurea*	Elevated CO_2 levels	Exposure to elevated CO_2 levels induced increased flavonoid production in *Hypericum* spp. after blossoming. Similarly, exposure of *Echinacea* spp.'s elevated CO_2 levels induced significant changes in the levels of caftaric acid and total phenols in the roots	Save et al. (2007)
Brassica oleracea	Elevated CO_2 levels	The total glucosinolate concentration of broccoli inflorescences increased by 14% in elevated CO_2 levels. This was primarily due to 37% increases in glucoiberin and glucoraphanin	Schonhof et al. (2007)
Zingiber officinale	Elevated CO_2 levels	Elevated CO_2 levels induce significant increases in total flavonoid, polyphenolics, soluble carbohydrates, starch, and plant biomass in all ginger varieties tested	Ghasemzadeh and Jaafar (2011)
Digitalis lanata	Elevated CO_2 levels	Tripling the atmospheric CO_2 content increased the concentration of digoxin in *D. lanata* plants by 11% under well-watered conditions and by 14% under water-stressed conditions	Stuhlfauth et al. (1987)
Multiple plant species	Elevated CO_2 levels	Atmospheric CO_2 enrichment by 75% increased vitamin C concentration in a sour orange crop by 15%. The effect of atmospheric CO_2 enrichment on the phytochemical contents of other plant species was less definitive, with the levels of some compounds substantially increased, others decreased, and others not significantly affected	Idso and Idso (2001)

(continued)

Table 6.4 (continued)

Plant species	Climate change parameter	Phytochemical change	References
Hypericum perforatum	Elevated CO_2 levels	Elevated CO_2 levels resulted in concentrations of hypericin and pseudohypericin in St. John's wort that were more than double the levels in plants grown under ambient conditions	Zobayed and Saxena (2004)
Pinus taeda	Elevated CO_2 levels	Levels of catechin and proanthocyanidins increased by 11% in *Pinus taeda* needles in response to the elevated CO_2 treatments	Booker and Maier (2001)
Various tropical trees	Elevated CO_2 levels	The average leaf phenolic content was approximately 50% higher in young tropical trees grown at approximately twice the ambient CO_2 levels compared to the controls	Coley et al. (2002)
Nannochloropsis sp.	Elevated CO_2 levels	Production of eicosapentaenoic acid was significantly increased when grown in high CO_2 environments (20,000 ppm) when compared to growth of the alga under ambient conditions	Hoshida et al. (2005)
Papaver setigerum	Elevated CO_2 levels	Growth and total alkaloid content in wild poppy was investigated under experimental CO_2 levels of 300, 400, 500, and 600 ppm	Ziska et al. (2008)
Artemisia annua	Elevated CO_2 levels	The authors demonstrated that healthy *Artemisia annua* plantlets can be produced in vitro, using a liquid medium with CO_2 enrichment under photoautotrophic conditions. Furthermore, the elevated CO_2 conditions resulted in elevated levels of the sesquiterpene artemisinin	Supaibulwattana et al. (2011)
Mentha spp., *Thymus* spp.	Elevated CO_2 levels and varied O_2 concentrations	Thymol production was maximized when thyme shoots were cultured in a high CO_2 and moderate O_2 environment. The levels were considerably lower in shoots grown under either lower or higher O_2 levels. High levels of piperitenone oxide were obtained from mint cultures grown under 21% O_2 with 10,000 ppm CO_2 compared to those obtained with lower O_2 levels	Tisserat et al. (2002)

(continued)

Table 6.4 (continued)

Plant species	Climate change parameter	Phytochemical change	References
Populus nigra	Elevated CO_2 levels in conjunction with varied N levels	Soluble phenolics and soluble proteins decreased slightly in *P. nigra* wood in response to elevated CO_2 levels. Nitrogen supplementation stimulated overall secondary compound formation	Luo et al. (2008)
Labisia pumila	Elevated CO_2 levels in conjunction with varied N levels	The production of total phenolics and total flavonoids decreased with increased levels of nitrogen. Furthermore, the total flavonoid and total phenolic content increased substantially under elevated CO_2 levels	Ibrahim et al. (2011)

et al. 2008). Increased CO_2 also caused the poppy to produce more capsules, heavier capsules, and latex. *Scutellaria lateriflora* and *Scutellaria barbata* responded to CO_2 enrichment from 400 to 1200 mol.mol^{-1} CO_2 by growing faster and producing more biomass overall (Stutte et al. 2007). In addition, flowering time was sped up by 7–10 days. With CO_2 enrichment to 1200 mol mol^{-1}, the total flavonoid content rose by 50%, and, by 3000 mol mol^{-1}, it rose by 81%. Baicalein and wogonin concentrations did not change with rising CO_2, but scutellarein, baicalin, and apigenin concentrations did. Under ambient CO_2 conditions, *S. lateriflora*'s vegetative tissue had a total concentration of the bioactive flavonoids that was significantly higher than *S. barbata*'s (1144 vs. 249 mg.g^{-1} dry weight).

With enrichment to 1200 mol.mol^{-1} CO_2, the total content of the measured bioactive flavonoids increased 2.4 times, and with enrichment to 3000 mol.mol^{-1} CO_2, it increased 5.9 times. These findings unequivocally show that controlled environment (CE) production and CO_2 enrichment can improve the yield and pharmaceutical quality of the *Scutellaria* species (Studte and Eraso 2008). *S. lateriflora* and *S. barbata* grew more quickly and took 7–10 days less time to bloom when grown in a controlled environment (CE) with CO_2 enrichment (Stutte et al. 2007).

9.2 Effect of Global Warming on Plant Growth Parameters

The effects of warming on phenological change across the northern hemisphere appear to be particularly well-documented, according to numerous studies examining the effects on terrestrial ecosystems (McCarthy et al. 2001; Sparks and Menzel 2002).

Climate has a considerable impact on the physical, chemical, and biological properties of medicinal plants, including day of the week, amount of precipitation, and outside temperature. The length of sunshine, average rainfall height, average temperature, and thermal amplitude between day and night all have an impact on how physiologically and biochemically active plants are. It is crucial to decide on each of these beforehand (Endrias 2006).

Throughout their multi-seasonal life cycle, plants frequently experience high temperatures (Sarkar et al. 2009; Perez et al. 2009). Future ecological and agricultural effects of a rising global temperature could significantly limit crop production (Kurek et al. 2007; Qin et al. 2008).

10 Effect of Climate Change on Plant Secondary Metabolite Production

10.1 Effect of CO_2 on Plant Secondary Metabolite Production

Under well-watered conditions, the cardiac glycoside digoxin, the primary secondary metabolite (PSM) of foxglove (*Digitalis lanata*), increased by 11%, whereas under water stress, it increased by 14% (Stuhlfauth et al. 1987). Increasing the concentration of CO_2 enhanced the amount of disease-fighting compounds that treat cancer produced by spider lily bulbs by 56% (Idso et al. 2000). Under increasing CO_2, leaf phenolic levels were generally 48% greater. CO_2 had no effect on the growth of biomass, but it increased in starch, total nonstructural carbohydrates, and the carbon/nitrogen (C/N) ratios. The net photosynthetic rates of the St. John's wort plant were 124% higher and their dry weights were 107% higher in CO_2-enriched chambers than they were in ambient air. Treatment at 1000 ppm nearly doubled the plant concentrations of hypericin and pseudohypericin (Zobayed and Saxena 2004). Two types of *Zingiber officinale* showed high rates of photosynthesis, a reduction in stomata conductance, and improved water usage efficiency as a result of the high CO_2 concentration (at 800 ppm). Total phenols, total flavonoids, total soluble carbs, starch, and the plant biomass of *Zingiber officinale* increased noticeably with elevated CO_2.

Mehalaine and Chenchouni (2018) found that after a 5-year study of *Thymus algeriensis* and *Rosmarinus officinalis*, there were significant differences in essential oil (EO) yields. The highest oil content was accumulated by *R. officinalis* in 2010, 2012, and 2013 at 1, 0.93, and 0.88%, respectively. *T. algeriensis* produced more EOs in 2013 than in either of the previous 2 years (1.08, 0.67, and 0.59%, respectively). Oil accumulation was negatively impacted by air humidity and aridity in both species but significantly increased with an increase in precipitation, wind speed, and hygrometry. The findings revealed that both species' oil content significantly varied over the course of years. Additionally, EO accumulation in the investigated species was significantly influenced by climatic factors and *R. officinalis* accumulated more EOs than did *T. algeriensis*.

The results are useful for understanding how plants behave in semiarid climates and for choosing a cultivation strategy that will produce a lot of biomass and accumulate volatile oils. The diversity of plants has been molded by historical atmospheric and climate changes; to address this challenge, plants have developed novel developmental and metabolic features. Through the production of food, raw materials, and medicines, these adaptable traits contribute to humanity's well-being by enabling plants to flourish under a variety of growth conditions. However, the current, accelerated pace of climate change, brought on by human activities, poses unprecedented new difficulties for plants. Here, we explain how the modern climate change might affect plants, paying particular attention to their highly developed metabolism. We consider future research directions to better comprehend and mitigate the effects of rapid climate change on plant fitness and human use of plants, using cutting-edge techniques like synthetic biology and genome engineering (Xu and Weng 2020).

Holopainen et al. (2018) have presented strong evidence that the main climate change factors, namely, warming and CO_2, have opposing effects on the primary secondary metabolites (PSMs) of plants. While limiting terpenoids in the foliage and emissions, CO_2 increases phenolic content in the foliage. While terpenoids and emissions increase with warming, phenolic compounds in foliage decrease. Different abiotic stresses have different outcomes. Secondary compounds found in plants may aid trees in adjusting to a changing climate as well as pressure from prevailing and invasive pathogens and pests. The formation of cloud condensation nuclei from tree volatiles, the sequestration of CO_2 into PSMs in the wood of living and dead forest trees, and the effects of PSMs on soil chemistry and nutrient cycling are all examples of indirect adaptation.

The majority of the forest tree species produce terpenoids in their emissions as well as phenolic compounds in their leaves as a response to climate changes (CC)-related conditions. Major CC factors that frequently have divergent effects, like warming and elevated CO_2, have an especially pronounced impact on plant species. Warming reduces phenolics in foliage while boosting terpenoids in both emissions and foliage (Zvereva and Kozlov 2006; Peuelas and Staudt 2010). Conversely, increased availability of CO_2 increases the total phenolic content in foliage and decreases terpenoids in both foliage and emissions. However, phenolic levels in woody plant tissues decreased as a result of CO_2+warming (Zvereva and Kozlov 2006). Ozone (O_3) exerts a variety of effects on foliar terpene concentrations and volatile emissions, but it has been found to increase phenolic compounds. Terpenes' variable O_3 reactivity and variation in O_3 sensitivity within species may be one factor contributing to their variable responses (Valkama et al. 2007; Blande et al. 2014). Major terpenoid groups in foliage, like monoterpenes (MTs) and sesquiterpenes (SQTs), have received less attention when compared to other CC-related stresses.

The rates at which substrates are reassigned to secondary biosynthetic pathways from primary pathways are what connect secondary metabolism to primary metabolism. Multiple environmental factors that affect development, photosynthesis, and other aspects of primary metabolism will therefore also have an impact on secondary metabolism (Bryat et al. 1983). Because the ribulose-1,5-bisphosphate carboxylase/oxygenase enzyme is more active at high CO_2 levels, net photosynthesis typically increases. This may also have an impact on a plant's ability to grow and accumulate secondary metabolites (Ghasemzadeh and Jaafar 2011).

Depending on the organs, tissues, and stage of development, plants' flavonoids and other phenolic contents change. Climate UV and visible sunlight, the availability of nutrients and water, and atmospheric CO_2 concentration are additional environmental elements that affect them (Estiarte et al. 1999). Both genetic makeup and environmental factors affect how photosynthetic assimilates are used for carbon (C)-based secondary metabolites such as phenolic compounds. Carbon can be used to create C-based secondary metabolites like flavonoids, proanthocyanidins, lignins, and other phenolic compounds when it is available in excess of what is required for growth and maintenance due to elevated CO_2 conditions (which increases C supply) or mineral nutrient deficiency (which decreases C demand) (Booker and Maier 2001). However, adequate mineral nutrient availability, which encourages optimal growth, may lead to a decrease in the production of secondary metabolites from photosynthates.

Investigations have been conducted into the effects of elevated CO_2 in the Mediterranean environment and greenhouse conditions on the secondary metabolites of *Hypericum perforatum* and *Echinacea purpurea*. The phonological stage had an impact on the composition of flavonoids in *Hypericum* plants. After flowering, plants produced more flavonoids due to elevated CO_2. After 7 months, *Echinacea* spp., in high CO_2 conditions, revealed that increased CO_2 only promoted noticeable changes in caftaric acid and in the total phenolic levels at the root level (Save et al. 2007). Broccoli (*Brassica oleracea*) was used in another study that was conducted in a controlled greenhouse environment with both low (430–480 ppm) and high (685–820 ppm) CO_2 concentrations (Schonhof et al. 2007). The total glucosinolate concentration of the broccoli inflorescences increased by 14% as a result of elevated CO_2, primarily because two methylsulfinylalkyl glucosinolates experienced identical 37% increases (glucoiberin and glucoraphanin).

Two varieties of *Zingiber officinale* were subjected to various CO_2 concentrations (400 and 800 ppm). All portions of the ginger cultivars significantly increased in total flavonoids, total phenolics, total soluble carbohydrates, starch, and plant biomass when exposed to increasing CO_2 levels (Ghasemzadeh and Jaafar 2011). Digoxin concentration in foxglove (*Digitalis lanata*) increased by 11% under well-watered conditions and by 14% under water stress after the air's CO_2 content was tripled in a phytotron (Stuhlfauth et al. 1987). The increase, decrease, or lack of an impact on the protein contents of various foods was the range of the effect of atmospheric CO_2 enrichment on plant constituents that are important to human health (Idso and Idso 2001). When compared to the control, a sour orange crop with 75% more atmospheric CO_2 enrichment had a 7% higher vitamin C concentration (Idso et al. 2002). Another study found that treating St. John's wort with CO_2 at 1000 ppm led to a nearly 100% increase in plant hypericin and pseudohypericin concentrations (Zobayed and Saxena 2004). Elevated CO_2 treatments increased the amounts of total soluble phenolics (catechin and proanthocyanidins) in the needle extracts of loblolly pine (*Pinus taeda* L. by 11%, according to Booker and Maier (2001).

Another study in central Panama examined how young tropical trees' secondary metabolites responded to elevated CO_2 (to roughly twice the ambient level). Under elevated CO_2 levels, the total phenolic content of leaves was 48% higher on average. CO_2 had no impact on the growth of biomass, but it increased starch, total nonstructural carbohydrates, and the C/N ratios (Coley et al. 2002).

An alternative investigation of the marine alga *Nannochloropsi*s sp. that produces eicosapentaenoic acid, a polyunsaturated omega-3 fatty acid, was one of the secondary compounds examined under normal (370 ppm) and elevated (3000 and 20,000 ppm) CO_2 concentrations in the atmosphere (Hoshida et al. 2005). When 20,000 ppm CO_2 was supplied 12 hours before the exponential growth phase ended, production increased. Additionally, over the course of a 4-day cultivation period, two times as much eicosapentaenoic acid was produced overall compared to ambient air.

Papaver setigerum (wild poppy) growth and alkaloid levels were examined at experimental CO_2 levels of 300, 400, 500, and 600 ppm (Ziska et al. 2008). On a per-plant basis, the amounts of all four alkaloids (morphine, codeine, papaverine, and noscapine) increased significantly, with increases in carbon dioxide in the atmosphere being the cause of the largest relative increases (e.g., from 300 to 400 ppm). The authors came to the conclusion that as atmospheric CO_2 continues to rise, considerable effects on the development of secondary plant chemicals of therapeutic significance may be expected. Healthy *Artemisia annua* plantlets can be produced in vitro under photoautotrophic conditions using a liquid medium with CO_2 enrichment, producing plants that survive in ex vitro environments and accumulate artemisinin effectively (Supaibulwattana et al. 2011).

Another research examined the in vitro cultures of thyme (*Thymus vulgaris* L.) and mint (*Mentha* sp. L.) in environments with 350 or 10,000 ppm CO_2 and 5%, 10%, 21%, 32%, or 43% O_2 (Tisserat et al. 2002). The most thymol percentage resulted from thyme shoots cultured in 10% and 21% O_2 and 10,000 ppm CO_2. In shoots grown at either lower or higher O_2 levels, the levels were significantly lower. In comparison to mint cultures grown at lower O_2 levels, those grown under 21% O_2 with 10,000 ppm CO_2 produced higher levels of piperitenone oxide (Tisserat et al. 2002). Elevated CO_2 and nitrogen fertilization (alone or in combination) did not affect the lignin concentrations in wood during a 5-year experiment with *Populus nigra* (Luo et al. 2008).

In response to increased CO_2, the amount of total phenolics and soluble protein content in the wood slightly decreased. According to the same study, increased nitrogen supply promoted the synthesis of carbon-based secondary compounds and raised the protein content (Luo et al. 2008).

Three different types of medicinal plants from Malaysia were subjected to four levels of nitrogen fertilization (0, 90, 180, and 270 kg N/ha) and elevated CO_2 (1200 ppm) (Ibrahim and Jaafar 2011a, b). No discernible varietal differences were detected. However, as the nitrogen levels rose from 0 to 270 kg N/ha, the production of total phenols and flavonoids decreased in the order of leaves>roots>stems (Ibrahim et al. 2011). Additionally, under 1200 ppm exposure, these three varieties' total polyphenols and total flavonoids content peaked, with 800 and 400 ppm levels of CO_2 enrichment following for 15 weeks (Ibrahim and Jaafar 2011a, b).

10.2 Effect of Increased Temperatures on Plant Secondary Metabolite Production

It was found that the total phenylpropanoid concentrations increased at higher temperatures when two temperature levels were compared. However, the modifications in methyl cinnamate at various temperatures were remarkably similar (Tursunand and Telci 2020). At lower temperatures, it was discovered that the linalool concentration was higher. Phenylpropanoid levels peaked in both environments at the control CO_2 concentration and steadily decreased until 800 ppm. In addition, the linalool concentration increased steadily until 800 ppm. Rosmarinic acid concentrations were found to be at their highest at lower temperatures. In the current study, it was discovered that the components could change based on the temperatures and CO_2 concentrations (Tursunand and Telci 2020).

There is a need for more research on this topic, and the outcomes of future studies conducted in an environment with rising CO_2 concentrations and global warming will significantly influence how medicinal plant agriculture is planned in the future. Furthermore, the controlled environments used may also be used for the creation of beneficial chemicals if it is possible to increase the production of particular valuable compounds as a result of similar studies (Tursun and Telci 2020).

Given that there is a substantial negative link between the amount of precipitation and the level of volatile organic compound accumulation in the flowering shoots, rain during the flower development appears to have a detrimental impact on the yield (Nemeth-Zambori et al. 2017). During the vegetative stage, trans-pinocamphone predominated in the oil; however, as the plant grew, its content shrank while that of pinocamphone gradually rose (Zawislak 2013), from the pre-blooming stage (47.94%) through the full-blooming stage (48.22%) to the post-blooming stage (51.42%). This phenomenon showed that picking an appropriate harvesting stage is essential for obtaining the best essential oil quality (Kizil et al. 2010). Both pinocamphone and isopinocamphone, which are saturated bicyclic monoterpene ketones, are known to be produced from pinene via the allylic alcohol trans-pinocarveol and then reduced using two stereochemical optional bonds (Karp and Croteau 1992).

Numerous studies have looked at how higher temperatures affect plants' production of secondary metabolites, but no clear trends have been identified, and the findings of individual studies have been inconsistent (Jochum et al. 2007). In some studies, secondary metabolites were found to increase in response to high temperatures (Litvak et al. 2002), whereas in other studies, they were found to decrease (Snow et al. 2003). Because of this, it is less clear how secondary chemicals react to rising temperatures, though an increase in volatile organic compounds has typically been noted (Loreto et al. 2006).

Climate change has an impact on the yield and composition of volatile secondary metabolites in plants by affecting (a) environmental conditions, geographical variations, genetic factors, and evolution; (b) political and social conditions; and (c) the amount of plant material/space and labor requirements (Figueiredo et al. 2008). In

Ibadan, it has been demonstrated that *Datura metel* L.'s total alkaloid content peaks during the hot, dry season and declines during the wet, humid season (Cavaliere 2009). In 2008, the wild mint (*Mentha arvensis*, Lamiaceae) crops in northern India were reportedly damaged by the heavy monsoon rains that arrived earlier than normal, which also reduced the availability of menthol in the volatile oil (Cavaliere 2009).

There are 150 components in the chemical makeup of *Pituranthos chloranthus* volatile oils, and they change depending on the season and the location (Wallis et al. 2011; Neffati et al. 2009). An excellent source of bioactive phenolic compounds can be found in the high-altitude *Achillea collina* plant. Climate was determined to be the primary environmental factor impacting antioxidant capacity (half-maximal inhibitory concentration (IC_{50}) values ranged from 4.35 to 8.90 mg mL^{-1}), total phenolic content (from 31.39 to 49.36 mg gallic acid g^{-1} dray weight (DW)), and characteristics (as influenced by altitudes from 600 to 1050 m) (Giorgi et al. 2010).

Similar to this, ecological factors greatly influenced secondary metabolites and the yield of *Alisma orientalis* grown in Dujiangyan, China. The amount of aliphatic compounds was significantly higher than that in other areas (Cavaliere 2009).

The primary climatic variables that influenced the artemisinin content of *Artemisia annua* in Guangxi, China, were temperature and sunshine hours, with the rainfall amount coming in second (Sauve et al. 2006). Humidity and wind speed showed minimal to no impact on the artemisinin content; however, environmental conditions affecting the seedling stage and the flowering season did.

Recently, the individual effects of significant global change factors on plant secondary metabolites and their consequences for insect herbivores have been thoroughly reviewed by Bidart-Bouzat and Imeh-Nathaniel (2008). They emphasized that the effect of environmental stressors on plant secondary metabolites seems to be dependent on the plant species (and genotype), as well as on the chemical type, and may also be related to the type of stress. Such studies are remarkably scarce in the Indian Himalayan context. The growth cycles of alpine plants may be affected by warming temperatures and rising CO_2 levels, and the active components of the plants may change as a result of physiological changes (Chaturvedi et al. 2009). More research is being conducted on how plant secondary metabolic production and composition are affected by climate change.

The high temperature (30.36 °C), the maximum average daytime temperature (23.84 °C), and the high elevation (30 m) in this agroecological zone in El-Minya, Egypt, may all be contributing factors to the high yield in growth parameters and seed yield from this location. According to some studies (Caselato-Sousa and Amaya-Farfán 2012), the amaranth species grow better in hot climates than in other environments. Even in warm temperate zones where the nighttime temperature does not dip below 15 °C, the species of amaranth have a considerable ability to adapt to tropical and subtropical region climates where it can endure temperatures as high as 40 °C (Grubben and Denton 2004). In this regard, Modi (2007) reported that *Amaranthus hybridus* and *Amaranthus tricolor* plants' grain yield significantly decreased when the temperature went from 27/21 °C day/night to 33/27 °C or dropped to 21/15 °C. According to the author, this reduction under hot conditions (33/27 °C) is due to too much temperature for growth and less transferred assimilates to the grain. Hendawy et al. (2018) studied *Mentha piperita* var. multimentha plants that were cultivated in four different locations across Egypt (El-Sharkia, El-Fayoum, Ismailia, and North Sinai), and the researchers found that there were extremely significant variances across the four studied locations and a positive correlation between the yield of *Mentha* plants and temperate climatic conditions. The yield of essential oils varied greatly, with the EO ranging from 0.285 to 1.240% depending on the agroecological region of cultivation. Particularly in the plants grown in El-Fayoum and Ismailia, which may be explained by their high amount of total flavonoids and phenolic compounds compared to other locations, the chemical composition of volatile oils obtained from different locations were characterized by high menthone/menthol contents and high antioxidant activity. El-Fayoum had the highest concentration of oxygenated compounds in the EOs (90.62%), whereas El-Sharkia had the highest concentration of sesquiterpene hydrocarbons (6.68%). In other words, cultivation of *Mentha piperita* var. multimentha in different locations in Egypt with varying geographical and weather conditions had a statistically significant effect on the quantities of the major components. El-Gendy et al. (2022a) cultivated *Pimpinella anisum* in three different locations in Egypt and reported that the plants cultivated in hot temperatures (Aswan and El-Bahariya Oasis) outperformed those grown at lower temperatures (El-Minya location). The seed yield and chemical composition of the essential oils of *Foeniculum vulgare* have been studied in four different agroecological locations in Egypt (El-Minya Governorate, El-Bahariya Oasis, El-Sharkia Governorate, and Aswan Governorate), and the results indicated that 22 compounds have been reported to vary in response to both the geographical area and the season. The main constituents were identified as estragole, which ranged from 66.62 to 89.73% according to the growth location, as mentioned by El-Gendy et al. (2022b).

Cyperus esculentus L. tubers grown in Aswan and Bahariya in Higher Egypt had higher oil content than did those grown in the El-Minya and El- Sharkia Governorates in Egypt (Hammouda et al. 2020). The superiority of Aswan and El-Bahariya Oasis locations for production of *C. esculentus* tubers may be because of the environmental conditions of both locations, especially Aswan (soil, water irrigation, and climatic conditions), which are suitable for this plant.

11 Conclusions

There is no denying that climate change is taking place, and its immediate effects have been projected. Future climate will be determined by the actions we take now. The decisions we make today will affect the climate in the future. In order to achieve effective conservation, climate change management plans will need credible scientific data on both the nature of climate change and its possible influence on plants and plant communities.

Endangered plant species are believed to be more susceptible to climate change and may even go extinct due to their constrained geographical distributions.

It has been noted that as a result of monitoring, the climate system has changed during the last decades of the twentieth century:

1. Increased carbon dioxide concentrations in the atmosphere
2. Increased degrees of land and ocean temperatures
3. Changes in the amount and the time of location rainfall
4. Sea-level rise, especially in warmer regional temperatures

For these reasons, we can recommended:

1. Implementation of programs for selecting and breeding the varieties suitable for the changes in the climatic elements from their growth, yield, and active constituent's points of view.
2. Rehabilitating the species that suffer from the changes in their wild habitats.
3. Carrying out mitigation programs for the medicinal plant species that suffer from climate changes.
4. Future research should concentrate on testing the effects of multiple environmental factors at the same time in order to gain a more realistic understanding of how global climate change may affect secondary chemical production and the potential implications for coevolutionary associations between interacting plants and other living species.

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Chapter 7
Climate Change and Wine Quality

Rosanna Tofalo, Alessio Pio Rossetti, and Giorgia Perpetuini

Abstract Climate change has the potential to jeopardize the sustainability of wine production in various geographical areas, primarily by affecting wine quality, and safety. Climate has a considerable influence on wine characteristics, which is based on an intricate interplay between water availability, temperature, plant material, and vineyard management. The primary effects can be summed up as follows: high alcohol content, high pH and low acidity, development of undesirable microorganisms, accumulation of mycotoxins, and biogenic amines (BAs) in wines.

Both yield and quality have been improved by selecting plant material and vineyard management methods based on the climatic conditions. However, because of climate change, several adaptation strategies have been proposed. For instance, to respond to higher temperatures, new varieties have been selected and farming management methods have been modified.

This chapter provides an overview of the main impacts of climate change on grape composition and wine quality. Furthermore, the possibility of utilizing microorganisms to mitigate the negative aspects of climate change is investigated in the final section.

Keywords Climate change · Wine quality · Grape · Yeasts · Bacteria

1 Introduction

In 2021, global wine production reached 260 million hectoliters, the total vineyard area stood at 7.1 million hectares, global consumption reached 236 million hectoliters, and the overall exports increased to 111.6 million hectoliters, resulting in a total revenue of 34.3 billion euros (OIV 2022).

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The quality of a wine is influenced by several factors, including grape characteristics, soil, viticultural and winemaking techniques, and climate. According to the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report, Earth's temperatures will rise by up to 3.1 °C by the end of this century. This change could result in an increase in droughts and in a reduction in crop yields and quality, thus negatively impacting grape growing and wine production (IPCC, 2018).

Climate change is associated with an increase in plant diseases and variations in the chemical and organoleptic characteristics of wines, inducing variations in their yield, and quality. For instance, high temperatures could cause alterations in alcohol and sugar concentration, an increase in the acidity level, and a low aroma complexity (de Orduna 2010).

This chapter examines the effects of climate change on the wine industry. The chapter is divided into four sections. The first part offers an overview of the winemaking process and the microorganisms involved, the second one discusses the effects of climate change on grape and wine quality, the third is focused on the main mitigation strategies available, and, finally, in the fourth part, future research directions are suggested.

2 The Winemaking Process

The potential to make a good wine is already present in the grapes even at the time of their harvest, and, it is for this reason that winemaking starts at the vineyard; as such, it is up to the winemaker to bring this process to fruition (Pretorius 2016). Every day, winemakers have to make several decisions on the best technology, method, and strategy to implement in each step of the winemaking process to achieve the style of wine desired. They also have to face several challenges year after year, and they cannot ignore climate change. Despite the technological differences between the processes to produce red and white wines, it is possible to summarize five key phases in winemaking: (1) harvesting, pressing, and crushing; (2) fermentation; (3) clarification and stabilization; (4) maturation and aging; and (5) bottling, labeling, and packaging (Fig. 7.1; Jolly et al. 2014). The main steps in winemaking are listed below:

Grape harvesting: Grapes are manually or mechanically harvested. Climate has a significant impact on grape harvesting, since it influences grape maturation, sugar, and acid content. For instance, extreme heat temperatures could result in premature veraison and sugar accumulation (Jones et al. 2005). After harvesting, grapes are delivered to wineries where rotten and unripe grapes are discarded (Ribéreau-Gayon et al. 1998).

Grape crushing and pressing: Red wine fermentation takes place in the presence of the grape skins, whereas the skins, seeds, and stems are removed after crushing for white wine production. During maceration, the polyphenols contained in the grapes are leached into the must in order to confer color, structure, and aroma to red wines (Ribéreau-Gayon et al. 1998).

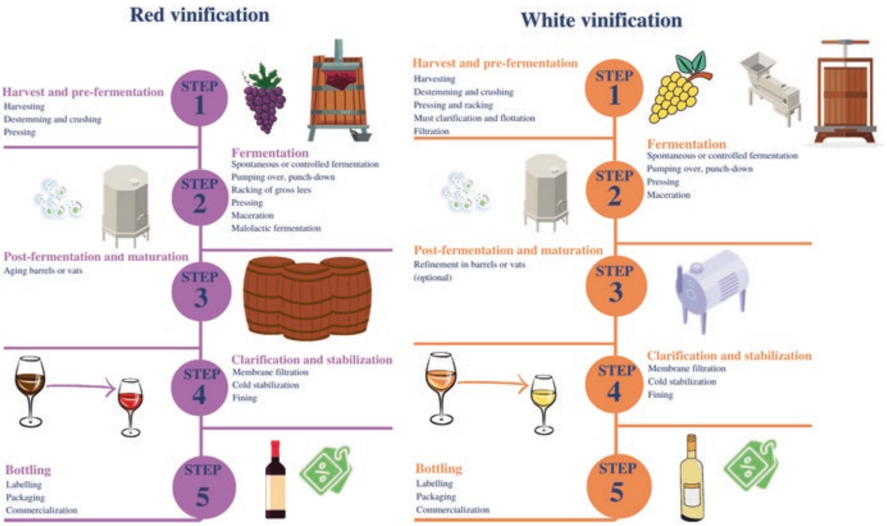


Fig. 7.1 The main steps involved in red and white wine production

Alcoholic fermentation (AF): Fermentation can be driven by grape-borne or starter yeasts. *Saccharomyces cerevisiae* is responsible for the conversion of grape sugars into ethanol and carbon dioxide (CO_2). Red wine fermentation takes place at 18–30 °C and lasts about a week. White wine fermentation occurs at 12–18 °C and lasts several weeks. During red wine fermentation, grape solids (skins, stems, etc.) combine with CO_2 to produce a solid cap on top. To keep red grape solids in touch with the must, the cap is often blended in.

Malolactic fermentation (MLF): After AF, red wine undergoes MLF. Malolactic bacteria – naturally present in the must or inoculated – convert malic acid into lactic acid and CO_2. This process deacidifies the wine and improves its flavor. It also stabilizes the wine, reducing gas generation in bottled wine (Ribéreau-Gayon et al. 1998).

Wine clarification and stabilization: Clarification consists of the elimination of lees. The lees contain tartrates, pectins, gums, proteins, and dead yeast cells. Wine can be clarified and stabilized by simply keeping it in storage while the larger particles settle (settling or *débourbage*). Before the final *débourbage*, the lees can be agitated (*bâtonnage*), and, then, the upper part is separated from the solids present at the bottom of the vessels. Cold filtration, centrifugation, and flotation can speed up this process. For instance, young wines – rich in tartrate – can be treated with filtration to reduce their concentration to values below those at which crystals would eventually form in the bottle. Wines can also be treated with fining agents to reduce their astringency and/or bitterness, prevent protein precipitation, and stabilize their color (Ribéreau-Gayon et al. 1998).

Wine maturation and aging: “Maturation” and “aging” are often confusing terms. Maturation is performed in the presence of wood, e.g., in oak barrels, whereas aging refers to the storage of wine in a bottle. During oak barrel maturation, several chemical transformations take place and the most important one is the polymerization of tannins to obtain smoother and rounder wines. Generally, these transformations are essential to confer wines their aroma, owing to the formation of new compounds associated with vanilla, oakiness, and toasty nuances. The aging of bottled wines is a simple evolution of wines (Ribéreau-Gayon et al. 1998).

3 Yeast Evolution During Wine Fermentation

Grape must fermentation relies on the development of a wide array of microbes. A variety of filamentous fungi, yeasts, and bacteria can be naturally detected on berry and grape must. The species and abundance of indigenous microbes depends on several variables, including the harvesting type (manual or mechanical), temperature, transport to the winery, and grape conditions (temperature, sulfur dioxide – SO_2 – addition). Lactic acid bacteria (LAB) and acetic bacteria mainly belong to the following genera: *Lactiplantibacillus* spp., *Leuconostoc* spp., *Pediococcus* spp., *Oenococcus* spp., *Gluconobacter* spp., and *Acetobacter* spp. Moreover, other bacteria can colonize this niche, with the main ones being *Enterococcus* spp., *Enterobacter* spp., *Bacillus* spp., *Burkholderia* spp., *Serratia* spp., and *Staphylococcus* spp. Several studies have focused on the characterization of the grape-borne yeast biota, and a total of 40 genera and 100 species have been described (Jolly et al. 2014; Capozzi et al. 2015). However, some yeast species are more widely distributed than are others. Although *Saccharomyces cerevisiae* is primarily responsible for converting grape sugars into alcohol, its presence is rare in grapes. The main genera occurring in grapes belong to the basidiomycetes and are *Aureobasidium* spp., *Cryptococcus* spp., *Rhodosporidium* spp., and *Rhodotorula* spp. During ripening, they are replaced by ascomycetous yeast, particularly *Hanseniaspora* spp., *Metschnikowia* spp., and *Candida* spp. (Jolly et al. 2014). The main species are *Hanseniaspora uvarum*, *Metschnikowia pulcherrima*, and *Starmerella bacillaris*. Generally, the presence and quantity of yeasts on the surface of grapes are influenced by a variety of variables in addition to the ripening stage. The presence of particular yeast genera is influenced by local and climatic factors, grape variety, disease pressure, degree of grape damage, and vineyard management (Bagheri et al. 2015; Perpetuini et al. 2022). Physical damage caused by insects, birds, or invasive fungal species, as well as fruit aging and dehydration, can all have an impact on the microbiota of grape surfaces (Barata et al. 2008). For instance, in rot settings, fermentation-related organisms, such as the wild vineyard *Saccharomyces* species, predominate (Barata et al. 2008).

In this context, it is important to underline that not all these species are able to survive during must fermentation. In fact, even if the must is rich in nutrient compounds, it can only support a small number of microbial species.

The fermentation process is initially characterized by yeasts originating from grapes and deriving from the winery. More than 20 yeast genera have been found in fermenting must and the main ones are *Brettanomyces* spp., *Candida* spp., *Cryptococcus* spp., *Debaryomyces* spp., *Filobasidium* spp., *Hansenula* spp., *Hanseniaspora* spp., *Issatchenkia* spp., *Kluyveromyces* spp., *Lachancea* spp., *Metschnikowia* spp., *Meyerozyma* spp., *Ogatea* spp., *Pichia* spp., *Rhodosporidium* spp., *Rhodotorula* spp., *Saccharomyces* spp., *Saccharomyces* spp., *Sporobolomyces* spp., *Starmerella* spp., *Torulaspora* spp., *Vishniacozyma* spp., *Wickeramomyces* spp., *Yarrowia* spp., *Zygoascus* spp., and *Zygosaccharomyces* spp. (Pretorius 2016). Immediately after crushing, the oxygen is depleted and the release of sugars causes a rise in osmolarity, thus creating a stressful environment for many species. During the first stage of must fermentation, non-*Saccharomyces* are the main yeasts detected. In particular, weakly fermentative yeasts such as *Hanseniaspora* spp. dominate the early fermentation stages and are then replaced by yeasts with a moderate fermentation capacity (e.g., *Torulaspora delbrueckii*, *Lanchancea thermotholerans*, *Starm. bacillaris*). When the ethanol content increases, the majority of non-*Saccharomyces* yeasts disappear and *S. cerevisiae* becomes the dominant species. In fact, the ethanol exerts a strong inhibitory effect against non-*Saccharomyces*, and only few of them can tolerate concentrations higher than 10%. The role of non-*Saccharomyces* yeasts has been misjudged for a long time (Padilla et al. 2016). Only recently their role has been better studied. In particular, it has been demonstrated that non-*Saccharomyces* yeasts possess a variety of hydrolytic enzymes – including β-glucosidase, β-lyase, esterase, and alcohol acetyltransferase – involved in the production of aroma compounds. β-Glucosidases are involved in the production of terpenes, whereas β-lyases allow the release of volatile thiols from the precursor bound to either cysteine or glutathione (Padilla et al. 2016). Non-*Saccharomyces* are also involved in the production of esters. Their production depends on the balance between the alcohol acetyltransferase enzymes that promote their formation and the esterase enzymes responsible for cleaving them (Padilla et al. 2016). The main esters produced by non-*Saccharomyces* yeasts include ethyl acetate, isoamyl acetate, 2-phenylethyl acetate, isoeugenyl phenylacetate, phenethyl propionate, and isobornyl acetate (Padilla et al. 2016). Moreover, these yeasts are also involved in the modulation of higher alcohol concentration in wines. These compounds positively contribute to wine aroma only at concentrations below 300 mg/L. Of particular interest are *Hanseniaspora* spp., *Pichia* spp., and *Zygosaccharomyces* spp., which are low producers of higher alcohols. However, some higher alcohols are highly desired in wines such as 2-phenylethyl alcohol, which has a floral, rose-like aroma and is produced at high levels by *M. pulcherrima*, *Pichia fermentans*, *Lachancea thermotolerans*, *T. delbrueckii*, and *Starm. bacillaris*. Besides aroma compounds, non-*Saccharomyces* yeasts can also produce some compounds influencing wine mouthfeel, e.g., polysaccharides and glycerol. Polysaccharides improve the mouthfeel, fullness, sweetness, and roundness of wines and reduce wine astringency (Juega et al. 2012). Glycerol is responsible for the sweetness of red and white wines. *Starm. bacillaris*, *Kluyveromyces* spp., *Saccharomycodes*, and *Schizosaccharomyces* spp. are considered high glycerol producers (Perpetuini et al. 2021).

To utilize these activities, mixed inocula *Saccharomyces*/non-*Saccharomyces* have been proposed to improve wine aroma complexity. A suitable yeast selection program for both *S. cerevisiae* and non-*Saccharomyces*, as well as the development of *ad hoc* mixed starter cultures, is essential for obtaining wines with distinctive traits reflecting the "terroir concept" (Barata et al. 2012).

The main oenological properties of non-*Saccharomyces* are reported in Table 7.1.

Bacteria are the main actors of MLF. At the end of the AF, only few bacterial species can survive, because of the high content of ethanol and low pH, and the main ones are *O. oeni* and some strains belonging to the genera of *Pediococcus* and *Lactiplantibacillus*.

Table 7.1 Compounds released by the main non-*Saccharomyces* yeasts of oenological interest and their consequent effect on wine quality

Non-*Saccharomyces*	Compounds	Effect on wine	References
Hanseniaspora spp.	Esters (acetate and ethyl esters), higher alcohols (phenylethanol), terpenes and norisoprenoids, acetic acid, sulfur compounds	Increased volatile acidity of wines, improvement of wine aroma complexity	Tristezza et al. (2016), Hu et al. (2018), Mendes Ferreira et al. (2001)
Starm. bacillaris	Higher alcohols, ethyl esters, terpenes, glycerol	Improvement of wine aroma complexity and mouthfeel	Russo et al. (2020), Tufariello et al. (2020), Bartowski et al. (2015), Styger et al. (2011)
T. delbrueckii	Linalool, higher alcohols, esters, lactones	Definition of wine aroma complexity through the substitution of common fruity esters with uncommon ones and lactones	King and Richard Dickinson (2000), Liu et al. (2017), Renault et al. (2015), Azzolini et al. (2012)
L. thermotolerans	Esters, terpenes, 3-methylthio-1-propanol	Increased concentration of terpenes, lactic acid, and volatile sulfur compounds in wines	Morata et al. (2018), Balikci et al. (2016)
M. pulcherrima	Terpenes, 4-methyl-4-sulfanylpentan-2-one, phenylethanol, β-damascenone, ethyl octanoate, ethyl acetate, 2-phenylethyl acetate	Increased concentration of ethyl esters, terpenes, and higher alcohols, reduced volatile acidity	Zhang et al. (2018), Ruiz et al. (2018), Varela (2016)
Pichia spp.	Esters, terpenes, volatile phenols, higher alcohols, thiols, glycerol (*Pichia kuyveri*)	Improvement of wine aroma complexity and mouthfeel	Perpetuini et al. (2020a), Saez et al. (2011)

4 Consequences of Climate Change on Grape Quality

Dormancy, bleeding and budbreak, shoot and leaf growth, flowering and fruit set, veraison and ripening, and harvest are the main phenological stages of the grapevine, and the period between them varies widely according to the climate, grapevine variety, and geographic location (Fig. 7.2). Numerous studies have examined the connection between grapevine physiology and climate change scenarios (Holland and Smit 2010). The efforts made in these types of studies have been essential to comprehend the influence of climate change on farming practices and grape/wine quality. Climate change negatively impacts vine growth and phenology and grape characteristics (Ollat et al. 2016) (Fig. 7.3).

Increasing temperatures have an impact on several aspects of grape quality. Temperature is believed to be the most important atmospheric factor for vine growth (Franga et al. 2019). Extreme hot temperature during flowering can result in premature veraison, a change of color and sugar accumulation, and a substantial grape mortality through abscission (Jones et al. 2005). Grapevines exposed to extreme heat stress may significantly reduce their photosynthetic production, resulting in several physicochemical changes (White et al. 2006). Photosynthesis decreases above 25 °C, even with continuous sun exposure. Furthermore, above 30 °C, there is a drastic reduction in grape size and weight as well as a deregulation of the

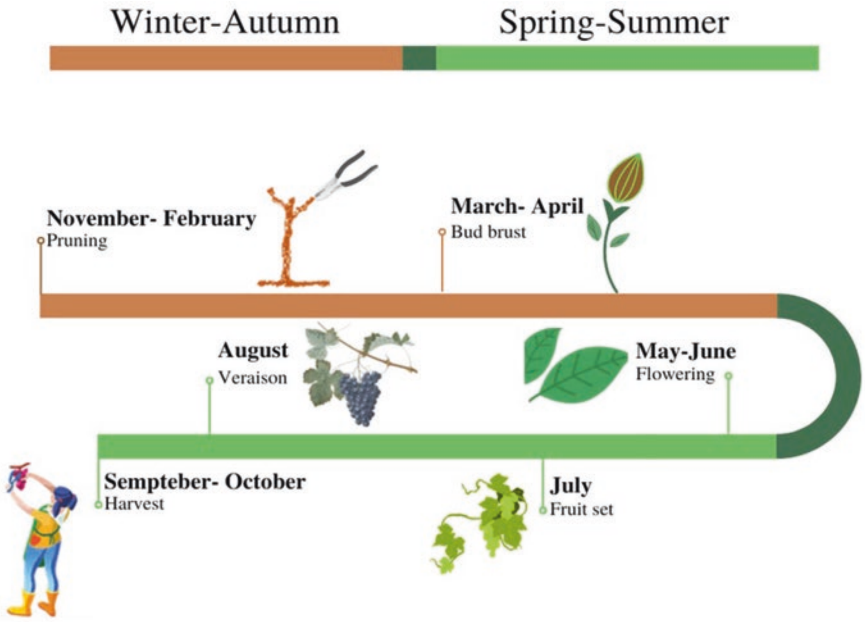
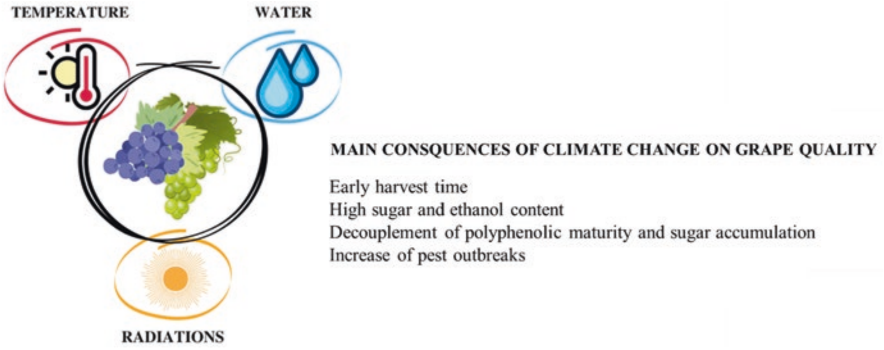


Fig. 7.2 The grapevine life cycle. Grapevines are perennial plants. The main steps of the grape lifecycle: dormancy, bleeding and budbreak, shoot and leaf growth, flowering and fruit set, veraison and ripening, and harvest



MAIN CONSQUENCES OF CLIMATE CHANGE ON GRAPE QUALITY

Early harvest time
High sugar and ethanol content
Decouplement of polyphenolic maturity and sugar accumulation
Increase of pest outbreaks

Fig. 7.3 The main climate change-related factors influencing grape quality and related consequences

metabolic pathways and sugar accumulation (de Orduna 2010). The high temperatures also have a negative impact on grape acidity. Malic acid amount is significantly influenced by the temperature and maturity of grapes, and the total amount of this organic acid decreases as the temperature increases. Moreover, global warming seems to promote the accumulation of potassium (Holland and Smit 2010), resulting in higher pH values. Global warming is also responsible for alterations in flavonoid formation and their final concentration in grapevine. These compounds are important for grape quality and wine production due to their contribution to color, flavor, fragrance, astringency, wine stabilization, and antioxidant properties (Santos et al. 2018). Downey et al. (2006) have underlined how a hot climate and long sun exposure of grapes could inhibit anthocyanin formation and reduce wine color stability. The effects are both quantitative and qualitative with accumulation of malvidin, petunidin, and delphinidin coumaroyl derivatives (de Oroduna 2010). High temperatures could also result in a substantial decrease of some volatile compounds (Robinson et al. 2014). For instance, higher temperatures resulted in lower levels of varietal aromas (Belancic et al. 1997).

Climate change will also increase vine susceptibility to droughts, either as a result of reduced precipitation or higher evapotranspiration due to higher temperatures. Several yield parameters, including berry size and bud fertility, are influenced by water deficits.

The consequences of drought depend on the stage of grapevine development. For instance, vine growth depends on moderate-to-high soil water during budburst and shoot/inflorescence development. At this stage, water stress may result in stunted stem growth, poor flower cluster development, and poor berry set. However, too much water during the initial phases of development may potentially overstimulate growth, which could result in heavy canopies, thus amplifying the risks of disease. Severe water stress during blooming and berry ripening may result in a decreased leaf area, which would limit photosynthesis (Santos et al. 2018).

In viticulture, solar radiation is another important factor. High levels of sun radiation could promote the accumulation of sucrose, phenolic compounds, and numerous aroma compounds during ripening (Santos et al. 2018).

There are notable secondary effects linked to climatic fluctuations, such as increase in grape salinity and the higher incidence rate of brushfires. Climate change could favor the onset of Pierce's disease caused by *Xylella fastidiosa* (Daugherty et al. 2009), the diffusion of *Guignardia bidwellii*, the fungus responsible for black rot, *Metcalfa pruinosa*, a flatid planthopper, or *Scaphoideus titanus*, the vector of the phytoplasma grapevine disease. Furthermore, high temperatures are associated with the diffusion of *Botrytis cinerea* – a mold that causes bunch rot in grapevines.

5 Consequences of Climate Change on Winemaking

As stated above, grapes are sensitive to even small changes in climatic conditions. The quality of grapes is influenced by three factors: temperature, sun radiation, and water condition. The effects of these factors induce an increase in sugar content and pH and a reduction in total acidity (Parker et al. 2011). Increased temperatures advance veraison (the moment when the color of the berry changes and sugar accumulation starts) (Parker et al. 2011). This phenomenon represents a challenge for winemakers since sugar accumulation and polyphenolic maturity are decoupled, resulting in unbalanced grapes (Pons et al. 2017). Therefore, they have to decide between a late harvest, which results in wines with a high alcohol content and a bitter taste, and an early harvest, which produces wines with a low color density and poor aroma complexity.

The main impact of climate on wine quality is the increase in ethanol content. Reduction in ethanol content is one of the main challenges of the wine industry, since the use of water is allowed only for the preparation of enzymes and yeasts (OIV 2019). Therefore, new methods have been proposed and the main ones are osmosis, nanofiltration techniques (Schmidtke et al. 2012), and the selection of yeast strains that are able to synthetize pyruvic acid, glycerol, and other metabolites from ethanol (Ciani et al. 2016; Tofalo et al. 2016a).

Another consequence of high temperature is the increase in pH. In fact, higher temperatures cause a drop in malic acid with a consequent reduction in wine acidity and an increase in pH. The occurrence of high pH values represents a problem since it may encourage microbial growth, including spoilage microbes, and the fungal contamination and the subsequent accumulation of toxins like ochratoxin A (OTA), which can pass into wines. The antimicrobial treatments of the plant coupled with the addition of preservatives to the wine could prevent this problem. Last but not least, it is significant to note that nitrogenous compounds increase throughout ripening (Garde-Cerdán et al. 2009). Therefore, overripened grapes are characterized by high nitrogen concentration. This phenomenon could favor protein haze formation. A possible solution is the addition of higher amounts of a fining agent to stabilize proteins. Moreover, the accumulation of nitrogenous compounds could favor biogenic amine (BA) formation.

The main consequences of climate change on winemaking are detailed below.

5.1 Development of Spoilage Microorganisms

The growth of spoilage microbes is promoted by increased temperatures and higher pH values associated with advanced harvest dates. This phenomenon could result in sluggish or stuck of AF and the production of metabolites with a negative impact on wine quality and human health. For instance, an increase in acetic acid, pyruvate, acetaldehydes, and OTA has been reported (de Orduna 2010).

5.2 Increase in Sugar and Ethanol Content

Ethanol can exert a negative impact on microbes' viability, causing growth inhibition or cell lysis. This effect results in sluggish or stuck of AF (Coulter et al. 2008). Similarly, it could negatively impact MLF since ethanol affects the membrane integrity of the involved bacteria. Several studies have focused on the effect of ethanol on the volatility of wine aromatic compounds. Higher alcohols, esters, monoterpens, and pyrazines have all shown a reduction in their volatility (Robinson et al. 2014), whereas linalool and 3-mercaptohexanol-1-ol have shown an increase with a consequent reduction in their sensory threshold (de Orduna 2010).

5.3 Increase in pH

An increased pH is associated with an increase in oxidative reactions, which negatively impact both wine color and aroma. In fact, under this condition, the formation of colorless hemiketal anthocyanins is favored (Ribéreau-Gayon et al. 1998). Moreover, a high pH favors the stability of esters, but a lower release of aroma compounds from glycosidically bound precursors is observed (de Orduna 2010). Finally, a high pH is associated with protein haze formation.

5.4 Health Consequences

The unbalanced composition of grapes could favor the accumulation of toxic compounds for human health. As mentioned above, winemakers anticipate the harvest date even before grape flavor development is completed. Therefore, nitrogen-based fertilizers are added to favor the formation of volatile compounds (Gutiérrez-Gamboa et al. 2018). However, this fertilization raises the amount of amino acids in the berry, particularly arginine, which enhances the accumulation of ethyl carbamate in the resulting wines.

Urethane, or ethyl carbamate, may cause cancer (IARC 2007). Yeasts and LAB synthesize it by reacting ethanol with carbamyl molecules, typically urea or citrulline. Arginine metabolism in yeast produces urea and citrulline. Therefore, grapes with larger concentrations of this amino acid or those subjected to nitrogen fertilization are associated with higher production of ethyl carbamate (De Orduna 2010).

Biogenic amines are organic bases with low molecular weight, mainly produced by LAB through amino acid decarboxylation. They carry out physiological functions including regulation of body temperature, gut pH, and brain function (Tofalo et al. 2016b), but, when they are consumed in large quantities, they are associated with negative effects, especially in sensitive individuals (Tofalo et al. 2016b). Histamine, tyramine, and putrescine are the most prevalent BA in wine; their precursors are histidine, tyrosine, and ornithine, respectively, and are mainly produced during MLF (Perpetuini et al. 2020b). They are associated with skin irritation, headaches, edemas, and rashes (Tofalo et al. 2016b). Nitrogen-based fertilizers coupled with delayed harvest can induce an increase in BA, since grapes are richer in amino acids (Smit et al. 2013). Moreover, the current tendency to produce wines with low SO_2 content is associated with the development of LAB-producing BA.

According to De Jesús et al. (2018), the effects of high temperature are connected with greater OTA content in wines. A correlation between temperature and the occurrence of OTA in grapes and wines has been observed, suggesting that southern European wines contain more OTA than their northern counterparts. Yeast binding, filtration, and the addition of fining agents may be used to decontaminate the wine but only with limited success (Quintela et al. 2013).

6 Climate Change Adaptation Strategies

Since 1880, Earth's temperature has risen by 0.08 °C per decade while the rate of warming is double. In fact, in 2021, Earth was about 1.1 °C warmer than it was in the late 1800s.

Adaptation to climate change reduces susceptibility to its negative impacts and maximizes its advantages. Subnational jurisdictions and entities develop and strengthen weather and climate risk reduction measures. Proper strategies are needed to limit warming to 1.5 °C to guarantee sustainable development.

Concerning the wine sector, it should be noticed that climate change is predicted to be advantageous for viticulture in some regions by enhancing fruit maturity and opening new areas for cultivation, but it is predicted to be harmful in others by endangering the ability to grow enough grapes and make wine (Santos et al. 2018). Current viticultural and vinicultural areas in Europe may be dramatically altered by changes, and future scenarios could result in a reduction in the viticultural suitability of the current wine-producing areas. As for the strategies that can be adopted to deal with this problem, they can be divided into short- and long-term strategies (Table 7.2).

7 Short-Term Adaptation Strategies

Short-term adaptation measures are typically centered on specific problems. These actions can be implemented during the grapevine growing season. Several of these measures necessitate alterations to management practices and are briefly described.

7.1 Cultural Crop Strategies

Some strategies have been proposed to postpone the ripening. The main ones include reduction of canopy area to reduce the consumption of water, use of anti-transparent materials and a shade-net environment to minimize both carbon absorption and water consumption, and harvesting sooner to achieve moderate sugar concentration and proper acidity (Stoll et al. 2013).

7.2 Protection from High Temperatures

A possibility is the use of chemicals able to preserve or improve plant growth. The main compounds used to achieve this goal include kaolin (an inert white clay with reflecting qualities) and potassium silicate (Basile et al. 2015; Bedrech and Farag 2015). In particular, kaolin application allows improving the antioxidant potential of grape berries and the levels of secondary metabolites (e.g., phenols, flavonoids, and anthocyanins) (Dinis et al. 2016; Bernardo et al. 2017).

7.3 Irrigation

Irrigation improves crop quality when rainfall falls short of grapevine water needs. France, Spain, Portugal, and Germany, where grapevines are rain-fed, have implemented irrigation strategies. Drip irrigation is the most effective method (Sauer et al. 2010). Automated, intelligent, real-time irrigation systems should be optimized to face global warming (Koech and Langat 2018).

Table 7.2 Main short- and long-term strategies applied to face climate change challenges

Adaptation strategies	Possible solution	Positive effect	References
Short-term			
Crop cultural practices and techniques	Modification of canopy geometry Reduction of canopy size Application of anti-transparent materials Earlier harvest	Reduction of carbon assimilation and water consumption Achievement of moderate sugar levels and right acidity	Stoll et al. (2013)
Extreme heat and sunburn protection	Use of sunscreen materials Use of shade net	Kaolin forms an inert particle film upon the leaf Increase in canopy and fruit zone reflective capacity	Bedrech and Farag (2015)
Irrigation	Implementation of irrigation deficit (ID)	Enhancement of water savings	Flexas et al. (2010)
Soil management	Use of mulches Spontaneous or cultivated herbaceous cover crops	Moderate soil temperatures, suppress diseases and harmful pests Positive contribution to soil fertility	Xi et al. (2010)
Long-term			
Training systems implementation	Minimal use of pruning systems Limiting the canopy height Change in row orientation Optimization of vineyard orientation	Delay in the maturation period, reduce sugar levels, and protect the cluster zone from the radiations and sunburns	Stoll et al. (2013), Duchene et al. (2012), Wolkovich et al. (2018)
Varietal or clonal rootstock selection	Selection of heat-tolerant varieties Grapevine breeding of heat-tolerant varieties Planting new vineyards on rootstocks	Enhanced resistance toward the primary abiotic stresses	Jones (2006), Duchene et al. (2012), Ollat et al. (2016)
Vineyard relocation	Moving the vineyard to new areas	Shifts to cooler sites, such as those located at higher latitudes, at higher elevations, at coastal zones, or in areas with overall lower solar radiation and cooler temperatures	Karvonen (2014)

7.4 Pest and Disease Management

Pest and disease management requires monitoring, ongoing innovation, and adaptability through the transfer of technologies from areas where pests are well-handled or through the use of novel pest management methods, e.g., the application of natural chemicals (Dam et al. 2019).

7.5 Soil Management

It is essential to preserve soil health. Tillage may reduce yield and soil in terms of water and carbon storage (Gomez et al. 2009). Mechanical cultivation could have a negative impact on the soil microbiota and could favor organic matter mineralization and soil erosion. Compost protects soil fertility. In fact, its use protects the soil microbiota, organic matter content, soil porosity and structural stability, nutrient availability, and soil quality. Composting a vineyard requires consideration of nutrient intake because high nitrogen supply might cause bunch rot (Tello and Ibanez 2017). Mulches may improve soil moisture, reduce soil temperature, and prevent the diffusion of pest and diseases (Judit et al. 2011). At least during the rainy season, all vineyards should have herbaceous cover crops covering the soil, in order to prevent soil erosion, evaporation, and infiltration (Xi et al. 2010).

8 Long-Term Adaptation Strategies

These measures are utilized to adapt to climate change over the course of a number of growing seasons or prior to the planting of a vineyard. The main strategies are reported below.

8.1 Training Systems

The main strategies include: (a) minimum pruning to delay the maturation and the development of bunch rot; (b) modification of the ratio of the leaf area to the fruit weight to reduce the sugar content; and (c) modification of canopy geometry in order to reduce the level of radiations (Grifoni et al. 2008). Gobelet or Guyot systems could be applied to conserve water (Flexas et al. 2010).

8.2 Selection of Varietals/Clonal Rootstocks

Cooler winemaking regions (North Europe) may use southern European varieties, whereas varieties adapted to high temperatures may be planted in southern Europe (Morales-Castilla et al. 2020). Heat-tolerant varieties could be developed through breeding approaches (Santos et al. 2018). Moreover, rootstocks protect plants against soil-borne pests and diseases. Therefore, planting new vineyards on rootstocks could represent another long-term strategy (Ollat et al. 2016; Pavlousek 2011).

8.3 Grapevine Relocation

This strategy is required if regions become too warm and arid (Moriondo et al. 2013). Vineyard site selection should consider cooler areas at higher latitudes or along the coast (Karvonen 2014; Moriondo et al. 2011).

9 Microorganism-Based Strategies to Face Climate Change Effects

Microorganisms can represent a useful tool to face the consequences of climate change on wine quality. Recently, Berbegal et al. (2019) have provided an extensive review about the microorganism-based approaches that could be used to overcome the main negative effects exerted by climate change on wine quality: (a) enhanced growth of spoilage microorganisms; (b) increase in sugar and ethanol content; (c) decreased acidity and raised pH of wines; (d) sensory imbalance and color loss; and (e) safety concerns associated with mycotoxins and BA accumulation.

9.1 Biocontrol of Spoilage Microbes' Development

Biocontrol of spoilage microorganisms could be achieved through two main strategies: addition of microbial metabolites that could act as biopreservatives or the use of selected microorganisms as a starter or a protective culture (Varela 2016). Biocontrol activity is the result of the competition for nutrients and/or the production of compounds exhibiting antimicrobial activity (e.g., bacteriocins or yeast killer toxins). For instance, *M. pulcherrima* exerts its biocontrol activity *via* iron depletion (Oro et al. 2014), *Pichia membranifaciens* is able to produce killer toxins against spoilage yeasts (Alonso et al. 2015), *T. delbrueckii* can be used as a bioprotective agent to replace SO_2, and *Lactococcus lactis* produces lacticin 3147, which inhibits LAB.

9.2 Reduction of Ethanol Content

As stated above, the higher concentration of ethanol induced by increased temperature could alter the wine bouquet, thus exalting the bitterness sensation. In this context, microorganisms could represent a useful tool to lower the ethanol concentration. It should be possible to select *S. cerevisiae* strains with a reduced efficiency concerning alcohol yields or to drive strains to evolve in environments that favor glycerol synthesis over ethanol production. Another strategy could be the co-inoculation or sequential inoculation of *S. cerevisiae* and non-*Saccharomyces* (e.g., *H. uvarum*, *Schizosaccharomyces pombe*, *L. thermotolerans*). Non-*Saccharomyces* yeasts possess two interesting features: some strains are good fermenters at low temperatures producing wines with low ethanol content and some possess an oxidative metabolism, and, therefore they are able to respirate sugars under a controlled flow rate of oxygen (Contreras et al. 2014; Ciani et al. 2016). Finally, metabolic engineering could be utilized to alter the carbon fluxes in the cell and produce low-ethanol producer strains. Several studies have redirected the carbon toward glycerol in order to reduce the flow of carbon to ethanol (e.g., Remize et al. 1999).

9.3 Reduction of pH

Non-*Saccharomyces* yeasts and malolactic bacteria are well-known organic acid producers. *L. thermotolerans* and *Starm. bacillaris* have been proposed for the biological acidification of musts, since the first is a good producer of lactic acid and the second of acetate, succinate, malate, and lactate (Morata et al. 2018; Masneuf-Pomerade et al. 2015).

9.4 Improvement in Wine Sensory Characteristics and Color

Non-*Saccharomyces* yeasts are well-known for the production of aroma compounds. *Saccharomyces cerevisiae* and non-*Saccharomyces* can produce vinylphenolic pyranoanthocyanins and pigments contributing to color stability. *S. pombe* and *Starm. bacillaris* are involved in improving red wine color through the production of vitisin A (Tofalo et al. 2021).

9.5 Reduction of Toxic Compounds

Climate change is also responsible for the accumulation of some toxic compounds in wine such as OTA and BA. The main bacteria responsible for BA production in wine are LAB. Therefore, a strategy to mitigate their accumulation could the selection of either decarboxylating negative bacteria to be used as starter cultures or yeast strains able to consume malic acid (Garofalo et al. 2015). Another possibility could be the selection of BA-degrading bacteria, or the use of multicopper oxidases, of microbial origin (Niu et al. 2019). OTA reduction by yeasts is a well-known strategy. In fact, yeasts are able to adsorb OTA on the cell well, thus reducing its concentration in wine (Caridi et al. 2012).

10 Conclusions and Future Perspectives

Consumers are paying more and more attention to the connection between a wine and the region where it is produced, thus increasing the susceptibility of the entire wine industry to climate change.

According to the 2019 ProWein Business Report, the wine industry is responding to climate change challenges. Changes in vineyard locations, selection of heat-tolerant grapevine varieties, and application of more appropriate soil management techniques are the main mitigation strategies applied to prevent market instability. In general, climate change is seen as a significant danger to viticulture, posing threats or challenges to most aspects of the winemaking industry.

Implementation of new strategies for vineyard management on the basis of local climate change projections will contribute to the resilience of the wine sector. The winemaking industry should design adequate adaptation measures to deal with the effects of climate change, mainly by implementing good regional/local plans, especially in areas that will be most negatively impacted.

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Chapter 8
Crop Responses to Drought Stress

Deepu Pandita

Abstract Climate change is leading to a hotter and parched world. The world's population is also continuously growing. In such scenarios, both agricultural "thirst" and human thirst will be enhanced. A drought causes adverse comprehensive physiological, morphological, and biochemical changes, leading to reduced crop growth and yield and, ultimately, to decreased food security. Water scarcity is one of the key abiotic stresses responsible for the massive decline in crop yields globally. To fine-tune drought resistance, production of plants with high water use efficiency (WUE), and water deficient tolerant plants with high yields is needed. This chapter endeavors to record the developments in understanding the responses of crop plants to droughts and the basic plant machinery required to mitigate drought stress.

Keywords Climate extremes · Drought stress · Antioxidant · ROS · Abiotic stress · Water use efficiency · Crop plants

1 Introduction

Drought is a misfortune to agriculture directly and to humanity indirectly. In the past decade, the global losses in crop production due to droughts totaled ~$30 billion. The estimated world population will undergo an upswing from the current 7.5 billion to 9.7–10 billion by 2050, and, of these, 5 billion people are predicted to live in drought zones (United Nations 2011; Koncagül et al. 2018). Additionally, given the current scenarios for climate change globally, the need of water for agricultural purposes is predicted to double by 2050, with an increase in water scarcity and a decrease in the availability of fresh water by 50% (Gleick 2000). Agriculture accounts for more than 70% of global water use (FAO 2020). For the continuously increasing world population, global sustainable agricultural production also needs to rise to succeed in fulfilling the basic necessities of humans. Water is essential for

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the survival of plants, and the adverse environmental conditions of water deficiency hinder the growth and development of plants and crop productivity. This is why various strategies should be designed to grow plants with high water use efficiency (WUE) and boost agricultural yields in the face of the increased challenges of water scarcity in modern agriculture and to combat the most critical factors and major challenges of drought stress (Kabbadj et al. 2017).

Diverse defense mechanisms or adaptation and acclimation strategies underlying the metabolic pathways of a plant, such as modifications of its morphology, physiology, biochemistry, and anatomy, as well as its molecular nature, are activated after periods of water deficiency to preserve the plant's hydration status; but severe water shortage might cause plant death (Zingaretti et al. 2012; Zlatev and Lidon 2012; Abobatta 2019; Kapoor et al. 2020). Moreover, adaptation processes such as short- and long-term development and growth take place (Abobatta 2019). Droughts can lead to a decrease in cell division and growth rate as well as yield and water usage efficacy and an increase in root differentiation, size of leaves, and plant shoot length. A drought can also alter the movement of the stomata and water and mineral nutrition (Kumawat and Sharma 2018). Stomatal closure, in turn, damages the cell membrane and reduces enzymatic activities, mainly of adenosine triphosphate (ATP) generation and photosynthesis (Kumawat and Sharma 2018, Sharma et al. 2020a). Reactive oxygen species (ROS) and reactive nitrogen species (RNS) are generated during drought stress, which reduces the redox-regulating capability of cells (Laxa et al. 2019; Sharma et al. 2020b). Plant crops mainly experience moderate drought conditions due to persistent rainfall deficits, decreased groundwater levels, and/or restricted access to water. This causes significant damages to the overall yield (Eshed and Lippman 2019). Plants sense water deficiency in the form of stress signals and initiate survival approaches like preventing loss of water, taking up a balanced, optimum water amount to their essential organs, and maintaining appropriate water content in their cells, thus resisting drought stress. This property known as drought resistance, is a complex trait of survival or can be referred to as the ability of plants to adapt to harsh stress conditions using escape, avoidance, and tolerance mechanisms (Larcher 2005; Fang and Xiong 2015; Basu et al. 2016). Drought tolerance depends on the ability of plants to tolerate physiological activities under severe drought conditions by remodeling of gene regulation and metabolic pathways to decrease or repair the subsequent damage (Fang and Xiong 2015; Perlikowski and Kosmala 2020). To cope with drought stress, plants undergo a number of modifications and responses, as shown in Fig. 8.1.

2 Impact of Drought Stress on Morphological Features

A plant's vascular system communicates about the availability of water in soil through signals from the roots to the shoots and diffuses food produced by photosynthesis from the shoots to the roots. A plant's vascular tissues also play a role in the battle against droughts (Scharwies and Dinneny 2019).

Fig. 8.1 Drought responses displayed by a plant

In drought stress scenarios, the root system of plants displays morphological changes of coordinated cell division, root elongation, root differentiation, and root adaptation. Elongated and deeper roots with decreased branching angles in soil zones enable effective water and nutrient absorption from the deep layers of the soil (Rellán-Álvarez et al. 2016; Dinneny 2019). The shallow root systems are more positive for using water captured in soil surfaces of low precipitation zones (Dinneny 2019). Roots in soil with a nonhomogeneous distribution of water show hydropatterning by favoring the emergence of lateral roots toward soil areas with a higher content of water. This process is also mediated by auxin signaling (Robbins and Dinneny 2018; Dinneny 2019). Second, hydrotropism, involving growth of root tips toward regions with a higher water content, also improves the architecture of the root system for acquisition of moisture (Dietrich et al. 2017). The stomata open or close on the surface of plant leaves, consistent with the turgidity of guard cells. Turgor-based modifications in the shape of guard cells are influenced by the structure of the cell wall, cell membrane, tonoplast surrounding vacuoles, and cytoskeletal dynamics. The closure of the stomata is a swifter defense mechanism against dehydration (Buckley 2019). The productivity of crops becomes susceptible to droughts if they take place during the reproductive stage of the plants. In *Arabidopsis* *thaliana*, early flowering takes place to escape from droughts. This is connected to phloem loading and transport of photoperiod-dependent, protein-encoding flowering locus T (FT) from the leaves of the plant to the shoot apical meristem (Andrés and Coupland 2012).

3 Influence of Drought Stress on Biochemical Features

3.1 Oxidative Damage

A drought activates different biochemical mechanisms as well as plasma membrane fluidity, production of osmolytes, peroxidation of lipids, generation of ROS, rigidity of cellular membranes, and enzymatic activation of the oxidative defense system (Qi et al. 2018; Roychowdhury et al. 2019). Drought stress-induced ROS production causes substantial damage to cellular components, lipid peroxidation, and proteins (Sapna et al. 2020). ROS has a catastrophic influence on lipid membranes, proteins, photosynthetic pigments, and nucleic acids. Various ROS are produced in plants as a byproduct of metabolic processes in the cell organelles of chloroplasts, the mitochondria, and peroxisomes. ROS play role not only in vital signaling processes but also as a toxic by-product of aerobic metabolism (Mittler 2017). The superoxide radical (O_2•−), singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), and hydroxyl radical (OH•) types of ROS are primarily produced by enzymatic or nonenzymatic processes in photosynthesis and also in the electron transport system of the mitochondria by partial reduction or oxidation of atmospheric oxygen (Mittler 2017). The production of ROS beyond a plant's quenching ability is known as a disruption of redox signaling and redox control. ROS at an optimum level help plants adapt to drought stress (Jones 2006) (Fig. 8.2).

3.2 Enzymatic and Nonenzymatic Antioxidants

Under normal conditions in plants, ROS production remains in equilibrium by scavenging through enzymatic and nonenzymatic cascades (Hernández-Jiménez et al. 2002). The balance between ROS production and ROS scavenging gets disturbed by stress factors. Disorders of cellular homeostasis accelerate cellular ROS levels and generate oxidative stress (Hasanuzzaman et al. 2015; Roychowdhury et al. 2019). ROS-generated oxidative stress causes substantial damages to DNA, proteins, lipids, cell structure, and membrane integrity and causes oxidative injury in plants. This leads to reduced growth and development of plants (Hernández-Jiménez et al. 2002). To survive under ROS-based oxidative stress conditions, plants use numerous components (enzymatic and nonenzymatic antioxidants) of

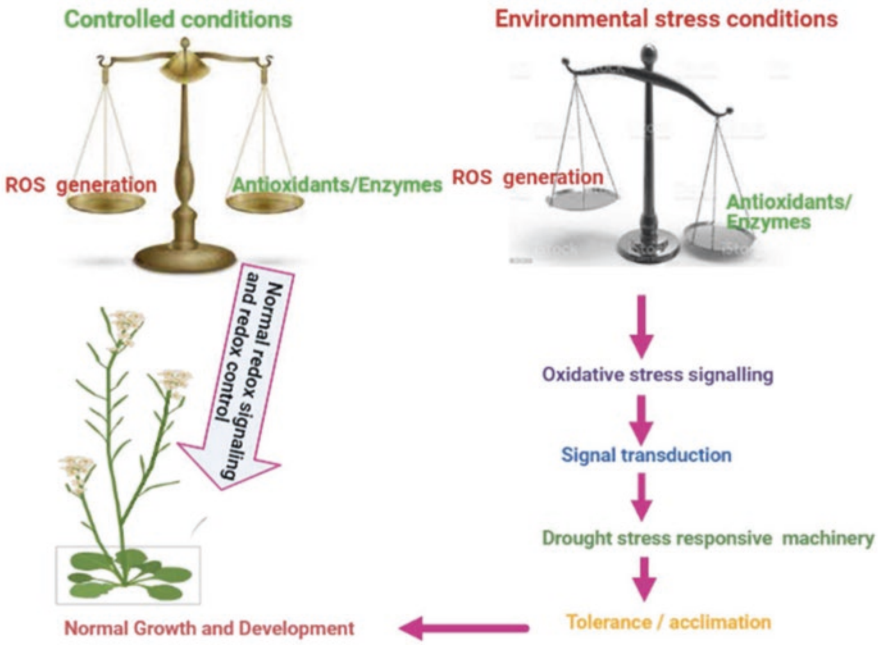

Fig. 8.2 Plant growth and development under normal conditions and drought stress

ROS homeostasis modulation (Rai et al. 2018). The cells have enzymatic and nonenzymatic components. Enzymatic antioxidants include superoxide dismutase (SOD), monodehydroascorbate reductase (MDHAR), ascorbate peroxidase (APX), catalase (CAT), dehydroascorbate reductase (DHAR), and ascorbate (AsA). Nonenzymatic antioxidants include carotenoids and flavonoids, glutathione (GSH), proline, glycine betaine, and α-tocopherol (Hasanuzzaman et al. 2015; Roychowdhury et al. 2019).

4 Influence of Drought Stress on Physiological Features

Physiological responses to drought offer escape mechanisms comprising physiological and morphological adaptations (Lamaoui et al. 2018). The reduced surface area of leaves and a decline in the number and conductance of the stomata, extension of the plant root system, increase in the thickness of leaves, and folding of leaves to reduce evapotranspiration are adaptive responses (Earl and Davis 2003; Anjum et al. 2011; Gregorova et al. 2015; Abobatta 2019). The growth and productivity of plants decline under droughts due to changes in plant water relations, CO_2 assimilation reduction, membrane damage of the affected tissues, cellular oxidative stress, and inhibition of enzymatic activities. Plants show osmotic adjustment by accumulation and integration of compatible solutes like proline, sugars, and free amino acids (Tatar and Gevrek 2008). The turgor pressure maintenance and cell volume at a low water potential are facilitated by osmotic adjustment and are important for metabolic functions. Osmotic adjustment recovers metabolic activities after droughts (Bennett et al. 2012).

A drought at a higher intensity declines the activities of both the photosynthetic enzymes and the chlorophyll content in leaves and delays photosynthesis (Anjum et al. 2011; Alghabari et al. 2015). The proportion of chlorophyll a/b and biosynthesis of the chlorophyll pigment in leaves change during droughts. Lesser chlorophyll content, inactivation of the key photosynthetic enzymes, and modification of the thylakoid membranes take place due to droughts. The lowering of chlorophyll content is because of overproduction of $O_2^{\bullet -}$ and H_2O_2, which degrade chlorophyll and cause peroxidation of lipids. In the stomata and in mesophyll cells, photosynthesis and CO_2 conductance decrease under drought. The activity of the rubisco enzyme is affected by loss of CO_2 uptake. Moreover, a decrease in the activities of sucrose phosphate synthase, nitrate reductase, and ribulose bisphosphate (RuBP) has been reported (Anjum et al. 2011; Singh and Thakur 2018). A number of investigations have reported the recovery of photosynthesis from moisture stress in various crops and the recovery from drought oxidative stress, membrane stability index, and antioxidative mechanisms (Osakabe et al. 2014; Atta et al. 2020).

5 Escape, Avoidance, and Tolerance Mechanisms

To fight against drought stress, plants adopt three survival strategies, known as escape, avoidance, and tolerance. Because of these mechanisms, response to a drought fluctuates from the molecular level to the plant level (Galindo et al. 2018). Under long drought stress scenarios, plants follow the escape or avoidance mechanism; however, in brief but severe drought eras, plants show drought-induced tolerance (Perlikowski and Kosmala 2020).

5.1 The Adaptive Escape Mechanism

To escape the malignant influences of a drought on plant fitness and yield, some plants adapt synchronization of their growth period, life cycle shortening by fast development, self-reproduction, and seasonal growth or planting time before the start of drought season, thereby not succumbing to the drought stress (Rosenthal et al. 2010; Álvarez et al. 2018; Perlikowski and Kosmala 2020). To escape from a drought, new seeds are produced before the drought ends the plant's life cycle. For this, plants develop swiftly and cut their vegetative growth period with a short life cycle (Araus et al. 2002). Early flowering by plants is possibly the finest adaptive escape mechanism to adapt to droughts (Tekle and Alemu 2016). However, chances are that this mechanism can reduce a plant's growth period and compromise its yield (Blum 2011).

5.2 The Adaptive Avoidance Mechanism

Drought avoidance is also referred to as dehydration avoidance (Schuppler et al. 1998). The avoidance strategy involves maintenance of high water potentials in plant tissues under the scenarios of water limitation (Cameron et al. 2006; Perlikowski and Kosmala 2020). The high water potential is upheld by a decrease in transpiration water loss and an increase in water use efficiency and water absorption from the deepest root systems (Dobra et al. 2010). The avoidance mechanism rearranges both the morphology and the cellular metabolism of a plant. Examples of morphological changes include development of deeper and thicker prolific root systems, stomatal closure, rolling of leaves, xeromorphic structures such as hairy structures on the leaves and cuticles, and accumulation of wax on the surfaces of leaves (Schuppler et al. 1998; Cameron et al. 2006; Boulard et al. 2017; Perlikowski and Kosmala 2020). In a nutshell, plants reduce transpiration, limit vegetative growth, increase prolific root systems, and avoid dehydration during a drought (Schuppler et al. 1998). However, the overdevelopment of such morphological traits reduces productivity and the size of the vegetative and reproductive plant parts (Wasaya et al. 2018).

5.3 The Adaptive Tolerance Mechanism

The initial strategy of drought-tolerant plants to manage droughts includes changes in their root system architecture. The root system of a plant is modified in terms of size, density, length, proliferation, expansion, and growth rate (Tzortzakis et al. 2020). The tolerance mechanisms at photosynthetic levels include a decrease in the plant's total leaf area and restricted growth of new leaves. The presence of trichomes on leaves permits plants to tolerate droughts and further reduces the rates of water loss through transpiration (Zhang et al. 2019; Tiwari et al. 2021). The rate of light reflection increases on the leaves, which declines the temperature of leaf surfaces (Tiwari et al. 2021). Osmotic fine-tuning, antioxidant activity, stomatal closure, solute accumulation, and increase in the root–shoot ratio are other common approaches to resiliency to droughts (López-Galiano et al. 2019). Drought-tolerant plants endure desiccation and grow and survive in dry conditions through osmotic adjustment and protection mechanisms involving production of molecules to stabilize proteins (Chapin III et al. 1993; Vinocur and Altman 2005), desiccation tolerance (Ingram and Bartels 1996), detoxification (Noctor et al. 2014), or repair of xylem embolism (Lens et al. 2016).

6 Biotechnological Approaches to Increasing Drought Tolerance

To design drought-tolerant plants for crop improvement, such as *Oryza sativa* (Barik et al. 2019; Ghazy et al. 2021), *Triticum aestivum* (Pour-Aboughadareh et al. 2020; Li et al. 2021), *Hordeum vulgare* (Cai et al. 2020; Baidyussen et al. 2021), *Glycine max* (Faillace et al. 2021), and *Zea mays* (Kamphorst et al. 2021; Santos et al. 2021), the tools and techniques used include not only plant breeding but also transgenic lines, genome editing, and omics approaches. The gene *Gh_A06G1257* (*GhALDH7B4*) of the aldehyde dehydrogenase family plays a role in drought tolerance. Metabolites like valine, glutarate, proline, glutamate, and tryptophan also play roles in drought tolerance (Kumar et al. 2021). Under drought conditions, the CLE25 peptide produced in the roots translocate to the leaves to initiate abscisic acid (ABA) production by activation of the NCED3 biosynthetic enzyme. ABA synthesis leads to closure of the stomata and enhanced water balance and drought tolerance (Takahashi et al. 2018).

Water use efficiency (Hatfield and Dold 2019) influences the subsistence of plants under drought conditions (Schulz et al. 2021). Increasing the WUE of crops is the key objective of plant breeding and genetic engineering (Nuccio et al. 2015). The MdATG8i-OE (autophagy protein) gene overexpression in apple-generated plants with higher WUE in long-term moderate drought (Jia et al. 2021). Genetic engineering tools improved the WUE in *A. thaliana* and *T. aestivum* under controlled conditions by improving the functions of PYR1/PYL/RCAR (pyrabactin resistance 1/PYR1-like/regulatory component of ABA receptors) and SnRK2 (SNF1-related protein kinase 2) and repressing PP2C (clade A type 2C protein phosphatase), which is a negative regulator (Okamoto et al. 2013; Park et al. 2015; Wang et al. 2018b; Mega et al. 2019). ABA pathway genes and related transcription factors (TFs) and signaling feedback were identified among ABA-mediated stress responses to drought (Song et al. 2016). The bioactive ABA mimic called opabactin increases ABA receptor activation and downstream signaling to improve WUE and drought tolerance in *A. thaliana*, *Solanum lycopersicum*, and *T. aestivum* (Vaidya et al. 2019).

The brassinosteroid signaling negative regulator brassinosteroid-insensitive 2 (BIN2) is dephosphorylated by ABA-insensitive 1 (ABI)1 and ABI2. ABA activates BIN2 by inhibition of ABI1 and ABI2 (Wang et al. 2018a). ABA signals join with the brassinosteroid pathways. BRI1-EMS-suppressor 1 (BES1) represses ABA induction of responsive to desiccation 26 (RD26) transcription factors (TFs) (Chung et al. 2014). WRKY46, WRKY54, and WRKY70 TFs interact with BES1 and promote plant growth while repressing drought responses (Chen and Yin 2017). Genome editing tools like clustered regularly interspaced short palindromic repeats/CRISPR-associated protein (CRISPR/Cas) have been used to improve crop traits and yields in drought stress-tolerant plants like *S. lycopersicum* (gene edited: SlMAPK3) (Wang et al. 2017), *Arabidopsis thaliana* (genes edited: UGT79B2, UGT79B3) (Wang et al. 2017), *Arabidopsis thaliana* (gene edited: MIR169a) (Zhao et al. 2016), and *O. sativa* (genes edited: OsDERF1, OsPMS3, OsMYB5, OsEPSPS, OsMSH1) (Zhang et al. 2014). Table 8.1 provides the details of various transgenics generated with drought-tolerant traits.

Table 8.1 Transgenics designed for drought tolerance

Transgenic plant	Gene transferred to the transgenic plant	Original gene source	References
Arabidopsis thaliana	Ethylene response factors (AtERF019)	*A. thaliana*	Scarpeci et al. (2016)
A. thaliana	Ethylene response factors (AtERF53)	*A. thaliana*	Hsieh et al. (2013)
A. thaliana	Ethylene response factors (CarERF116)	*Cicer arietinum* L.	Deokar et al. (2015)
A. thaliana	Basic leucine zipper (ZmbZIP16)	*Zea mays*	Ying et al. (2012)
A. thaliana	Basic leucine zipper (OsbZIP16)	*Oryza sativa*	Pandey et al. (2018)
A. thaliana	*T. aestivum* shaggy kinase 5 (TaSK5)	*O. sativa*	Christov et al. (2014)
A. thaliana	Glutathione peroxidase (GPX2)	Synechocystis PCC 6803	Gaber et al. (2006)
A. thaliana	Glutathione S-transferase (GST)	*Lycopersicon esculentum*	Xu et al. (2015)
Arachis hypogaea	Dehydration responsive binding protein 1A (DREB1A)	*Arachis hypogaea*	Bhatnagar-Mathur et al. (2014)
Glycine max (L.) Merr.	Dehydration responsive binding protein (AtDREB1A, AtDREB2CA, AtAREB)	*A. thaliana*	Fuganti-Pagliarini et al. (2017)
Gossypium hirsutum L.	Glutathione reductase (GR)	*Nicotiana tabacum*	Mahan et al. (2009)
L. esculentum	CAT-2	*Escherichia coli*	Mohamed et al. (2003)
L. esculentum cv. Zhongshu No. 5	Ascorbate Peroxidase (APX)	*Pisum sativum*	Wang et al. (2005b, 2006)
Medicago sativa L.	Mn superoxide dismutase (SOD) + Fe SOD	*Nicotiana plumbaginifolia* and *A. thaliana*	Rubio et al. (2002)
N. tabacum	POD	*Ipomoea batatas*	Kim et al. (2008)
N. tabacum	Glutathione reductase (GR)	*A. thaliana*	Ding et al. (2009)
N. tabacum	Monodehydroascorbate reductase 1 (MDHAR1)	*A. thaliana*	Eltayeb et al. (2007)
N. tabacum	Dehydroascorbate reductase (DHAR)	*A. thaliana*	Eltayeb et al. (2006)
N. tabacum	Glutathione S-transferase (GST)	*Prosopis juliflora*	George et al. (2010)
N. tabacum	Glutathione S-transferase (GST)	*Gossypium* spp.	Yu et al. (2003)
N. tabacum	GhMPK2	*Gossypium* spp.	Zhang et al. (2011)
N. tabacum	TaSnRK2.9	*Triticum aestivum* L.	Feng et al. (2018)
N. tabacum	Cu/Zn superoxide dismutase (SOD)	*O. sativa* L.	Badawi et al. (2004)
N. tabacum	Cu/Zn superoxide dismutase (SOD) + APX	*Pisum sativum*	Faize et al. (2011)

(continued)

Table 8.1 (continued)

Transgenic plant	Gene transferred to the transgenic plant	Original gene source	References
N. tabacum	Ascorbate peroxidase 3 (APX3)	*A. thaliana*	Yan et al. (2003)
N. tabacum	Ascorbate peroxidase 2 (APX2)	*Cucumis sativus* L.	Fotopoulos et al. (2008)
N. tabacum	Glutathione S-transferase (GST)	*Pyrus pyrifolia*	Liu et al. (2013)
N. tabacum	BdCIPK31	*Brachypodium distachyon*	Luo et al. (2017)
O. sativa	Dehydration responsive binding protein 1C (AtDREB1C)	*A. thaliana*	Ishizaki et al. (2013)
O. sativa	Dehydration responsive binding protein 1A (DREB1A)	*A. thaliana*	Datta et al. (2012)
O. sativa	GhABF2	*A. thaliana*	Liang et al. (2016)
O. sativa	SAPK9	*Oryza rufipogon*	Dey et al. (2016)
O. sativa	Mn superoxide dismutase (SOD)	*Pisum sativum*	Wang et al. (2005a)
O. sativa cv. Pusa Basmati 1	Cu/Zn superoxide dismutase (SOD)	*Avicennia marina*	Prashanth et al. (2008)
Solanum tuberosum	Dehydroascorbate reductase (DHAR)	*A. thaliana*	Eltayeb et al. (2011)
Solanum lycopersicum L.	Basic leucine zipper protein (SlbZIP1)	*S. lycopersicum* L.	Zhu et al. (2018)
T. aestivum cv. Oasis	Glutathione reductase (GR)	*E. coli*	Melchiorre et al. (2009)
T. aestivum L.	Dehydration responsive binding protein 3 (TaDREB3)	*T. aestivum* L.	Shavrukov et al. (2016); Morran et al. (2011)
T. aestivum cv Oasis	Mn superoxide dismutase (SOD)	*Nicotiana plumbaginifolia*	Melchiorre et al. (2009)

7 Conclusions

Plants undergo morphological, physiological, biochemical modifications to fight against drought stress. They also adapt mechanisms of escape, avoidance, and tolerance to sustain under such critical water-deficit conditions. Genome editing machineries like CRISPR/Cas and transgenics have been crafted to improve plants' tolerance to drought stress. However, probe into the machinery of how a plant sustains growth during moderate water deficiency and developing stratagems to advance plant fitness in droughts can offer answers to the forthcoming global food scarcity. The reaction of signaling at the cell level to droughts is crucial for elucidating such agricultural glitches (Eshed and Lippman 2019).

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Chapter 9
Crop Responses to High Temperature Stress

Deepu Pandita

Abstract Plants face a variety of temperatures in their whole life cycle and require continuous adaptation on diurnal and periodic levels. The different organs of a plant have different optimal temperature ranges. The heat stress caused by a high global temperature adversely limits crop performance, growth and development, and metabolism, and several biological processes like photosynthesis for food production and respiration affect the water balance and plasma membrane stability of the leaves and cause abortion of flowers, reduced seed size, and significant yield loss in agricultural crop species. Various defense mechanisms adopted by plants against heat stress include maintenance of membrane stability and generation of antioxidants against ROS and stress proteins and thermo-protectants besides phytohormones. The exogenous usage of these molecules and overexpression in transgenic plants for enhancing their endogenous levels may provide improved tolerance to heat in plants. Updated information about the crop responses to heat stress whether developmental, physiological, and/or biochemical will be highlighted here.

Keywords Heat stress · Crops · Thermo-protectants · Antioxidants · ROS · Phytohormones · Transgenic plants

1 Introduction

Due to their sessile nature, plants face a wide range of drought, salinity, and low and high temperature stresses which affect almost all agricultural and horticultural crops (Serrano et al. 1999; Iba 2002). Temperature stress affects plants in their whole life cycle and also at both the daily basis and seasonal levels. Therefore, for plants continuous adaptation is a prerequisite (Hatfield et al. 2011; Lobell and Gourdji 2012; Gourdji et al. 2013; Ray et al. 2015). Due to the increasing threat of climate change and global warming, the intensity of temperature stress increases and adversely

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results in a substantial impact on the performance and yield of agricultural crops worldwide and in turn threatens global food security (Beck et al. 2007; Christensen and Christensen 2007; Lesk et al. 2016; Liu et al. 2016; Schauberger et al. 2017).

Furthermore, even a single degree Celsius (°C) rise in temperature outside the threshold levels is deliberated as heat or temperature stress for plants (Wahid et al. 2007; Hasanuzzaman et al. 2013). Heat stress affects performance, metabolism, growth and development, and productivity, shortens plant life cycle, enhances senescence, and sternly influences crop production and yield, in turn impacting global food security (Porter 2005; Hasanuzzaman et al. 2013; Asseng et al. 2014; Lesk et al. 2016; Liu et al. 2016; Schauberger et al. 2017). Each degree increase will reduce yield by 6% in wheat or 10–12% in rice (Nelson et al. 2010; Asseng et al. 2014).

Heat stress causes morphological changes; affects the germination of pollen grains, growth of the pollen tube, viability of female ovules, positions of the stigmata and style of the carpel, number of pollen grains loaded on the stigmatic surface, fertilization and postfertilization events, growth of endosperm, proembryo and fertilized embryo, and reduced photosynthesis and yield in plants (Vollenweider and Günthardt-Goerg 2005; Kim and Portis 2005; Foolad 2005); and induces reactive oxygen species (ROS) production which leads to severe cell damage and even plant cell death (Schoffl et al. 1999; Apel and Hirt 2004).

2 Influence of Heat Stress on Plants

Heat stress led to the fluctuations at morphological, anatomical, physiological, and biochemical levels in plants (Fig. 9.1). Heat stress may directly or indirectly injure plants.

1. *Direct injury*: The direct injury to plants is at the levels of proteins and leads to protein aggregation and protein denaturation and increase in membrane fluidity.
2. *Indirect injury*: The indirect injury to plants consists of enzyme inactivation in cellular organelles of green chloroplasts and powerhouses of mitochondria, inhibitions in the protein synthesis, increase in the degradation of proteins, and damage of integrity of plasma membranes causing cell injury or even cell death in a short span of time and failure of organization at cellular levels (Schoffl et al. 1999; Howarth 2005).

2.1 *Seed Germination and Plant Vegetative Growth*

A high temperature affects the grain number, seed size, and early seed setting; fast-tracks senescence in photosynthetic organs; induces chlorophyll loss, thereby limiting seed setting and delaying or reducing the germination of the seeds or loss of

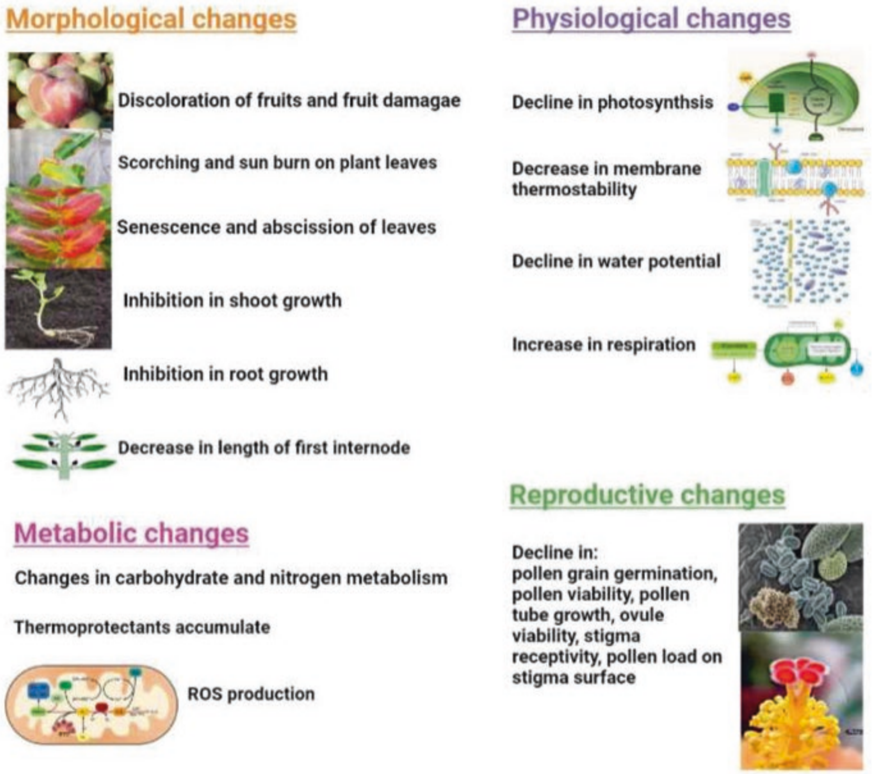

Fig. 9.1 Morphological, reproductive, physiological, and metabolic modifications in heat conditions

vigor and the emergence and formation of seedling; and critically reduces the frequency and time of growth and development of crop species (Gan et al. 2004; Wahid et al. 2007; Ren et al. 2009; Kumar et al. 2011; Hatfield et al. 2011; Devasirvatham et al. 2012; Piramila et al. 2012; Asseng et al. 2014; Wang et al. 2015; Zhao et al. 2016).

Morphological variations like sweltering and sunburning of plant leaves, branches, and shoots, senescence and abscission of the leaves, inhibition of root and shoot growth, stunted growth, decreased height in wheat, reductions in shoot dry mass, decrease in length of the first internode, reduced internodes, improved tillering, early senescence, chlorosis, inhibition of the first leaf growth in wheat, decreased tiller number, negative influence on growth and biomass, discoloration, and damage of fruits take place in the vegetative parts of plants under stress scenarios of high temperatures, and these ultimately reduce yields in crop plants (Hall 1992; Ebrahim et al. 1998; Vollenweider and Günthardt-Goerg 2005; Wahid 2007; Mingpeng et al. 2010; Kumar et al. 2011; Johkan et al. 2011; Laghri et al. 2012; Savicka and Škute 2012; Al-Busaidi et al. 2012; Kumar et al. 2013).

Heat stress delays the initiation of stem elongation and ends in faster stem growth rates without changing the total time to heading stage in plants like wheat and barley (Borràs-Gelonch et al. 2011; Karsai et al. 2013; Kiss et al. 2017). Temperature above the optimum declines the number of plant leaves and tillers and ultimate shoot height (Hemming et al. 2012; Karsai et al. 2013; Dixon et al. 2019). In *Arabidopsis*, elongation of the hypocotyl and petiole, hyponasty of the leaves, and decreased stomatal density are induced by high ambient temperatures referred to as thermo-morphogenesis (Quint et al. 2016; Casal and Balasubramanian 2019; Vu et al. 2019). Heat improves the cooling ability of tomato by promoting stomatal opening and leaf hyponasty (Havko et al. 2020). The leaves and coleoptile of seedlings of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare*), rice (*Oryza sativa*), and maize (*Zea mays*) and the hypocotyl of soybean (*Glycine max*) and tomato (*Solanum lycopersicum*) are maximally extended at moderate heat stress conditions (Parent and Tardieu 2012; Quint et al. 2016; Alsajri et al. 2019).

The responses of root system architecture to soil temperature gradient include decline in length of the primary roots, density of the lateral roots, and variations in angle under which roots emerge (Nagel et al. 2009; Lundholm 2009; Ulrich et al. 2014; Onwuka 2016). This impacts nutrient uptake in the high temperature regime (Hendrick and Pregitzer 1996), but root secondary developmental parameters like the numbers of the root tips and forks are enriched (Alsajri et al. 2019).

2.2 Plant Reproductive Growth

At the early reproductive stages, the plants are very vulnerable to high temperatures and suffer damage to the buds, flowers, fruits, and seeds, which in turn result in stark declines in crop grain productivity and yield (Thakur et al. 2010; Zinn et al. 2010; Draeger et al. 2020). Monocots display a long reproductive-phase establishment due to a lengthy pause between the first spikelet primordia formation, inside the leaf sheath, and up to the moment an ear is pushed out and the plant reaches the heading stage (Gol et al. 2017; Gauley and Boden 2019). Therefore, they are more susceptible to higher temperature and lead to a substantial loss of quality and quantity of grains (Bheemanahalli et al. 2019; Lohani et al. 2019).

Floral identity shows a low plasticity against ecological oscillations (Klingenberg 2019; Fal et al. 2019). *EXTRA GLUME 1* (*EG1*) gene in rice encodes mitochondria-localized functional lipase, which functions upstream of floral identity genes (*OsMADS1*, *OsMADS6*, *OsG1*) for promoting floral development in a high temperature-dependent manner (Zhang et al. 2016). Heat stress causes structural and functional abnormalities in the reproductive system leading to the catastrophe of decrease in size and number of flowers and produces the following floral anomalies:

Flowers of smaller sizes
Asynchronous development of both reproductive organs (androecium and gynoecium), including anther indehiscence for pollen dispersal, anther development, and pollen formation
Low pollen viability
Reduced or no pollination
Decline in the germination of pollen grains and pollen tube growth or elongation in the style of female carpel
Alterations in the positions of the stigma and style
Presence of elongated stigmas
Reduced stigma receptivity
Reduced number of pollen grains on the stigma
Reduced ovule number and loss of viability of the ovules
Reduced fertilization efficiency or limited postfertilization events
Abnormal growth of the endosperm, proembryo, and fertilized embryo leading to the loss of young pods; abscission of buds, flowers, and pods; and substantially reduced yield (Warrag and Hall 1984; Saxena et al. 1988; Takeoka et al. 1991; Hall 1992; Brown and Zeiher 1998; Nakano et al. 1998; Angadi et al. 2000; Suzuki et al. 2001; Morrison and Stewart 2002; Foolad 2005; Boote et al. 2005; Devasirvatham et al. 2010; Zinn et al. 2010; Board and Kahlon 2011; Kaushal et al. 2013; Kumar et al. 2013; Draeger and Moore 2017; Yu et al. 2017; Zhang et al. 2018; Matsui and Hasegawa 2019; Begcy et al. 2019; Gonzalo et al. 2020)

Endo et al. (2009) found that some functions of tapetal tissues and adhesion of the pollen grains to the receptive stigma followed by pollen germination showed negative effects. Several reproductive processes disturbed by high temperature stress are shown in Fig. 9.1.

2.3 *Plant Physiology*

The physiological effects of high temperature on crops include denaturation, aggregation, and degradation of cellular proteins, chlorophyll degradation, enhanced fluidity of lipids in the plasma membrane, increase in permeability of the plasma membrane, interruption of function of cellular organelles, protein biosynthesis inhibition, reduced rate of net photosynthesis, and cell death (Los and Murata 2004; Cossani and Reynolds 2012; Nagar et al. 2015).

2.4 *Biochemical Processes*

A high temperature affects several biochemical processes in plants (Fig. 9.1). A high day temperature impacts photosynthesis (light-dependent reactions and carbon assimilation) and photorespiration (Crafts-Brandner and Salvucci 2002;

Ainsworth and Ort 2010; Gupta et al. 2013; Nagar et al. 2015; Sharma et al. 2015; Ahammed et al. 2018; Kume et al. 2019; Bianchetti et al. 2020), while respiration is mainly disturbed by high night temperatures (Dusenge et al. 2019). High temperatures lead to a drop in efficiency of photosynthesis and a rise in rates of processes like respiration and photorespiration and also disturb the development of plant reproductive system (Prasad et al. 2017; Ferguson et al. 2021). Efficient photosynthesis depends on how the Rubisco enzyme (carboxylase or oxygenase) discriminates between CO_2 and O_2 as the substrate. Photorespiration, a major productivity limitation for C3 crops, is exacerbated as temperature increases. A decreased $[CO_2]/[O_2]$ ratio due to the reduction of stomatal conductance caused by warm temperature results in the decreased Rubisco specificity for CO_2 relative to O_2 (Walker et al. 2016). In comparison to Rubisco, the rate of regeneration of ribulose 1,5-bisphosphate (RuBP) which is an CO_2 acceptor is more sensitive to higher temperatures (e.g., less ATP supply caused by the impaired electron transport) (Sage 2002). The mean night temperatures increase at a quicker rate than temperatures during daytime, which speeds up respiration and results in crop yield and quality reduction (Davy et al. 2017; Dusenge et al. 2019; Impa et al. 2019; Sadok and Jagadish 2020; Coast et al. 2020; Impa et al. 2020; Schaarschmidt et al. 2020).

3 Defense Responses to Heat Stress

Plants react defensively to heat stress by various defense mechanisms at the basic molecular, cell, biochemistry, physiology, and complete plant levels (Sung et al. 2003; Wahid 2007; Yeh et al. 2012). Thermo-tolerance is essential to plants that experience diurnal temperature oscillations and are incompetent to escape to more positive milieus. Some temporary avoidance or acclimation mechanisms include alterations in the orientation of plant leaves, transcriptional cooling, change in the composition of lipids of the plasma membrane, reflecting sun light, leaf shading of plant tissues sensitive to injury by the sun, and widespread rooting (Lehman and Engelke 1993; Wahid 2007). The process of early maturation leads to smaller yield losses and is recognized as an escape mechanism (Adams et al. 2001; Toker et al. 2007). Ion transporters, late embryogenesis abundant (LEA) proteins and factors (avert aggregation of proteins and defend synthesis of citrate), free-radical scavengers, osmoprotectants, ubiquitin and conjugated ubiquitin synthesis, and dehydrins expressed in the leaves are players in signaling cascades and transcriptional regulators that respond to the consequences of heat stress and are involved in the mechanisms of heat tolerance (Arora et al. 1998; Wang et al. 2004; Goyal et al. 2005; Wahid and Close 2007; Huang and Xu 2008).

Under various plant stresses, the accumulation of thermo-protectants, for instance, glycine betaine, proline, and trehalose, takes place inside the plant system

(Hare et al. 1998; Sakamoto and Murata 2002). The accumulation of thermo-protectant proline has been described in barley (*H. vulgare*) and radish (*Raphanus raphanistrum* subsp. *sativus*) (Chu et al. 1974), wheat (*T. aestivum* L.) (Ahmed and Hasan 2011), maize (*Z. mays* subsp. *mays*) (Kumar et al. 2012), tomato (*S. lycopersicum*) (Kou et al. 1986), mulberry (*Morus* alba L.) (Chaitanya et al. 2001), *Brassica* vegetables (Takeda et al. 1999), *Brassica rapa* L. (Hossain et al. 1995), apple (*Malus domestica*) (Park et al. 2001), cotton (*Gossypium* spp.) (Ronde et al. 2001), and tobacco (*Nicotiana* spp.) (Cvikrova et al. 2012). Glycine betaine osmolyte enhanced the germination of seeds and yield in rice during heat stress (Chen and Murata 2002; Naidu and Williams 2004). The accumulation of glycine betaine under high temperature stress has been found in *Z. mays* and *Saccharum officinarum* (Quan et al. 2004; Wahid and Close 2007).

Tolerance to heat stress is induced by different phytohormones known as brassinosteroids, salicylic acid, polyamines, abscisic acid, and ethylene. The putative signaling molecule of nitric oxide (NO) regulates physiological processes and also induces stress tolerance in various plants (Mishina et al. 2007). The level of endogenous signal of salicylic acid (SA) upsurges in 30 minutes subsequent to heat stress as observed in pea and induces heat resistance (Dat et al. 1998; Pan et al. 2006). Brassinosteroids protect plants under several abiotic stress conditions (Vardhini and Rao 2003) and enhance pollen germination and crop yield and quality (Hewitt et al. 1985; Prusakova et al. 1999; Singh and Shono 2005; Thussaganpanit et al. 2012). Abscisic acid (ABA) has an important role in regulating the growth and development of plants. When exposed to abiotic heat stress, the abscisic acid levels increase in plants such as pea, tomato seedlings, pepper seedlings, wheat, tobacco, and dwarf bean seedlings. ABA induces thermo-tolerance by upregulation or downregulation of numerous genes (Hiron and Wright 1973; Daie and Campbell 1981; Teplova et al. 2000; Xiong et al. 2002; Tong-Xiang et al. 2009; Pospisilova et al. 2009) and by producing molecular chaperones known as heat shock proteins (HSPs), e.g., HSP 100, HSP 90, HSP 70, HSP 60, and small HSPs (Trent 1996; Pareek et al. 1998; Hartl et al. 2011). HSPs are induced or enhanced with increase in temperatures, and their transcription and translation upsurge at all stages of development in plants, protecting plant cells from heat stress (Blumenthal et al. 1990; Vierling 1991; Rousch et al. 2004). HSP expression shows a positive correlation with acquisition of thermo-tolerance, and their overexpression enhances thermo-tolerance in *Nicotiana*, *G. max*, and *Z. mays* (Barnett et al. 1980; Lin et al. 1984; Hernandez and Vierling 1993; Schoffl et al. 1999; Queitsch et al. 2000; Ortiz and Cardemil 2001), advances photosynthesis, maintains cell integrity, assimilates partitioning with water and nutrient efficiency of plants, provides protection for protein stability and protein functional confirmation, and prevents protein denaturation (Wang et al. 2004; Camejo et al. 2006; Momcilovic and Ristic 2007; Tripp et al. 2009). To combat oxidative damage of ROS, plants have detoxification enzymes like guaiacol peroxidase (POX), ascorbate peroxidase (APX), catalase (CAT), and superoxide dismutase (SOD) (Dat et al. 2000; Jiang and Haung 2001).

4 Heat Stress Sensing Mechanisms

In sensing mechanisms, membranes detect a rise in temperature (Wise et al. 2004). In stress conditions, the fluidity of cell membranes enhances, and membrane sensors sense transition in the physical phase, leading to modifications in conformation and events of phosphorylation and dephosphorylation (Plieth et al. 1999). There are in total four sensors for perceiving heat shock stimulus. The Ca^{2+} channels are bound to the plasma membrane, histone sensor is found inside the cell nucleus, one unfolded protein sensor is located in the endoplasmic reticulum, and the other unfolded protein sensor resides in the cytosol (Saidi et al. 2009; Sugio et al. 2009; Kumar and Wigge 2010; Deng et al. 2011; Mittler et al. 2012; Srivastava et al. 2014).

The cell membranes are the foremost to sense high temperature stress resulting in calcium channel activation for inducing Ca^{2+} influx crosswise the cell membrane and generating heat shock responses (Gong et al. 1998; Liu et al. 2006; Saidi et al. 2009; Wu and Jinn 2010). The Ca^{2+} influx leads to an increase in the cytoplasmic Ca^{2+} concentration. At the CaM3 calcium-dependent kinases, Ca^{2+} associates with calmodulin. This in turn leads to the activation of transcription factors such as mitogen-activated protein kinases (MAPKs) and calcium-dependent protein kinases (CDPKs) or ROS-producing nicotinamide adenine dinucleotide phosphate oxidase (NADPH) (Zhang et al. 2009). The cascade signaling at the level of nucleus produces antioxidants and compatible osmolytes for cell water balance and osmotic adjustment. ROS production is essential for signaling besides producing antioxidants (Bohnert et al. 2006). The antioxidants are part of antioxidant defense mechanism for adaptation to high temperature stress and thermo-tolerance (Maestri et al. 2002). Increase in the fluidity of cell membranes also activates lipid signaling. In lipid signaling, the activation of phospholipase D (PLD) and phosphatidylinositol-4,5-bisphosphate kinase (PIPK) takes place. This in turn leads to the accumulation of phosphatidic acid (PA) and D-myo-inositol-1,4,5-triphosphate (IP3) (Mishkind et al. 2009) which further activates Ca^{2+} channels and inward Ca^{2+} flux. Heat shock tolerance can also be achieved by heat-activated metabolite accumulation, e.g., of nitric oxide (NO) and hydrogen peroxide (H_2O_2). The accumulation of NO and H_2O_2 further induces analogous signaling cascades or additional tolerance mechanisms at molecular levels (Hua 2009). Fluctuations in fluidity of the membrane initiate ROS accumulation subsequent to an increase in Ca^{2+} influx into the plant cells. ROS accumulation causes programmed cell death in plants under stress (Mathur and Jajoo 2014). A high temperature activates unfolded proteins (UPR) in the endoplasmic reticulum (ER-UPR) and cytosol (Cyt-UPR) (Mittler et al. 2012; Deng et al. 2013). The activation of ER-UPR splices the basic leucine zipper (bZIP) transcription factor. The bZIP passes to the nucleus and activates the gene expression of brassinosteroid (BR) signaling pathway (Che et al. 2010; Deng et al. 2013). On the other hand, cytosolic unfolded protein response (Cyt-UPR) show activation by heat shock factors (HSF, HSFA2) (Sugio et al. 2009). The high temperature stress influences the habitation of histones in the nucleosome by substituting H2 A with histone H2 variant (H2A.Z). One such example is in *Arabidopsis* plant, where ARP6 (actin-related protein 6) replaces histone (Clapier and Cairns 2009; Erkina et al. 2010).

5 Transgenic Crops with Enhanced Tolerance to Heat Stress

The heat shock proteins (HSPs) and biomolecules act as thermo-protectants to alleviate heat stress. A number of transgenic food crops have been designed with enhanced thermo-tolerance properties. Increased thermo-tolerance has been accomplished in plants like *Arabidopsis thaliana* (Alia et al. 1998), *Z. mays* (Queitsch et al. 2000), *Nicotiana* spp. (Alia et al. 1998; Park and Hong 2002; Yang et al. 2005), *O. sativa* (Katiyar-Agarwal et al. 2003), and *Medicago sativa* (Saurez et al. 2008). Thermo-tolerance in *A. thaliana* was induced by the overexpression of ascorbate peroxidase (APX1) gene transferred from *Pisum sativum* and HvAPX1 from *H. vulgare* (Shi et al. 2001). The overexpression of stay-green genes deferred senescence and generated heat-tolerant genotypes in *Sorghum bicolor* (L.) Moench under high temperatures (Nyugen 1999) and *T. aestivum* L. (Rehman et al. 2009). Fertilization independent endosperm 1 (FIE1) gene from *A. thaliana* controls the size of seeds during high temperature stress by regulating the early endosperm development in *O. sativa* (Folsom et al. 2014). In photosynthetic organisms, the photosystem II (PSII) complex is the bull's eye of heat stress. The damaged PSII is repaired by D1 subunit protein encoded by the chloroplast gene *psbA*. The addition of heat-responsive promoter for the psbA expression protects PSII from severe loss of D1 protein, stimulates plant growth, achieves efficient photosynthesis, and increases the biomass, grain yield, crop productivity, and survival of bioengineered transgenics like *A. thaliana*, *Nicotiana* spp., and *O. sativa* under heat stress conditions (Chen et al. 2020). The thermostability of Rubisco activase (Rca) is considered as a promising way to increase the rates of photosynthesis and thermo-tolerance in crops (Scafaro et al. 2019). For example, the introduction of Rca from maize into rice slightly improves the thermo-tolerance with respect to photosynthesis (Yamori et al. 2012). For the rate of regeneration of the CO_2 acceptor ribulose 1,5-bisphosphate (RuBP), overexpressing a bifunctional cyanobacterial fructose-1,6-bisphosphatase (FBP)/SBP in *G. max* under higher temperature scenarios substantially increases assimilation of carbon (Kohler et al. 2017). The overexpression of *Z. mays* elongation factor thermal unstable Tu (EF-Tu) gene transferred to *T. aestivum* increased tolerance to heat stress in it. The photosynthesis improved, stability of thylakoid membranes increased, denaturation of leaf proteins decreased, and pathogen resistance increased in transgenic wheat plants (Akter and Islam 2017; Ni et al. 2018). The overexpression of *Z. mays* phosphoenolpyruvate carboxylase gene (ZmPEPC) in *T. aestivum* also imparted tolerance to heat stress by the increased activity of photochemical and antioxidant enzymes, extended maintenance of chlorophyll content, changed proline accumulation, and upregulation of genes involved in photosynthetic machinery (Guo et al. 2016; El-Esawi et al. 2019). The overexpression of histone acetyltransferase *TaGCN5* gene from *T. aestivum* in *A. thaliana* imparted tolerance to heat stress through histone hyperacetylation (Hu et al. 2015). The conclusions were again confirmed by investigating upregulated genes – *TaHSF1*, *TaHSF4*, *TaMBF1c*, *TaHSP17.4*, *TaHSP26*, and *TaHSP101* – under heat stress only (Ni et al. 2018). Some examples of bioengineering approaches for heat-tolerant crops with improved high temperature tolerance are listed in Table 9.1.

Table 9.1 Heat stress-tolerant transgenic crop plants

Transgenic crop plants	Genes transferred to transgenics	Source of gene	Reference(s)
Arabidopsis thaliana	HSP26	*Triticum aestivum*	Chauhan et al. (2012)
A. thaliana	TaHsfA2d	*T. aestivum*	Chauhan et al. (2013)
A. thaliana	TaHSF3	*T. aestivum*	Zhang et al. (2013)
A. thaliana	AtHSF (*A. thaliana* transcription factor) and gusA (β-glucuronidase)	*Escherichia coli*	Lee et al. (1995)
A. thaliana	HvAPX1 (*Hordeum vulgare*) ascorbate peroxidase gene	*Hordeum vulgare*	Shi et al. (2001)
A. thaliana	CodA (choline oxygenase)	*Arthrobacter globiformis*	Alia et al. (1998)
A. thaliana	APX1(ascorbate peroxidase)	*Pisum sativum*	Shi et al. (2001)
A. thaliana	SP1 (stable protein 1)	*Populus tremula*	Zhu et al. (2008)
Glycine max	Fructose-1,6-bisphosphatase (FBP)/SBP	*Cyanobacteria*	Kohler et al. (2017)
G. max	P5CR (pyrroline-5-carboxylate reductase)	*A. thaliana*	De Ronde et al. (2004)
Lycopersicon esculentum	ySAMdc (yeast S-adenosyl methionine decarboxylase)	*Saccharomyces cerevisiae*	Cheng et al. (2009)
Medicago sativa	ScTPS1 (*Saccharomyces cerevisiae*) trehalose-6-phosphate synthase 1; ScTPS2 (*Saccharomyces cerevisiae*) trehalose-6-phosphate synthase 2	*S. cerevisiae*	Saurez et al. (2008)
N. tabacum	MT-sHSP (mitochondrial small heat shock proteins)	*Lycopersicon esculentum*	Sanmiya et al. (2004)
N. tabacum	BADH (betaine aldehyde dehydrogenase)	*Spinacia oleracea*	Yang et al. (2005)
N. tabacum, Saccharomyces cerevisiae	EsDREB2B (*Eremosparton songoricum* dehydration-responsive element-binding protein 2)	*Eremosparton songoricum*	Li et al. (2014)
Oryza sativa	TamiR159	*T. aestivum*	Wang et al. (2012)
O. sativa	TaMBF1c	*T. aestivum*	Qin et al. (2015)
O. sativa	Rca (Rubisco activase)	*Zea mays*	Yamori et al. (2012)
O. sativa	FIE1 (fertilization independent endosperm 1)	*A. thaliana*	Folsom et al. (2014)
Solanum melongena	OAD (oat arginine decarboxylase)	*Agrobacterium tumefaciens*	Prabhavathi and Rajam (2007)
T. aestivum	TaHsfC2a	*T. aestivum*	Hu et al. (2018)
T. aestivum	TaFER-5B	*T. aestivum*	Zang et al. (2017)
T. aestivum	TaHsfA6f	*T. aestivum*	Xue et al. (2015)
T. aestivum	BADH (betaine aldehyde dehydrogenase)	*Atriplex hortensis*	Wang et al. (2010)
T. aestivum	Elongation factor (EF-Tu)	*Zea mays*	Akter and Islam (2017), Ni et al. (2018)

6 Conclusion

The climate change and snowballing temperature impact crop productivity from the seedling stages to the grain-yielding stages. Climate-smart crop plants will survive in a better way under high temperature-associated scenarios.

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Chapter 10
Crop Responses to Metal Toxicity

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Abstract Sustainable crop production is the key to global food security. With progress in industrialization, threats of pollution have increased, and one of them is metal toxicity. An increase in metal concentration in soil, over the prescribed safety limits, affects crop productivity and enhances the chances of food toxicity. To overcome the toxic effects of metal adulteration, it is necessary to understand crop responses to metal toxicity. In this chapter, the physiological, biochemical, and morphological changes in crop responses to metal toxicity are discussed. Moreover, various management options to alleviate metal toxicity are also discussed. This chapter will provide a deep understanding of the metal toxicity in plants and also its possible remediation.

Keywords Metal toxicity · Plant response · Management option · Molecular techniques

1 Introduction

Plant roots are the main contact region for heavy metal (HM) ions, and, as plants basically cannot move and thus remain in their original place, they have to grow in the same environment. Heavy metals, such as cadmium (Cd), zinc (Zn), iron (Fe), arsenic (As), and platinum (Pt), are elements that have high density, a high atomic

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number, and a high atomic weight. Many heavy metals, like cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn), iron (Fe), and nickel (Ni), play different essential and nonessential roles in plants depending upon their concentration. Although some heavy metals, like Fe, Zn, Cu, and cobalt (Co), are necessary, they are only required in minor amounts for proper functioning, and their inability to function well causes many diseases (Tchounwou 2018). Some heavy metals, like Cd, As, Pb, are not necessary for plants, and their abundance causes deleterious effects (Rai 2019). Soil contamination by heavy metals occurs through many hazardous human activities, pollution-causing biological and chemical reactions, and leaching of heavy metals into the soil, all of which are hazardous to plants (Mishra et al. 2019). Heavy metals in excessive concentration cause negative effects on plants, humans, and microorganisms. Fertilizers, sludge, and industrial wastes are bioaccumulated by plants cultivated in soil containing these pollutants, usually on roadsides in urban areas. They cause oxidation loss in plants and also affect the formation of chlorophyll (Chl). Heavy metals present in soil are absorbed by the roots and are transported up the plants, and, being stable, these carcinogenic metals remain in the plants for a long time. When food crops, vegetables, and fruit plants are irrigated with contaminated water, especially in urban areas, heavy metals accumulate in food, and, when this food is consumed by humans, it causes skin allergies, nervous system disorders, and many other disorders (Rai 2019). Here, the adverse effects of some heavy metals are elaborated. Lead is a heavy metal that imposes a negative impact on plant root growth and elongation.

Nickel, in excessive amounts, imposes harmful effects on the biological processes in plants, such as mineral nutrition, photosynthesis, and water uptake. It has the capacity to produce reactive oxygen species (ROS), which, when elevated, may lead to oxidative stress. Chromium (Cr) is recognized to be a noxious metal that can grounds unadorned destruction to plants and animals, and it prompted oxidative stress includes initiation of lipid per oxidation in plants that grounds unadorned destruction to cell membranes (Panda and Choudhury 2005). Cadmium is a heavy metal found in soils and plants (Konate et al. 2017). Cadmium reaches the root cells through Zn-regulated transporters and iron-regulated protein transporters like the low-affinity Cd transporter (Page and Feller 2015). Some of the effective factors related to Cd uptake in wheat are pH, organic matter, cation exchange capacity, Fe content, and soil texture. Through increasing Fe content and clay minerals, we can decrease Cd uptake by plants (Retamal-Salgado et al. 2017).Organic alteration is effective in decreasing Cd uptake (Guo et al. 2018). Biochar application in soil can reduce Cd accumulation in wheat grains by up to 97.8% (Abedi and Mojiri 2020).

Heavy metal accumulation is also a major problem in plants grown in metal-contaminated soils. Lead and Zn are the most abundant metals in tomato, and the least is Cd. The roots are the most contaminated plant part, and plants take up heavy metals through the xylem pathway and then store them in the leaves (Piscitelli et al. 2002). Some plants like tomatoes, grown in contaminated soil and irrigated by industrial wastewater usually in urban areas, are noted to have more heavy metal concentration in the order of roots>stems>fruits (Khan 2011). A high concentration of heavy metals does not travel up plants and reach fruits because of certain defense mechanisms and synergy factors, but mobile heavy metals like Cd move through the phloem to reach the fruits, although in low concentration; however, tomatoes grown in contaminated soil can be consumed.

When heavy metals enter the roots, processes like metal compartmentalization and biosynthesis occur as defense mechanisms, and chelates of heavy metals, enzymatic transformation, and precipitation of heavy metals also reduce heavy metal concentration (Page and Feller 2015). The risk of heavy metal toxicity can be lowered by stress tolerance mechanisms and by avoiding stresses (Tiwari and Lata 2018). For this, biological, chemical, and physical remediation measures should be taken, agricultural lands should not be treated with industrial wastewater, soil should be vitrified, and leaching of metals, electrokinetic remediation, and phytoextraction should be implemented (Raffa et al. 2021). Phytovolatilization, bioaccumulation, and rhizofiltration are modern solutions to lower the concentration of heavy metals in soil.

2 Morphological Response of Crops to Heavy Metals

Crops show numerous changing and morphological responses to heavy metal toxicity. High quantities of these heavy metals affect the normal growth and function of the roots, stems, leaves, flowers, fruits, etc. In response, some defense mechanisms are generated by crops to overcome these stresses. When plants are exposed to heavy metals, at first, they try and prevent heavy metal accumulation through the roots. Plants can also overcome HM toxicity by mycorrhizal activities, release of organic compounds from the roots, and many other detoxification activities (Page and Feller 2015). Genotyping and phytoremediation are also other methods that can be used to lower heavy metal accumulation in plant roots.

An increase in the toxicity level of Cd in plants affects the normal growth of the roots and shoots. Cadmium toxicity increases the ROS level and affects the size of leaves, elongation of roots and stems, etc. Reduction in root hair growth occurs as the level of Cd rises in soil; it is also the cause of cohesion and turgor of cells present in the roots. Phytoremediation of heavy metal accumulator plants is a modern solution to decreasing Cd toxicity in the roots and stems of plants. Plants initiate several mechanisms to lower the concentration of Cd toxicity. Plants release chemicals like citrate, malate, etc. from the roots, which lower Cd toxicity by binding it. Nickel is extremely important for regulating the normal growth and functioning of plants but in an extremely low quantity; as its level exceeds, it becomes toxic. Nickel toxicity in plants causes hazardous effects like hindering normal shoot and root growth, decreasing leaf area, and chlorosis. At a higher concentration, nickel decreases the levels of Fe^{+} and Zn^{2+} by reducing the absorption of these cations by plants. Zinc toxicity is a cause of damage to the leaf structure and is also responsible for crystal formation on leaves; it also reduces the root and shoot lengths and affects plant morphology in a negative manner (Page and Feller 2015). Cobalt hinders normal plant growth and normal germination of seeds. When plants are exposed to arsenic,

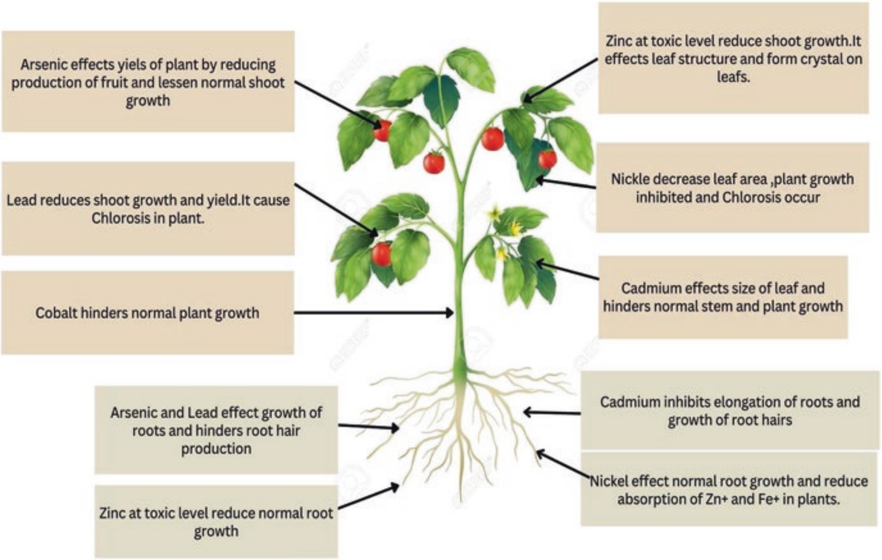

Fig. 10.1 Effects of various heavy metals on different parts of a plant

they show a decrease in yield and in the biomass of the roots and shoots. The effects of heavy metals on various plant parts are shown in Fig. 10.1.

Heavy metals become toxic at a certain level. This level varies in different crops. When seedlings of crops like sugar beet, soybean, and lettuce are exposed to Cd (5 mg L^{-1}), the germination of these crops is reduced.

3 Physiological Response of Crops to Heavy Metals

Hazardous and nonhazardous heavy metals can be differentiated on the basis of their physiology. Heavy metal toxicity results in the inhibition of growth and in the yellowing of leaves. Heavy metals like Cd, Ni, Pb, Zn, and Cr bring about changes to the plant physiology, especially by affecting the roots and shoots, as displayed in Table 10.1. These heavy metals exert a significant effect on the contents of Chl as they decrease the photosynthetic rate and also adversely damage the cell membranes. Oxidative damages such as structural changes of the cell membranes and plants response to tackle heavy metal attacks are shown in Fig. 10.2. Hazardous heavy metals enter plant tissues and inhibit physiological processes during metabolism as heavy metals affect photosynthesis, water uptake, and nitrate assimilation. When heavy metals accumulate in plants in huge amounts, they bring about toxicity in them. When plants are exposed to a large number of heavy metals, they exhibit changes in their physiology and structure. Several physiological and biochemical processes are negatively affected by metals, especially in plants grown in

Table 10.1 Effects of heavy metals on the plant physiology for different crop plants as observed in various studies

Crop	Heavy metal	Effect	References
Zea mays	Copper	Lower seeding growth through hindrance in metabolism	Wang et al. (2012)
Solanum lycopersicum	Copper	Retard growth and cell division	Zhang et al. (2018)
Lactuca sativa	Copper	Inhibit root elongation at the molecular level	Hong et al. (2015)
Triticum aestivum	Zinc	Reduce the photosynthetic rate and plant biomass	Li et al. (2020)
Triticum aestivum	Zinc	Reduce germination and grain yield	Reis et al. (2018)
Zea mays	Iron	Decrease Chl content	Li et al. (2016)
S. lycopersicum	Zinc	Reduce biomass	Wang et al. (2018)
Phaseolus vulgaris	Zinc	Reduce photosynthesis and respiration rate	Cruz et al. (2019)
Triticum aestivum	Manganese	Reduce nutrient uptake	Dimkpa et al. (2018)
Triticum aestivum	Nickel	Affect plant growth adversely by higher concentration	Rizvi A et al. (2020)
Lycopersicon esculentum	Nickel	Negatively affect yield and development of plants at 100 mg/kg	Vischetti C et al. (2022)
Oryza sativa	Nickel	Cause various stresses affecting roots and shoots; decrease moisture content	Llamas et al. (2008)
Avena sativa	Nickel	Cause death of plant and phytotoxicity	Vischetti C et al. (2022)
Saccharum officinarum	Aluminum	Reduce nutritional efficiency; affect growth of sugarcane sapling	Borges et al. (2020)
Triticum aestivum	Aluminum	Affect chlorophyll content, plant height, root dry weight, and shoot dry weight of wheat crops	Baquy et al. (2017)
Oryza sativa	Aluminum	Affect growth of rice crops	Rasheed et al. (2020)
Oryza sativa	Arsenic	Decrease yield of grain, root, and straw of rice crop	Kaur et al. (2017)
Zea mays	Lead	Pb stress leads to the yield and quality loss of maize	Dey et al. (2007)
Oryza sativa	Lead	Hamper rice germination, root/shoot length, growth, and yield	Ashraf et al. (2015)
Triticum aestivum	Lead	Negatively correlate with the morphological parameters of plant growth	Lamhamdi et al. (2011)
Hordeum vulgare	Lead	Reduce the content of chlorophyll, Ca, and Mg	Pourrut et al. (2011)
Lycopersicon esculentum	Cadmium	Reduce plant growth, biomass, leaf number, and leaf area	Rehman et al. (2011)

(continued)

Table 10.1 (continued)

Crop	Heavy metal	Effect	References
Saccharum officinarum	Cadmium	Inhibit growth of callus	Ricardo et al. (2002)
Cicer arietinum cv. pars	Cadmium	Reduce plant growth and protein content in roots	Khadijeh et al. (2011)
Oryza sativa	Cadmium	Reduce plant growth, photosynthetic rate, and chlorophyll content	M Jaffar et al. (2005)
Triticum aestivum	Cadmium	Decrease seedling biomass, seed germination, and shoot and root elongation	Amirjani (2012)
Gossypium herbaceum	Arsenic	Sensitivity of wild cotton rats to the immunotoxic effects of low-level arsenic exposure	Savabieasfahani et al. (1998)
Oryza sativa	Arsenic	Negative effects of zinc oxide nanoparticles on arsenic stress in rice (*Oryza sativa* L.): germination, early growth, and arsenic uptake	Wu et al. (2020)
Helianthus annus	Arsenic	Toxicity of arsenic (As) affects seed germination	Imran et al. (2013)
Oryza sativa	Arsenic	Arsenic accumulation affects metabolism in rice	Abedin et al. (2002)

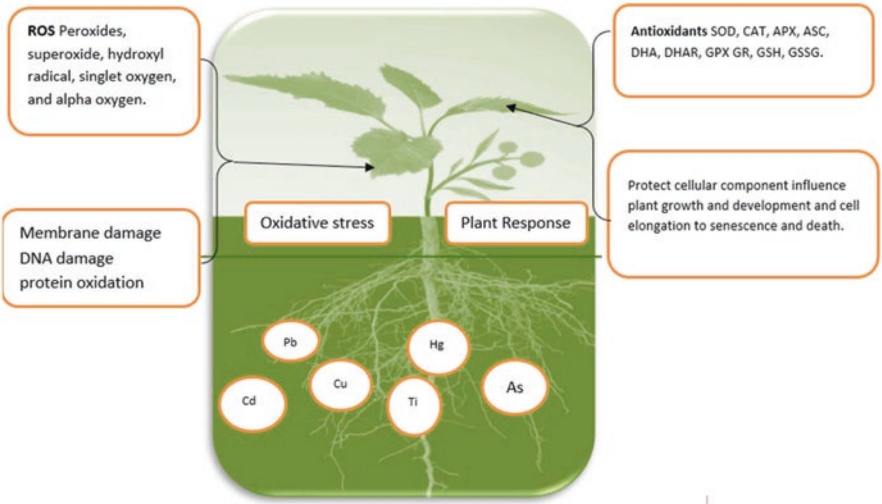

Fig. 10.2 Oxidative stress damage and plant response to heavy metals

metal-polluted areas, which undergo physiological changes as a result of growth reduction and biomass production inhibition (Sreekanth et al. 2013).

In plants, heavy metals show their toxicity by disturbing chloroplasts and, ultimately, crop productivity. Deposition of higher metals on the leaves of plants accidentally disturbs stomatal functioning, which then directly or indirectly affects photosynthesis and transpiration. Lead and Cd effect the photosynthetic carbon consumption content of leaves, which was a consequence of assembled restriction of stomata and non-stomata aspects. Copper put negatively effect on both photochemical and CO_2 fixation reactions because both are relative conscious of copper.

Due to the interference of metal ions with photosynthetic enzyme and chloroplast membranes reduction of photosynthesis occurs. Heavy metals also cause reduction of photosynthetic pigment and chlorosis. When the central atom of Chl, magnesium is changed by heavy metal, it causes destruction mechanism in stressed plants. As the result of malfunction of photosynthesis owing to the stop of photosynthetic light harvesting in the affected Chl molecules. The rate of reaction changes with light intensity. In low-light intensity, all the central atoms of Chl accept heavy metals. High-light intensity destroys Chl, which shows that most of the Chl is unattainable by heavy metal ions (Küpper et al. 1996).

When plants are polluted with heavy metals, they affect both the production of secondary plant metabolites and their growth. Heavy metals in medicinal plants activate the synthesis of bioactive compounds. Some scientists have concluded that heavy metals play an important role in altering the secondary plant metabolites. The most extreme hurdles for the development and growth of plants are biotic stresses like heat, availability of salt, and plant nutrients. Plants use many types of tolerance mechanisms like cell wall maintenance and synthesis of secondary metabolites. Secondary metabolites play a vital role in the interaction between the environment and plants. Increasing levels of atmospheric CO_2 and soil pollution both affect the production of secondary metabolites.

4 Antioxidant Response

An antioxidant is a substance, which at a low concentration, slows down or inhibits the oxidation of substances like proteins, carbohydrates, etc. Antioxidants can be categorized into three important groups: first-line defense or primary antioxidants, second-line defense or secondary antioxidants, and third-line defense or tertiary antioxidants. Primary antioxidants include glutathione reductase (GR), superoxide dismutase (SOD), catalase (CAT) and minerals like Cu, selenium (Se), Zn, manganese (Mn), etc. (Hasanuzzaman et al. 2020). SOD converts the superoxide radical into molecular oxygen and hydrogen peroxide (H_2O_2), although both peroxides and CAT turn H_2O_2 into water. Hence, the two virulent species, H_2O_2 and the superoxide radical, are transformed into nontoxic water. In the well-organized peroxides from cytosol and cell membrane, individually selenium and vitamin E both seem to be important. By cytosolic superoxide dismutase the antioxidant activity of cu is utilized. Secondary antioxidants consist of glutathione, albumin, vitamin C, bilirubin, falconoid, vitamin E, uric acid, and carotenoids. Glutathione (GSH) is a predator of various free radicals like hydroxyl radicals ($^{\bullet}$HO) and superoxide and many types of lipids and can assist to exfoliate various gasped oxidizing air pollutant. Tertiary antioxidants repair proteins, damaged DNAs, and oxidized lipids and peroxides, besides hindering the proliferation of chain reaction in the proxy lipid radical. These group of enzymes alleviate the damage to cell membranes and help in the recovery of impaired biomolecules, for example, methionine, protease, and lipase.

Reactive oxygen species survive under molecular or ionic conditions in plants. Molecular conditions contain H_2O_2 and singlet oxygen ($^1O_2$), whereas ionic conditions include $^{\bullet}$HO and superoxide anions ($O_2^{\bullet-}$) (Apel and Hirt 2004). Genetic defects and the environmental stresses produced the ROS to enhance the ruling capacity of antioxidants. Two dissimilar roles are played by the ROS in plants for the triggering of the defense under stresses they act as indicating molecules at low concentration and at high concentration they destroyed the cellular components of the plants. If the abiotic stress is constant due to increased production of ROS, it can damage the cell by catalyzing the lipids, oxidizing the protein, destroying the enzymatic hindrance and nucleic acids, and organizing cell death. The density of a plant is regulated by the equilibrium between antioxidative capacity and ROS. Reactive oxygen species production is managed by the collaborative and functional mechanisms of ROS-scavenging antioxidants that regulate the intracellular concentration of ROS (Apel and Hirt 2004). We can categorize these mechanisms into two groups: non-hydrolytic and hydrolytic antioxidants. The defense system of antioxidants under control conditions protects the plants from free radicals and active oxygen.

Reactive oxygen species exhibit the outcome of heavy metals (Zn, Cd, Pb, and Ni), which exert harmful effects and act as signaling molecules. Reactive oxygen species directly produced by the Haber Weiss reaction and by hindrance of antioxidant enzymes. Lead has been the cause of phytotoxicity in plants for a long time now, and it accumulates in different parts of plants and negatively affects various physiological processes such as photosynthesis, mineral nutrition, and enzymatic activities. Lead accumulation in the soil inhibits the germination of seeds and retards seedling growth. At high concentrations and period of exposure, these effects are more prominent. Plants can use the steady-state balance to protect their cells from oxidative damage or stress. ROS forage generated during the several environmental strains requires the activity of some hydrolytic (dehydroascorbate reductase (DHAR), GR, CAT, APX, monodehydroascorbate reductase (MDHAR), peroxides (POD), and SOD)and non-hydrolytic (phenolic compounds, GSH, non-protein amino acid, ascorbate (As A) and alkaloids) in plant's antioxidant defense system and try to direct the flood of tempting oxidation and protect the plant cells from oxidative stress. The presence of these antioxidant defense systems in just about the whole cellular area show the significance of eliminating ROS for biological existence. The existence of these antioxidant defense systems is not only limited to intracellular parts but are also present in the apoplast (the space outside the plasma membrane) in narrow ranges. Plants excite their antioxidant response together with the inference of enzymes, e.g., manufacturing of non-hydrolytic free radical, CAT and SOD predators (Kampfenkel et al. 1995). The initiation of the ascorbic acid-scavenging system is also a parameter to take into account in the production of ROS. Cd hardiness in seedlings and measurement for Cd accretion in mature plants are correlated with the expression level of the glutathione synthetase gene of *Escherichia coli* in *Brassica juncea*. The decrease in the ratio of GSH and activation of the antioxidant enzymes, for example, SOD and GR, depend upon the presence of heavy metals, in particular Cd. Ascorbic acid (AsA) is the major reducing substance in plant cells to detoxify H_2O_2. Glutathione is a major antioxidant and is instantaneously involved in the removal of ROS. Glutathione plays an important role in the restoration of other water-soluble antioxidants such as AsA and the AsA–GSH cycle. The increased activity of SOD reduces abiotic stress, and adjust the plant to stress conditions. Catalases are common antioxidant enzymes that uses either a cofactor also known as titrimetric CA molecule that consists of four structural subunits hemi containing enzymes and catalyze the degradation of H_2O_2 to molecular oxygen and water. In this way it protects the cell from oxidative stress. Ascorbate peroxidases (APX) are also H_2O_2 scavenging hemi containing enzymes in water and an AsA-GSH cycles, catalyzes the reduction of H_2O_2 by using AsA an electron donor to water and DHA produced by water(Yang et al. 2022).

5 Molecular Responses of Crops to Heavy Metals

A molecular response is the mechanism in which genes carry out vital functions in the intake and translocation of materials under heavy metal stress, and the function of specific genes alters under heavy metal stress owing to downregulation or upregulation mechanisms in plants. So, overexpression shows changes in uptake or downregulation. Different genes perform different functions, and each gene has a different role in different pathways.

Heavy metal (HM) toxicity has become a big problem in recent years worldwide and poses an acute threat to both environment and human health. A higher concentration of HMs exerts negative effects on plants. Cellular metabolism is due to the creation of ROS which pick out the key biopolymers home. Especially, hindrance of photosynthesis has been told off in HMs, because HMs can decrease the Chl molecules by increase the Chl job and by re-publish the Mg ion which in the porphyrin ring influence both overall plant growth and yield. To deal with metal poisoning, plants have developed different protection strategies to minimize heavy metal transport, such as separation of the metals into vacuoles (Bohórquez et al. 2015). To reduce the harmful reaction of HM exhibition and their collection, plants have involved sudden ways like Chelation and sub-cellular categorization (Asiminicesei et al. 2020).

Chelation of HMs has been extensively explained in a variety of ways: green sickness, an interrupted water balance, a minimal opening, and stop of cytoplasmic enzymes harmful to cell structures (Velásquez-Ferrín et al. 2021). Metals exert their toxic effects on plants primarily by harming chloroplasts and breaking up photorespiration (Sachdev et al. 2021). Plants require many metal elements for their growth, development, and reproduction, which must be taken up from the soil and held by the roots. Once absorbed by the roots, metal ions are transported to various parts of the plant by vascular bundles.

Zinc is important in photosynthesis and respiration, and Zn deficiency lowers the photosynthetic rate, Chl content, and protein hydroxylation. Cadmium and Zn both show decrease in Chl. Heavy metals such as Cd, As, and Ni are considered extremely toxic. Despite the fact that the precise mechanism of their toxicity is nonspecific, their accumulation in plants results in genetic damage by double-strand breaks and alters the choice of the DNA repair pathway (Morales and Berkowitz 2016).

Environmental toxins like toxic metals can change phenotypic characteristics such as DNA methylation, histone modification, and non-coding RNA expression (Poston and Saha 2019). Heavy metals can also affect the gene expression mechanism by mutational mechanisms (Feng et al. 2021). Nickel and Cd are believed to damage DNA by hindering the repair enzymes. Activation of nickel and Cd cell amplification is carried out by changing different signaling pathways and transcription factors, through ROS, although this mechanism is poorly understood.

The genes *ZIP9*, *ZIP6*, and *ZIP3* are part of the zip family of metal carriers and participate in metal transport in plants (Chen et al. 2021). When heavy metals contaminate a plant growth medium, its growth and productivity are both adversely affected (Chen et al. 2021). Plants exposed to heavy metal stress show changes in their ability to manufacture metabolites. The metabolic process of metals consists of transporting the correct metal ion to the required place. Intake, carry, absorbtion, preservation and excretion must believe that physiologically essential metals are catch on, although in not higher amount, and these harmful metals are excreted or cause a minute harm. After coming into plant cell, the heavy metals apply their cytostatic and carcinogenic effects and create disturbance of protein structure (Kumar et al. 2022).

6 Effects of Cadmium Stress on Mineral Uptake and Assimilation

Plants need nutrients for their proper growth and development. Some of these essential elements are needed in higher amounts (macronutrients), others in lower amounts (micronutrients). These elements are absorbed by the roots and distributed through the plant parts. The presence of HMs, such as Cd, can affect both the uptake of elements by the roots and their distribution to other plant parts. This can occur due to various reasons such as contention with the same transporters and disturbance in water uptake, thus affecting enzymes in the transport process. The effects of Cd are dependent on plant species and experimental sites. Cd toxicity causes a range of damages to plants from germination to yield, although the degree of damage is time- and concentration-dependent. Reduced seed germination and plant growth is due to intervention with enzymatic and photosynthetic activities and membrane damage(Luo et al. 2016). At high rates, cadmium reduces the nutrient and water uptake of plants and causes oxidative damage. Nitric oxide is an important gaseous molecule that takes part in the development and physiological process of plants, including the defense response against toxic metals in plants (Shivaraj et al. 2020).

7 Management of Heavy Metals

7.1 Selection of Crops

The knowledge of proper methodology is difficult to study for the selection of crops that detoxify the heavy metals is insufficient. For the covering of HMs acquiescent genotype, use of hydroponic system that contains HMs is an adequate method. Different plants use different mechanisms to detoxify HMs. Heavy metal-tolerant genotypes have different ways to detoxify HMs, which can be used for the selection of the tolerant variety (Malik et al. 2023). Conventional breeding methods play an important role in selecting HM-tolerant plants. Genetic engineering and marker-assisted selection are the modern biotechnological processes, which are also used for improving HM-tolerant varieties. Plants planted in metal-polluted areas alter their metabolism, lower biomass production, metal accumulation, and growth, and also change their biochemical and physiological processes (Das and Jayalekshmy 2015).

Pollution of soil with toxic metals is a widespread environmental issue. For the removal of the toxic residues from soil, phytoremediation through green plants is prescribed. Decontamination of soil using green plants is a viable and liberal process. Some plants can be used to recover contaminated soil such as sunflower, date palms, alfalfa, and corn, willow, certain mustards, and poplar tree. Phytoremediation is derived from the Greek words “phyto” meaning plant and “remedium” meaning “restoring balance;” in this situation, this means remedy for soil contamination. Phytostimulation, phytofiltration, phytostabilization, phytoextraction, and phytotransformation are the different types of phytoremediations. Plants that take up toxins from the soil are known as super plants. Plants used for phytoremediation must be able to work effectively and tolerate the toxic substances in the soil. Alpine penny grass is a phytoremediation plant and absorbs 10 times greater Cd than does other phytoremediation plant (Sharma et al. 2015). For the removal of Zn, (Hg), Pb, Cu, and Se from the soil, Indian mustard works as a phytoremediation plant; mustard and canola are also used as phytoremediation plants. Indian grass is known as a native phytoremediation plant capable of removing agrochemical residues like herbicides and pesticides. Western wheat grass and buffalo grass work as phytoremediation plants for the removal of hydrocarbons.

Plants are used as cleanup agents in phytoremediation for the removal of toxic materials from soil such as Fe, Zn, Mn, and Cd. Sometimes in plants, genes of the same species that have the capability of resistance against toxic substance can be transferred between varieties of the same species for the removal of toxic chemicals (Oladoye et al. 2022). Some plants species used as a phytoremediation that reduced the organic compounds and detoxify the heavy metals, such as Pb in the period of 24 h. The sunflower plant eliminates 95% of uranium from polluted soil and also has the potential to remove radioactive metals. The roots of the willow plant have the power to assemble toxic substances at polluted sites (Licinio et al. 2022). The root system of the poplar tree has the ability to absorb greater amounts of water; consume carbon tetrachloride, whichis a carcinogen; and deteriorate petroleum hydrocarbons like benzene. Accumulation of HMs has also been examined in vegetables, as tomato is one of the salt-tolerant crops (Raja et al. 2022).

Certain superior woody species like trees, used for phytoextraction, have an abyssal root system that prevents scattering of polluted soil in the circumferential environment and reduces soil erosion. For the phytoremediation trees are approved due to their non–edible characteristics than crops and plants, decrease the possibility of introducing of HMs into food-web. We use plants in phytovolatilization for the uptake of toxic substance from soil and plants transfer this toxic substance into harmless volatile form. We can use this technique for detoxification of heavy metals such as Hg, Se, and As and some organic substances (Mahar et al. 2016).

Good volatilizes of Se are identified from the Brassicaceae family members such as *B. juncea*. In plant tissues, the rate of transition of individual heavy metals depends upon the species (Romero-Esterez et al. 2019). Considerable cost is required for the removal of HMs from soil, and this is a long-term process. Through phytoextraction, high biomass-producing crops such as *Zea mays*, *Cannabis sativa*, *Nicotiana tabacum*, and *Helianthus annuus* efficiently remove HMs from polluted soil.

7.2 Management of Heavy Metals Through Tolerant Crop Varieties

Heavy metals have increased to a significant proportion in soil due to increasing pollution, and they have an adverse effect on the environment, with the most affected being plants (Bharti and Sharma 2022). However, these effects can be reduced by utilizing different conventional methods and also various disciplines of genetics like proteomics, metabolomics, etc. In addition, all these disciplines can be used to develop HM-tolerant varieties that could provide a wide tolerance to different HMs. Different mechanisms like bioaccumulation, signaling and phyto-associated microbes are advanced methods that are extremely helpful in reducing the effect of HMs. Heavy metals are accumulated by any part of a plant, i.e., leaves, roots, shoots, etc. Many microbes reduce the presence of HMs in soil and help plants to acclimatize to the HM environment. Genetically modified bacteria are now considered to develop heavy metal-tolerant varieties (Tiwari and Lata 2018). Several traditional methods are used such as the following:

7.3 Interspecific Methods

Genes of desired traits by the same species can be transferred between varieties of the same species to develop a new variety of required characteristics. Heavy metal-tolerant varieties can be produced by this traditional method, and many have been developed so far (Elango et al. 2022). A variety of rice known as brown rice has been developed, which accumulates Cd in low quantity, as Cd is the most hazardous HM accumulated in abundant concentration by rice in many countries around the world. Cadmium accumulation concentration in *Indica* and *Japonica* has been compared, where *Indica* accumulates more Cd than does *Japonica*. Therefore, by crossing these varieties of rice of the same species, a new variety with heavy metal tolerance can be created. In addition, the backcross method allows a breeder to improve the genetic structure of a plant by adding or fixing the desired traits of another plant. Qualitative traits are generally transferred through backcross methods, i.e., HM disease-resistant genes, etc. In the backcross method, multiline varieties are developed and genes are transferred by crossing the donor parent with recurrent parents, and then, after fixing the desired trait in the recurrent parent, it is crossed back again several times with the recurrent parent. This process is carried out to produce a recurrent parent with a gene of interest (GOI). This technique can be used to produce a heavy metal-tolerant variety (Sarma et al. 2022).

7.4 Pollen Culture and Anther Culture Methods

Genes can be manipulated by producing dihaploid plants by combining the most favorable genes in a pollen plant through efficient techniques like pollen and anther culture (Sharma et al. 2022). Researchers are working on different rice varieties to isolate a desired gene. Work has been conducted on chlorosis tolerance in rice. Callus was only observed in the cross of two hybrids, Prabhavati and Basmati 370; these plants were observed for their desired traits, and then evaluation of these cultures was conducted in different trials. Among these cultures, one was released as it had more tolerance to iron chlorosis as compared to the parents. Haploids were developed by anther culture on the basis of the best performing callus, and, then, iron chlorosis-tolerant diploids were selected and evaluated in different trials. The tested plants against iron chlorosis were selected as tolerant plants (Germana 2011).

7.5 Development of Heavy Metal-Resistant Varieties Through Transgenic Methods

Various transgenic techniques have been used for reduction of heavy metal toxicity in plants (Agnihotri and Seth 2019). There are four techniques for removing harmful HMs, namely, animal remediation, micro-remediation, physical remediation, and phytoremediation with emphasis on bioremoval features. In future, the practice of cell engineering or genetic engineering to generate ideal species would become approved and compulsory. Practical establishment in future should be to develop crops by genetic engineering which have more capacity to accumulate HMs (Wu et al. 2010). A gene carries a replicate of human mettallothionein-II treated gene, which was insert into *tobaccum* and *B. napus* cell through Ti-plasmid of *Agrobacterium tumefaciens* and in a constitutive manner transform MT protein expressed as a Mendalian trait. Self-pollinated, genetically engineered plants were cultured on media plates that contained Cd in toxic concentration. The results showed that the shoots and roots of that plants did not get affected by $CdCl_2$ concentration. Cd accumulation in seeds causes chlorosis. The results showed that plants such as *Brassica napus* can be genetically engineered to develop tolerance to heavy metal toxicity (Misra and Gedamu 1989). The phytoextraction technique refers to absorption of the HM contaminates from water and soil and then their transfer to the harvestable parts of plants. It has the potential to remove HM toxicity and promote the cleanup of soil (Bhargava et al. 2012). Stream waste, groundwater, and HM contamination of soil all cause worldwide environmental and human health problems. Phytoremediation is a process in which plants are used to remove and detoxify HMs and is an advanced and potent method for environment cleanup. Due to their biochemical and unique genetic and physiological properties, plants are the ideal species for water and soil remediation. Genetically engineered plants are developed for reclamation of the clean environment (Memon et al. 2001). New technologies are providing different ways to explore the genetic structures of plants and investigate the genes for desired characteristics using many innovative methods, like the in vitro culture breeding method, genetic engineering, use of bacteria, etc. In recent years, particular progress has been made to determine the native plants and to advance the genetically modified tree plants for the reclamation of HM contaminated environment.

7.6 Nutrient Management in Crops

Nutrient management includes efficient use of crop nutrients to boost productivity and protect the environment (Shah et al. 2010). It constitutes balancing soil nutrient inputs according to crop requirements. Due to reduction in the synthesis of Chl, the rate of photosynthesis is reduced, which results in nutrient deficiencies, which occur in the form of stunted growth, plant tissue damage, or discoloration of the leaves. Nutrients have specific channels but different capabilities, for example, some have fast access, whereas other have slow access. Aluminum (Al), Co, sodium (Na), Se, and silicon (Si) are useful components that opposed the HMs by minimizing the ion absorption and translocation from root to shoot. Silicon minimizes Cd metal toxicity from the area of rice grain. It is reported that Si penetration for wheat is 108 kg Si ha^{-1} in the shoots. Silicon uptake in wheat straw is between 73 kg Si ha^{-1} and 133 kg Si ha^{-1}. We can reduce Cd concentration individually by 23.38% and 54.26% in the shoots and by 42.53% and 77.36% in the roots under 50 and 100 mg kg^{-1} Cd by Si application, respectively (Guerriero et al. 2021).

8 Conclusions

Heavy metal toxicity has increased owing to industrialization. Threats of metal toxicity affect global food security. Day by day, heavy metal toxicity is increasing and is polluting the soil, leading to serious issues. With the progress in industrialization, threats of pollution are increased and this disturbs the ecosystem's uniformity. An increase in the concentration of HMs in soil, over the prescribed safety limits, affects crop productivity and enhances the chance of food toxicity. To minimize the toxic effects of HMs, plants show various responses at morphological, biochemical, and physiological levels. Metal toxicity can be managed by growing HM-tolerant crops, producing HM-tolerant varieties, and adopting different agronomic management approaches. In metal-polluted areas, industrial crops or crops that accumulate metals in nonfood parts should be promoted.

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Chapter 11
Waterlogging and Crop Productivity

Jawaria Abdul Majeed, Athar Mahmood, Safura Bibi, Atiqa Jabeen, Muhammad Mansoor Javaid, Hafiz Bashir Ahmad, and Javaria Nargis

Abstract Climate change is having a major impact on the natural world. Waterlogging occurs when free water covers the soil surface of crops. As an abiotic stress, flooding has a significant impact on around 16% of agricultural production regions globally. Both growth and yield of agricultural crops are gradually reduced due to harsh environmental conditions. Flooding disturbs the physiochemical properties of the soil that ultimately reduce the growth and physiological characteristics of the crops. Waterlogging induces oxygen loss barriers, which alter the uptake mechanism of nutrients. By developing root systems and secondary aerenchyma, the effects of waterlogging can be alleviated. Under hypoxic conditions, formation of the aerenchyma increases in most cereal crops. Some plants produce metabolic energy through the fermentation process in response to hypoxia rather than through oxidative respiration. This chapter will help understand the effects of waterlogging on crops and provide solutions to mitigate these effects to promote plant growth and productivity. To fulfill the food requirements of the growing world, it is mandatory to grow waterlogging-tolerant crops.

Keywords Waterlogging · Productivity · Anoxia · Hypoxia · Tolerant

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1 Introduction

One of the most significant stresses that plants encounters is waterlogging, which inhibits aerobic respiration growth, particularly vegetative growth and seed germination. Waterlogging stress causes plants to regulate their morphological structure, energy expenditure, endogenous hormone production, and signaling techniques (Ali et al. 2013). Waterlogging occurs when free water saturates the upper layer of the soil (Ashraf et al. 2011; Kaur et al. 2018). By combining water absorption by the roots and transpiration from the leaves, plants can grow normally. Adequate water is a necessity for typical plant growth; however, saturation of the soil's water-holding capacity or even oversaturation easily leads to waterlogging. Inhibition of root respiration and accumulation of toxins in case of waterlogging stress has a negative impact not only on vegetative growth but also on reproductive growth, ultimately leading to yield losses or even to complete crop failures (Zhou et al. 2007; Javaid et al. 2022a, b). Closure of the stomata during waterlogging as well as chlorophyll breakdown, leaf senescence, and yellowing make leaves less able to absorb light, which ultimately causes a decrease in the photosynthetic rate (Yan et al. 2018). Despite the reality that most plants struggle when they are flooded, they can adapt to the harm imposed by such environmental stresses using a variety of techniques (Doupis et al. 2017; Yin et al. 2019). The hypoxic condition in the rhizosphere reduces the oxygen intake by creating an anaerobic environment, which further results in plant mortality (Fukao et al. 2019). Plants' ability to tolerate waterlogging depends on their ability to tolerate anaerobiosis and chemical toxicity (Liu et al. 2020; Javaid et al. 2022b). Heavy rainfall and inadequate soil drainage are two of the main causes of waterlogging (Sundgren et al. 2018). Under waterlogging conditions, hypoxia, or a lack of oxygen, is a significant contributor to damage (Sanghera and Jamwal 2019; Javaid et al. 2020).

In plants, waterlogging has drastic effects, as shown in Fig. 11.1. Reactive oxygen species (ROS), including singlet oxygen and superoxide radicals, are produced in large quantities as a result of anaerobic respiration brought on by waterlogging (Zheng et al. 2017; Mehmood et al. 2018). Production of ROS initially aids in adaptive responses, including the development of the aerenchyma and adventitious roots, but excessive ROS under waterlogging stress causes severe oxidative damage (Shahzad et al. 2018; Tyagi et al. 2022). The gas exchange between plant roots and the atmosphere is severely hampered by waterlogging (Wollmer et al. 2018). The roots switch from aerobic respiration to anaerobic fermentation when the oxygen in soggy soil is quickly depleted, and CO_2 and ethylene concentrations rise. This has an adverse effect on several metabolic processes in plants, including the root cells' ability to synthesize adenosine triphosphate (ATP) (Pampana et al. 2016; Kaur et al. 2020). Therefore, waterlogging hinders mitochondrial respiration and diffusion of oxygen in plant tissues. This significantly slows down plants' regular physiological and biochemical processes (Phukan et al. 2016; Sarwar et al. 2018).

According to estimates, 12% of the world's arable land may experience regular flooding, which would reduce crop yields by about 20% (Kubik and Maurel 2016).

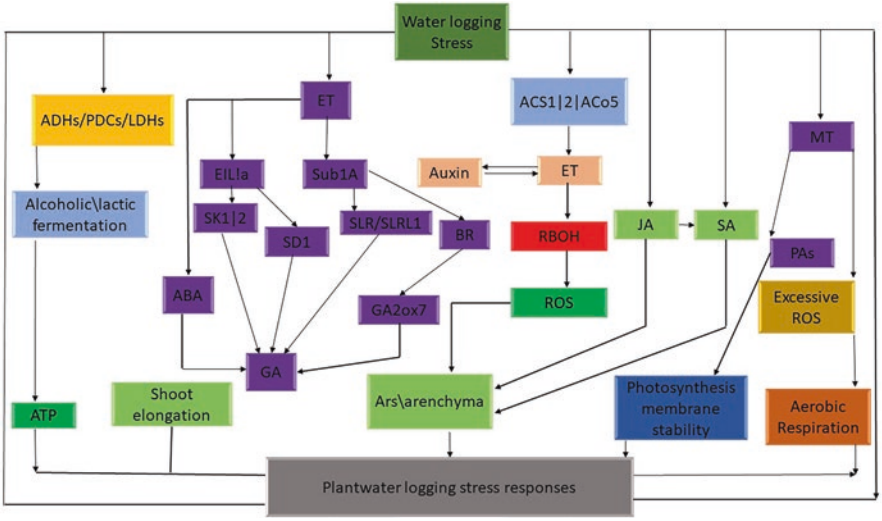

Fig. 11.1 Schematic diagram showing the genetic responses of waterlogging stress (Pan et al. 2021)

The Yangtze watershed, the plains of Huang-Huai-Hai, Sanjiang, and Songnen in China, and irrigated areas of the United States, India, Pakistan, Argentina, and Europe are among the places where soil waterlogging is predicted to become more frequent and severe in the near future as a result of global climate change (Ploschuk et al. 2018). Waterlogging is a major hazard worldwide, impacting 16% of American soils as well as agricultural regions in Russia, Pakistan, Bangladesh, China, and India (Manik et al. 2019).

One of the main abiotic stressors that significantly lowers agricultural output and has become a serious issue globally is waterlogging (Zhang et al. 2016; Jia et al. 2019). Around 17 million square kilometers of land are at risk of flooding, according to the National Aeronautics and Space Administration (NASA) (Leonardo 2019). Improved waterlogging tolerance is one of the main goals of barley breeding programmers in China and Japan, and, with the anticipated climate change, its significance will also grow in northern Europe (Karimi et al. 2018). Depending on the stage of growth, at present, waterlogging is said to diminish grain production by 20–25% or more (Ramirez-Cabral et al. 2016; Shrestha et al. 2021).

In all, 25% of the irrigated land in Pakistan has been impacted by salt and waterlogging. Moreover, 6.17 MH of land have been affected by temporary flooding or chronic waterlogging and 1.16 MH of the land have salt problems in addition to waterlogging problems (Dollinger and Jose 2018). In Pakistan, 230 MH of agricultural land are irrigated, and around 20% of the area, or 45 million hectares, is salty soil. According to estimates, waterlogging affects between 0.2 and 0.4% of all farmed lands each year as a result of poor management techniques (Harris et al. 2016).

Submergence is one of the abiotic stresses that affects 10–16% of soils and reduces the yields of the most important agricultural crops by about 80% (Liliane and Charles 2020). Being sessile, plants are vulnerable to a variety of abiotic stressors, including waterlogging, drought, salinity, heat, cold, and acidity, which can reduce production by 30–100%, depending on their severity (Choudhary et al. 2018). Due to the accelerating rate of global climate change, waterlogging will pose a significant threat to modern agriculture in the future, offering a challenge to researchers for the creation of submergence-tolerant crop cultivars with improving yield and quality (Hartman et al. 2019). In the past few decades, climate change has raised the likelihood of the occurrence of extreme weather events like droughts and flooding (Stott et al. 2016). According to estimates, flooding affects 10–12% of the world's agricultural regions, resulting in losses of more than $74 billion each year (Menéndez et al. 2020). Depending on the duration of the waterlogging, the type of soil, the varieties, and the stage of plant development, the yield reduction caused by waterlogging ranges from 20% to 25% (Tong et al. 2021), as shown in Fig. 11.2.

Waterlogging affects about 15% of the maize (*Zea mays* L.)-producing area, which reduces the yield by 20–30% (Du et al. 2017). It affects about 10–15 MH of the wheat (*Triticum aestivum* L.)-sown area, which results in yield losses of 20–50% (Manik et al. 2019). Flash floods and submergence affect more than 16% of the world's rice (*Oryza sativa* L.) cropland (Neog et al. 2016). Waterlogging affects between 10 and 15 million acres of wheat worldwide each year, resulting in yield

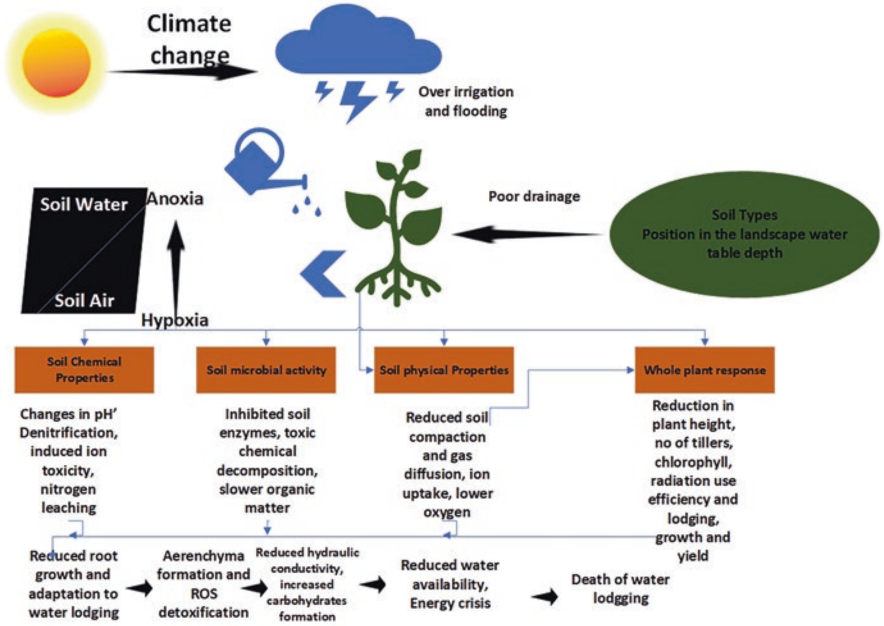

Fig. 11.2 Morphological, physiological, physical, and chemical mechanisms implicated in plant growth responses to waterlogging (Liu et al. 2020)

losses of 20–50% (Aryal et al. 2016). Other grain crops, including barley, canola, lupins, field peas, lentils, and chickpeas, also experience yield losses due to waterlogging.

2 Effects of Waterlogging

Root hypoxia is categorized as a stress that makes tomato (*Solanum lycopersicum* L.) and cucumber (*Cucumis sativus* L.) sensitive to waterlogging (Hou et al. 2019). However, genetic differences in their resistance to this stress have been found (Safavi-Rizi et al. 2020). Legumes are continually faced with a variety of stresses, the most important of which is waterlogging, which can result in yield losses of between 25 and 30% per year (Pasley et al. 2020).

Submergence in legumes can reduce photosynthesis, prevent biological nitrogen fixation by interfering with nodule development, result in nutritional deficiencies, increase the accumulation of toxic compounds, and, finally, induce plant mortality (Oves et al. 2016). Pigeon pea, cluster bean, lentil, soybean, pistachio, and chickpea are among the legume crops that are susceptible to submersion, mainly during the vegetative phases (Adak et al. 2016).

2.1 Effects of Waterlogging on Crop Productivity

One of the main abiotic stressors that impacts crop development is waterlogging (Lone et al. 2018). In many areas, waterlogging of the soil is a significant abiotic stress that significantly restricts crop development and lowers yield (Tian et al. 2021). It has turned into the primary obstacle to crop production in Australia's temperate high rainfall zone (HRZ), especially in areas with duplex soils (Ali et al. 2013; Franklin et al. 2020). The loss in the growth rates of some crops due to waterlogging makes crop production insufficient to fulfill the predicted food demand. Water is necessary for all plants to survive, but too much water, waterlogging, or floods causes stress and obstructs the passage of gases between the soil and the environment. Therefore, persistent waterlogging has a deleterious impact on nearly every stage of plant development throughout its life span and ultimately results in yield loss (Wang et al. 2017).

A valuable economic crop with an unpredictable growth habit and frequent waterlogging issues is cotton (*Gossypium hirsutum* L.). Cotton plant growth and development are negatively impacted by waterlogging stress, as is nutrient uptake. Reduced soil temperature, a less irrigated plowing layer, and decreased nutrient availability all contribute to a decline in the average production in cold, moist rice fields (Liu et al. 2016). Electrical conductivity, oxidation–reduction potential, and pH have all been found to vary in waterlogged soils (Tokarz and Urban 2015; Raja et al. 2022).

2.2 Waterlogging-Induced Anaerobic Respiration

Low oxygen levels (below 21% O_2) cause a transition from an oxygenated to a low-energy anaerobic state that supports plant development under waterlogging stress. It entails a number of biochemical adjustments, anaerobic digestion pathways, and the production of protective chemicals for the elimination of phytotoxic metabolites (Evans and Gladish 2017), which are crucial for plant survival under soggy conditions. Anaerobic respiration comes in two types: ethanolic fermentation and lactate fermentation (Du et al. 2017).

Pyruvate decarboxylase (PDC) initially converts pyruvate to acetaldehyde in the ethanolic fermentation process, and alcohol dehydrogenase (ADH) next turns acetaldehyde into ethanol by generating oxidized nicotinamide adenine dinucleotide (NAD^+). Lactate dehydrogenase (LDH) converts pyruvate to lactate during lactate fermentation by utilizing decreased nicotinamide adenine dinucleotide (NADH) (Zhang et al. 2017). Phytotoxins build up during fermentation, and carbohydrate stores are depleted (Loreti et al. 2016; Pucciariello and Perata 2017). In this situation, plants use glycolysis to generate energy and release sugar reserves that have been accumulated (Loreti et al. 2016). Fermentation's main feedstocks are water-soluble polysaccharides (WSPs). When the balance between carbohydrate metabolism and photosynthesis is off during waterlogging, the reserves of water-soluble carbohydrates (WSCs) can be reduced (Jurczyk et al. 2016), and these changes have an impact on the rate of fermentation and the survival of few species (Chen et al. 2013; Liu et al. 2017). Therefore, due to energy depletion, accumulation of phytotoxic chemicals (such lactate), and carbon loss (through ethanol loss from the roots), waterlogging and anaerobic metabolism cause severe growth inhibition and ultimately lead to the death of many plants (Tamang et al. 2014).

2.3 Effects of Waterlogging on Nutrient Composition

The fundamental cause of limited plant growth in damp soil is nutrient inadequacy, which ultimately results in wilting (Onyekachi et al. 2019). Waterlogging prevents the soil from absorbing the majority of necessary nutrients, which results in deficits of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) (Kathpalia and Bhatla, 2018). According to the early development stage as opposed to a later growth stage, the impacts of waterlogging on N, P, and K nutrition are more pronounced. After 65 days of waterlogging, the N concentration in cotton leaves reduced by 30% (Zhang et al. 2021). According to cotton roots, the stems and leaves had lower concentrations of N, K, and Ca^{2+} under waterlogging stress but higher amounts of Mn^{2+}, Fe^{2+}, and Mg^{2+}. The decrease in oxygen availability in the root zone, which affects root respiration and, in turn, the capacity of the roots to absorb nutrients may be the cause of this nutritional imbalance. Additionally, roots' ability to store energy is diminished in waterlogging circumstances, which prevents these nutrients from being actively transported to other organs (Tavanti et al. 2020).

Reduced root respiration under hypoxia may also result in root cell death, a reduction in cell permeability, and prolonged hypoxia, even the total loss of roots. Thus, it is clear that waterlogging prevents most key nutrients from being absorbed, creating a nutritional imbalance, even if other vital elements have been found to accumulate more often. As a result, nutritional imbalance contributes to yield loss under waterlogging conditions. In the presence of hypoxia, a reduction in root respiration may also result in root cell death, a reduction in cell permeability, and, in the case of chronic hypoxia, even in total loss of the roots (Xiao et al. 2020).

2.4 Crop Germination

When waterlogging occurs during seed germination or at the blossoming stage, the seedling dies and no more growth occurs. Sorghum seedling growth is impacted by waterlogging in a short range but increased death rate of seedling (Kyu et al. 2021).

2.5 Crop Morphology

Waterlogging is one of the biggest issues in agricultural productivity, which affects approximately 12% of the world's agricultural land. Crop productivity is decreased by waterlogging. Maize productivity is decreased as waterlogging periods increase (Huang et al. 2022). When organic substances are broken down, oxygen is required to create energy for productivity. The aerobic bacteria and roots in soil nearly lose most of their capacity to make energy when the oxygen level is low; as a result, they cease growth and may even die (Antar et al. 2021). Most crops and plants on land are aerobic organisms that depend upon the fast availability of oxygen either from underground or from aerial tissues. Waterlogging, which occurs when too much water is absorbed by the soil, severely affects crop development and yield, and, in many parts of the world, it has become a serious abiotic stress (Wei et al. 2013). Flooding or waterlogging inhibits root and shoot growth, reducing the overall yield (Tiryakioglu et al. 2015). Reduction in chemical reactions, energy currency, and other mechanism in crops are shown in Fig. 11.3.

2.6 Crop Productivity

Reduction in crop yield is due to the absence or loss of oxygen and/or denitrification or leaching of nitrogen and diseases can cause damage to the crops (Kaur et al. 2020). According to the stage of the affected crop and the intensity of the floods, the average yield loss due to waterlogging is estimated to be 15–25%, but it can reach up to 40% (Gomathi et al. 2015). Waterlogging, even when temporary and

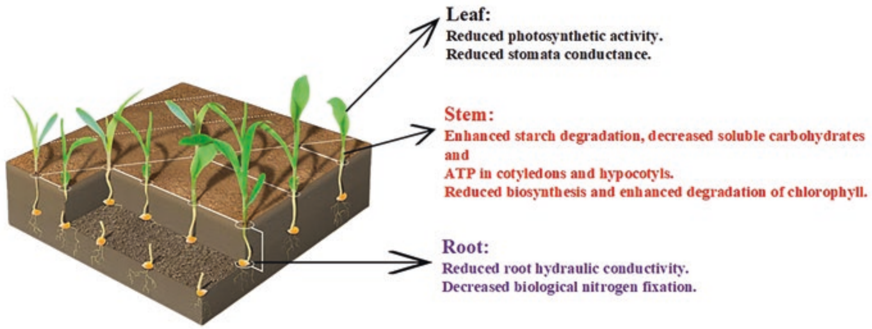

Fig. 11.3 Waterlogging effects on different parts of a plant (Manik et al. 2019)

short-lived, can have a significant impact on the development and production of dry land crops. There is reduction in the dry masses of both the shoots and roots (Robin et al. 2021). There is reduction in root growth due to waterlogging in wheat (Ploschuk et al. 2018). Wheat's grain production of the winter season can be reduced by almost 20 days at 32–94% by waterlogging, 52% in green gram, and 54% in chickpea (Basu et al. 2019). More number of enzymes such as ascorbate peroxidase (APX), superoxide dismutase (SOD), and catalase (CAT) have been proven to be harmful to tobacco rice, wheat, mung bean, sunflower, and sweet potato under waterlogging conditions (Hasanuzzaman et al. 2020). Earlier in the season, long-term waterlogging can result in reduction of crop productivity by up to 30% (Liu et al. 2021).

2.7 *Crop Physiology*

Waterlogging can have an impact on a number of physiological processes, including water and root–shoot hormone absorption interactions (Tong et al. 2021). They also reduce movement of ion across the roots, which results in shortage of nutrients and element toxicity such as in manganese (Mn), iron (Fe), sodium (Na), aluminum (Al), boron (B), and superoxide dismutase (SOD) (Kathpalia et al. 2018). In wheat, waterlogging decreases the rate of photosynthesis, total productivity, leaf extension, and the number of grains per spike (Du et al. 2023). Under temporary or permanent flooding conditions, quick waterlogging typically first causes deficiency of oxygen (anoxia or hypoxia) in plants and then results in chlorosis, leaf shrinking, and damage of the roots (De Oliveira 2021). Waterlogging causes a shortage in the supply of oxygen, and it has been proved to be dangerous for shoot and root systems (Zhang et al. 2021).

Oxygen-dependent activities are reduced in hypoxia, particularly in anoxia. The physiological interactions between the shoots and roots are changed, and both the uptake of carbon and the use of photosynthates are inhibited, particularly the oxygen internal transport (Nakamura & Noguchi 2020). Root hypoxia creates a photooxidative damage in leaves when production of ROS increases, like hydrogen peroxide (H_2O_2), hydroxyl radicles (OH•), and superoxide, which easily damage the leaf chloroplasts, and, also, yellowing of leaves and senescence occurs. Several well-known enzymes, including APX and SOD, reduce ROS (Kanojia & Dijkwel 2018).

The type and also the physiological age of the organism determine how waterlogging affects the respiratory rate. A higher rate of oxygen uptake in root tips is associated with respiration, which is necessary for other metabolic processes, such as the production of ATP. Under waterlogging conditions, plant roots suffer from hypoxia (a lack of oxygen), which suppresses the rate of metabolism and also lowers ATP synthesis. So, less ATP is produced and less energy is available for root growth, which inhibits vegetative growth. A reduced stomatal aperture decrease under lack of oxygen (hypoxia) also decreases the rate of photosynthesis. Senescence of the leaves, a decrease in chlorophyll concentration, and, ultimately, full inhibition of the photosynthetic process take place (Ding et al. 2022).

Photosynthesis inhibition occurs a few days before the reduction of chlorophyll contents. With more waterlogging, nitrogen contents in the leaves, shoots, and seminal roots reduce. However, adventitious roots' nitrogen content rises. Nitrogen is present in an excess amount in adventitious roots, followed by seminal roots because of the nutrient uptake ability of the aerenchyma (Mohammed et al. 2019). If the period of waterlogging increases, it causes more reduction in the photosynthetic activity of sorghum, cotton, and maize (Zhang et al. 2021). The sorghum species, especially germination-stage seeds, are extremely sensitive to water stress because they do not have enough oxygen (Zhang et al. 2020).

Due to a low amount of oxygen, electron transport chain and respiration are reduced, so, as a result, ATP production rate is decreased in sorghum. When the rate of ATP generation slows due to the lack of oxygen, permeability of the cell membrane in sorghum increased. Variations that occur in cotton by waterlogging are reduction of the rate of photosynthetic activity, leaf potential, and reduction in stomatal conductance (Pan et al. 2019). When changes in internal hormones take place, it helps in the internal connection between the shoots and roots and also affects the morphological adaptations of the stressed plants. When aerobic respiration in the root system of sugarcane is low, it negatively impacts nutrient uptake under waterlogging stress, as shown in Fig. 11.4. Moreover, it has been noted that under conditions of waterlogging, in plants, major changes in the morphology, physiology, and anatomy take place (Bhusal et al. 2020).

2.8 The Impact of Waterlogging on Different Compounds

The velocity of gas exchange between the atmosphere and the soil slows down due to the presence of too much water in the soil, which also impacts plant production and growth (Andrade et al. 2018; Garcia et al. 2020). While the amount of oxygen

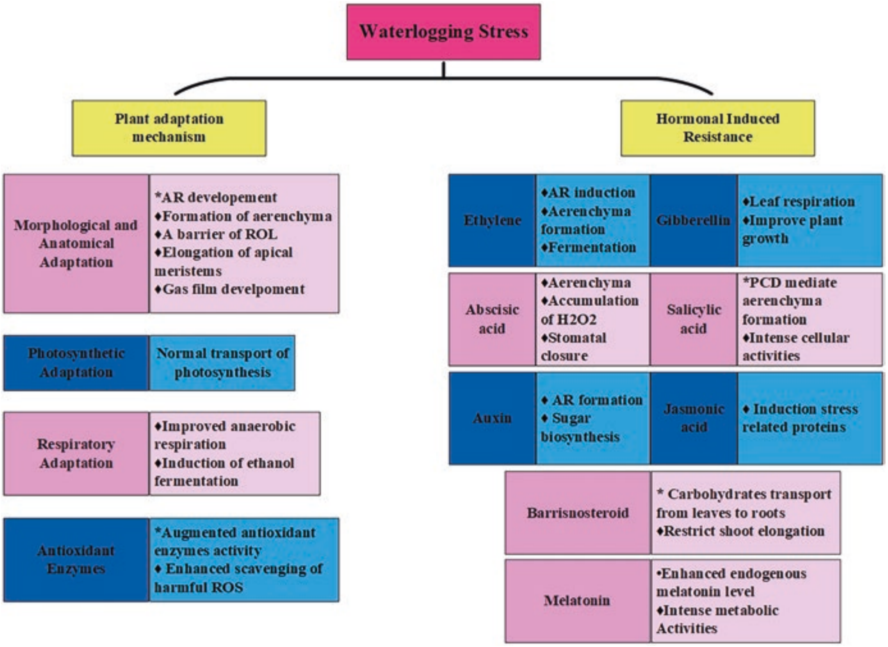

Fig. 11.4 Plants response toward waterlogging (Pan et al. 2021)

continuously drops due to waterlogging, methane, hydrogen sulfide, carbon dioxide, and ethylene increase at a rapid rate (Tyagi et al. 2022). This severely disturbs the stability of gas levels, makes a hypoxia or even anoxia conditions. It also lowers the capacity of soil for decline and also interferes with the exchange of minerals (Li et al. 2022). The absence of oxygen also reduces the aerobic nitrification and activity of the nitrifying bacteria, and, thus, conversion of nitrate into nitrogen is reduced, which results in nutrient loss (Walker et al. 2018). Additionally, under conditions of waterlogging, sulfate is quickly converted to hydrogen sulfide, thus decreasing the quantity of sulfur that plants can absorb and making them poisonous. Waterlogging also decreases oxidized substances like Fe^{2+} and Mn^{4+}, increasing the concentration of iron and manganese above what plants need for their nourishment (Kathpalia and Bhatla 2018).

2.9 Effects of Waterlogging on the Anatomy of Crops

Under waterlogging conditions, root diameter, aerenchyma number, aerenchyma width, cortex thickness, and stele width all decrease in rice plants. During flooding, the rhizosphere's limited oxygen supply has adverse effects on the plant roots. Due to the absence of oxygen, the soil increases the formation of the aerenchyma. The root aerenchyma of forage grass (*Brachiaria* spp.) is inhibited due to flooding conditions. The cortex thickness as well as the stele and diameter of the roots decrease due to flooding conditions as in rice crops (Fe et al. 2020).

3 Strategies for Improving Waterlogging Tolerance in Plants

The ability of plants to tolerate waterlogging depends on their type, water level depth, development stage at the time of waterlogging, and variety (Kaur et al. 2020). Plants can avoid the stress of waterlogging by increasing the synthesis of ethylene that leads to the formation of the aerenchyma, and, also, the surfaces of roots and adventitious roots become stronger due to this adaptative ability of plants (Wu et al. 2022).

4 Response of Plants to Hypoxic Conditions

Fundamentally, the response of plants to hypoxic conditions can be separated into three phases.

- Plant efficiently produces a group of components involved in signal transduction, and the second stage is activating.
- A metabolic adjustment occurs, which then gets involved in the fermentation process.
- The third stage depends on the strength of the plants and is involved in changing their morphology such as aerenchyma formation and root formation (Wei et al. 2013).

At their morphological and physiological stages, plants adopt different mechanisms or methods to prevent waterlogging or oxygen shortage. Some plants produce metabolic energy through the fermentation process in response to hypoxia rather than through oxidative respiration. The LDH, ADH and PDC are the parts of anaerobic proteins (ANPs) and they play a key role when respiration shifts from the aerobic to the anaerobic state. In order to maintain glycolytic metabolism under hypoxia, PDC catalyzes the irreversible changes of acetaldehyde from pyruvate and ADH transforms acetaldehyde to ethanol and stimulates NAD^+ (Borrego-Benjumea et al. 2020). From the transfer of pyruvate to lactate, LDH also creates NAD^+ (Farhana & Lappin 2023). Since the concentration of lactic acid is more harmful than alcohol, the change from alcohol to lactic acid production gives plants the capacity to survive under low oxygen conditions without having any cell injury, and this is regarded as a significant factor. Enzymes such as CAT and ascorbate peroxidase (APX) are envolved in controlling the levels of internal hydrogen peroxide (Anand et al. 2019).

5 Adaptations of Plants to Waterlogging

5.1 Morphological and Anatomical Adaptations

The majority of plants are resistant to waterlogging because it significantly reduces the rates at which oxygen and carbon dioxide diffuse through their roots and stems, inhibiting both respiration and photosynthesis. Under waterlogging conditions, certain plants undergo morphological changes; these plants alleviate the decline in the respiratory mechanism and injury caused by disturbing the energy metabolism. So, formation of the aerenchyma and adventitious roots is an important morphological adaptation, as shown in Fig. 11.4 (Pan et al. 2021).

5.2 Aerenchyma and Adventitious Root Formation

Waterlogging-induced adventitious root formation is a key process. This phenomenon is common in various plant species, including *Zea nicaraguensis*, tomato, cucumber, soybean, and wheat (Xu et al. 2017). Under hypoxic stress, new adventitious roots help in nutrient and water intake (Matsuura et al. 2022). The development of aerial roots to improve the period of waterlogging is specific for each species and depends upon water temperature, the growth period of the plants, and the duration of waterlogging (Liu et al. 2020). Waterlogging stress-sensitive species did not produce adventitious roots, whereas waterlogging-tolerant genotypes formed a greater number of adventitious roots in cucumber (Xu et al. 2017). Adventitious roots stimulated by waterlogging have a significant quantitative trait locus in them (Sanghera et al. 2019). Another characteristic of plants is to respond to water stress by the development of the aerenchyma. The aerenchyma has intercellular space, which helps plant tissues exchange gases and absorb oxygen (Luan et al. 2018). Under hypoxic conditions, the formation of aerenchyma increases in most cereal crops, including wheat, soybean, maize, and barley genotypes, which are waterlogged tolerant. This dramatically increases transparency in roots and also promotes the aerenchyma development in adventitious roots under waterlogging conditions. The aerenchyma develops in wetland plants like rice, not just in the roots but also in the leaves, stalks, and leaf sheaths (Luan et al. 2018).

5.3 Photosynthetic Adaptations

Stomatal conductivity of leaves, stomatal resistance, , closure of the stomata, and carbon dioxide uptake are all decreased when waterlogging occurs (Wu et al. 2022). Therefore, in order to continue growing and developing plants, light and CO_2 for photosynthesis are required. Under waterlogging conditions, enzymatic activities relating to photosynthesis decrease, as does chlorophyll synthesis in leaves, resulting in the senescence, shedding, and chlorosis of leaves; inhibition of new leaf development; decrease in the photosynthetic rate; and, eventually, plant death (Wu & Yang 2016). In the majority of plants, the main products of photosynthesis are sucrose and starch. The primary transport carbohydrate from the source to sink organs is sucrose, and this pathway is highly susceptible to waterlogging. The boll weight of cotton exposed to water was immediately decreased by decreasing the rate of photosynthesis, rate of transport of sucrose, and the primary activity of rubisco (Sun et al. 2022).

5.4 Adaptive Features in Tree Species

Tree species that live in habitats that face floods on a regular basis have developed a wide variety of adaptation techniques to deal with the stress caused by this waterlogging (Campbell et al. 2021). In reaction to floods, several flood-tolerant species have grown enlarged lenticels at the base of the stems (Messina & Conner 2019). In addition to allowing the plant to absorb oxygen, enlarged lenticels regulate the stem's release of gaseous chemicals into the atmosphere, such as carbon dioxide, acetaldehyde, and ethanol. Formation of adventitious roots is also an adaptive feature against waterlogging stress (Mui et al. 2021).

5.5 Adaptive Features in Soybeans and Figs

Soybean plants are capable of adapting to waterlogged soils by developing root systems and secondary aerenchyma (Goulart et al. 2020). Waterlogging stops roots from receiving oxygen, which limits respiration and significantly lowers a cell's energy status. So, to maintain ATP production, plants have adopted features under waterlogging stress conditions for the metabolic conversion of oxidative phosphorylation into anaerobic fermentation within their roots (Kaur et al. 2021). The fermentation pathways play an important role in adopting waterlogging tolerance strategies because they show a positive response when the amount of oxygen is low, but they are not used when aerobic conditions are present. So, if the fermenting pathways of plants are more effective, then they are more tolerant to waterlogging stress. Under wet stress conditions, lactic acid and ethanol are the two important fermentation pathways; two main enzymes are also involved, namely, LDH and ADH (Jitsuyama 2017).

5.6 Adaptive Features in Rice

In rice, the ratios of the cortex to the stem and the aerenchyma to the cortex relate to gaseous spaces and are necessary for the root's high capacity for oxygen transport. Transport of oxygen from the base of the shoots to the tips of the roots occurs (Yamauchi et al. 2019). Rice could develop a lysigenous aerenchyma process and barriers to the generation of radial O_2 loss (ROL) as an adaptive mechanism to waterlogging (Yamauchi et al. 2019).

5.7 Hormonal Adaptations

Waterlogging impacts the growth of the shoots by affecting root development. It disrupts the grain filling and consequently cause a decline in grain production (Wollmer et al., 2018). Due to waterlogging, abscisic acid hormones increases, while gibberellic acid and cytokinins decrease, resulting in a disturbance in the internal hormonal balance in plants. So, to avoid this situation, the hormones are applied exogenously. By stimulating a number of defense mechanisms, it has been discovered that phytohormones like cytokinin and gibberellic acid lessen the negative effects of waterlogging on crops. When cytokinin is exogenously applied, it raises its endogenous levels in plants, delays the aging of leaves, and improves photosynthetic efficiency, all of which would improve crop production. So, to overcome the negative effects in mung bean by waterlogging, cytokinin and gibberellic acid can be applied in the form of foliar treatment (Islam et al. 2021). Ethylene is a primary regulating hormone that helps combat the stress caused by waterlogging. In submerged shoot and root tissues, ethylene is produced from precursors 1-carboxylic acid (ACC) and 1-aminocyclopropane (Bashar 2018; Zeng et al. 2020).

6 Conclusions

Waterlogging is a serious problem to agriculture and reduces crop production and yield all over the world and also in Pakistan. It exerts deleterious effects on different crops. Cereal crops like barley, rice, wheat, maize, and oat are the major crops affected by waterlogging. It has major effects on the productivity of crops. It also affects the morphology, physiology, and anatomy of most crops. It induces anaerobic respiration and nutrient composition in plants. Different growth stages, especially the seedling stage, are disturbed by waterlogging. It also disturbs the photosynthetic activity in plants and different compounds in soil. Under severe conditions, these crops can survive by adopting tolerance strategies such as aerenchyma, and adventitious root formation occurs in plants as a morphological adaptation. Some species can tolerate this water stress, but most of them are sensitive to it. Plants that can survive under water stress conditions do so because they have an adaptation mechanism.

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Chapter 12
Phytoremediation of Atmospheric Pollutants in the Era of Climate Change

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Abstract It is now widely recognized that natural vegetation and many economically important crop species are significantly harmed by a variety of compounds that are found in the atmosphere in the form of pollutants. These pollutants are the result of anthropomorphic actions, which lead to increasing concentrations of harmful chemicals in the atmosphere. These include oxides of sulfur and nitrogen, ozone (O_3), volatile organic compounds (VOCs), carbon monoxide, fluorides, and organic particulate matter (PM). With regard to the effect of these chemicals on crops and other vegetable species, the amount and type of damage depend on the concentration of gaseous pollutants in the atmosphere, the duration of the exposure time for the crops, and the nature of the growing season. Furthermore, the genotype of the plant governs the extent of damage caused by these atmospheric pollutants and can result in either acute or chronic damage. Polluting chemical contaminants have a variety of direct impacts on vegetation, which can include the plants' heat exchange parameters, together with their biological properties, antimicrobial activities, gene functions, and yielding characteristics. In addition, they frequently show modifications to the foliar structure and photosynthetic processes, which can cause an

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increase in the emission of reactive oxygen species, which are harmful to the plants' biological, physiological, and biochemical processes. These species can include hydroxyl radicals, singlet oxygen, and hydrogen peroxide, and, consequently, the health of crops, for example, will require remedial action, such as the neutralization of free radicals by the formation and coordinated action of enzymatic and nonenzymatic antioxidants. In order to contribute to such remediation processes, this chapter has focused on these air pollutants and their impact on vital physiological functions such as photosynthesis, respiration, carbon allocation, and the stomatal function of plants.

Keywords Phytoremediation · Pollutants · Crop production · Reactive oxygen species · Physiology · Antioxidants

1 Introduction

When looking at the effects of pollutants on crop productivity, there is agreement that the most troubling materials are sulfur dioxide (SO_2), nitrogen oxides (NO_X), tropospheric ozone (O_3), carbon monoxide (CO), heavy metals such as lead, and suspended particulate matter (PM) (World Health Organization 2021). With respect to atmospheric pollutants, with which this report is mainly concerned, many have been found to be phytotoxic, with sulfur dioxide having been recognized as deleterious for more than a century and ozone having been known over the past 30 years to have many negative effects. Some 10 years ago, studies on gaseous nitrogen compounds such as nitrogen oxides (NO_X) and ammonia (NH_3) clearly established their deleterious impact on plant species (Su et al. 2016; Javaid et al. 2022). In these reports, the major sources of SO_2, NO_X, and CO pollutants were identified, levels of residual concentrations of these materials were noted, and the available scavenging processes for these gaseous pollutants were reported. It is further noted that pollutant sources account for up to one-third of the total amount of sulfur that emerges in gaseous form, with a net transfer of sulfur from land to ocean regions occurring via the atmosphere. In contrast, pollutant emissions of NO_2 only have a minimal impact on the global atmospheric nitrogen cycle, with natural emissions appearing to predominate (Robinson and Robbins 2017).

2 Major Air Pollutants

Apart from the materials noted above, there are other important contaminants that are produced by human and chemical actions, and, in this regard, Liu et al. (2018) have focused their attention on hydrogen sulfide (H_2S), ammonia (NH_3), sulfur dioxide (SO_2), and nitrogen oxides (NO_X), all of which are volatile organic compounds (VOCs). These materials are considered to be crucial elements in the creation of fine particulates, acid rain, undesirable odors, ground level ozone, global warming effects, and photochemical smog (Shu et al. 2018). These are also dangerous to human health and (i) have a negative impact on vegetation, (ii) cause building facility corrosion, (iii) contribute to tropospheric ozone layer depletion, (iv) create damaging haze conditions, (v) are responsible for initiating widespread acid rain, and (vi) produce heavy layers of photochemical smog (Waheed et al. 2021; Wang et al. 2020; Zhang and Gong 2018).

Of particular concern to this study is that plants are sensitive to the quality of the air around them; these air contaminants endanger the ecosystem's health, reduce agricultural productivity, and stunt plant development (He et al. 2018; Eea 2019; Yeung et al. 2019). Additionally, soil contamination due to harmful metallic elements and heavy metal-enriched particles also cause pollution problems for plants, and they represent severe environmental problems, especially in industrial regions of developed countries (Shahid et al. 2021). It has been observed that plants in contaminated areas are therefore simultaneously exposed to a variety of biotic and abiotic stress elements, leading to stress (Zhao et al. 2021). One of the major sources of global urban air pollution arises from transportation systems, where diesel and petrol are used as fuels (Safdar et al. 2021). In this area, one of the many possible passive air pollution mitigation methods that has been suggested is the use of roadside vegetation as a particulate and gaseous barrier (Barwise and Kumar 2020). Indeed, recent research (Rout et al. 2021) has suggested that certain toxins can be filtered by plants through their metabolism, being absorbed through the leaves. The capacity of plants to withstand air pollution is described by the air pollution tolerance index (APTI), and this measure is used to classify plants according to how sensitive or how resistant they are to air contaminants (Nadgorska et al. 2017). Well-chosen plants can serve as a significant sink for atmospheric pollutants, and four biochemical indicators have been used to describe their pollution tolerance index (APTI): ascorbic acid, relative water content (RWC), total chlorophyll, and pH of leaf extracts (Singh et al. 2019; Nadeem et al. 2021).

3 Crop Responses to Air Pollutants

In many industrialized nations, whilst planting vegetation to improve the air quality has gained widespread acceptance, not all plant species provide the same advantages for decreasing urban air contamination (Hewitt et al. 2020). Indeed, some species of flora serve as an origin for contaminants such as biogenic volatile organic carbon, indicating that when forming urban green belts, the plant species should be carefully chosen. It has been found that the most frequent consequence of air contamination is the inhibition of photosynthesis, leading to the interdependent yellowing of leaves and lowering of chlorophyll levels. A useful application of this understanding is that plant species, which have a low APTI, can be used as bioindicators of pollution in less contaminated areas, while those plant species with a high

APTI can be employed to reduce air pollution in highly polluted areas (Bharti et al. 2018; Molnar et al. 2020).

3.1 Crop Responses to Atmospheric Ozone

Ozone (O_3) is an air pollutant that both harms flora and has an unfavorable impact on human health. It has been recognized as a powerful greenhouse gas (Delang et al. 2021), being produced in the lower atmosphere by the chemical interactions of precursor gases such as volatile organic molecules, nitrogen oxides (NO_X), and carbon monoxide (Audran et al. 2018). Investigations have indicated that annual peak O_3 concentrations can surpass 60 ppb (Montes et al. 2022) and that ozone reduction can be achieved by chemical oxidation and its adsorption onto the leaf surfaces of the vegetative species (Schultz et al. 2017; Tanveer et al. 2020). The typical lifetime of O_3 in the troposphere is about 25 days, but it is less than 5 days at the surface boundary layer during summer, which effects the gas exchange parameters of plants (Young et al. 2013). Ozone directly harms plants by entering the leaf surfaces through the stomata and interconnecting with the aqueous apoplast to form reactive oxygen species (ROS), which accelerate senescence and, at adequately high concentrations, are a source of programmed cell death (Hasan et al. 2021). It is noted that chlorosis and necrosis of leaves are two signs of ozone damage (Emberson et al. 2018; Javaid et al. 2020).

Global croplands, which are located in areas with high O_3 pollution, can be considerably adversely affected in terms of crop productivity (Fischer 2019). According to estimates, ozone pollution reduces maize (*Zea mays*) and soybean (*Glycine max*) yields in a manner comparable to that of nutrition, heat, and aridity stress (Mills et al. 2018). According to various hypotheses regarding O_3 action on plants, the flux from the stomata and the amount of detoxification in the leaves indicate that the effect of O_3 on various crops can differ. Some work has shown that existing O_3 pollution lowers yield in four main staple crops: 6.7% for soybean, 7.2% for wheat, 2.6% for rice (*Oryza sativa*), and 3.6% for maize (Tai et al. 2021). Ozone levels are believed to have decreased maize yields in the United States by 10% between 1980 and 2010 and by 6.1% worldwide (Mills et al. 2018; Waheed et al. 2019). In this regard, recent estimations have shown that other pollutants, especially nitrogen dioxide and particulate matter, are more dangerous to maize than is O_3 (Lobell and Burney 2021). A separate investigation on four sugarcane hybrids, which was carried out in a greenhouse, revealed that phosphoenolpyruvate (PEP) carboxylase was more susceptible to O_3 than rubisco (Montes et al. 2022). Furthermore, in contrast to many C_3 species, some C_4 species, which are more prevalent in Africa, North America, South America, and East Asia, seem to be more resistant to increased O_3 levels. It was also shown that high O_3 concentrations formed gangrene damage symptoms and brown spots on leaves as well as increased stomatal resistance and decreased photosynthetic rates, which both shorten the grouting period and lower grain and crop yields (Wang 2017).

Currently, the annual global economic loss caused by rising O_3 concentrations and its consequent detrimental impact on crops ranges from $US 11 to $US 18 billion. Indeed, corn, soybean, and wheat productions are predicted to decrease by 4.5–6.3%, 10.6–15.6%, and 12.1–16.4%, respectively, by 2030 (Ren 2021). Additionally, the fall of these crops would result in a $US 12–35 billion annual economic loss, which will clearly have a significant impact on world food security. It is noted that ozone damage to plants primarily occurs in the summer because high ozone concentrations can occur during the anticyclone's high temperature season in the mid and late season. Around noon during the day, ozone levels are at their maximum, but dust, reactive hydrocarbons, and other atmospheric contaminants act to the lower ozone levels at night (Ran et al. 2021; Mudassir et al. 2018). Notwithstanding the work done on the impacts of airborne pollutants on agriculture, the area is still poorly understood, with global studies indicating that yield losses for staple crops could range from 3% to 16% as a result of O_3 pollution. In addition, global losses are expected to intensify by 2030, mostly as a result of rising O_3 levels in Asia (Emberson 2020) (Tables 12.1, 12.2, and 12.3).

3.2 *Crop Responses to Nitrogen Oxides*

Emissions from power plants, heavy industry, and transport are the major origins of nitrogen oxides. It has been estimated that the primary anthropomorphic sources of NO_X emissions arise from (i) combustion of fossil fuels (70%), particularly in the transportation and energy sectors, (ii) burning of biomass (20%), (iii) a range of

Table 12.1 Effects of ozone pollutants (at different concentrations) on some agricultural crops

Crop	Concentration	Effects	References
Wheat	70 ppb	Decrease in leaf area index (LAI) by 5.1–12.5%, photosynthetic rate by 2.8–11.8%, and yield by 2.2–14.2%;	Yadav et al. (2019)
Wheat	25–33 ppb	15–19% yield reduction in *T. aestivum*	Tomar et al. (2015)
Rice	1.0 and 1.5 times	Reduction in dry matter in plants under 1.5 × O_3 than in those under 1.0 × O_3	Tatsumi et al. (2019)
Rice	Four treatments of charcoal-filtered air (CF)	14.3 and 20.2% yield loss under O_3–1 and O_3–2	Chen et al. (2008)
Barley	Two times the ambient concentration (ambient concentration was 0.03–0.05 µl/L^{-1})	No effect on the growth and yield of both cultivars	Temple et al. (1985)
Potato	75 ppb and 150 ppb for 12 days	Reduction in growth parameters was observed at 45 days after planting (DAPS) Tuber plant was reduced by 54 and 69%; the fresh weight of the tuber plant was 48 and 68% for 75 ppb and 150 ppb at 45 DAPS, respectively	Mina et al. (2013)

Table 12.2 Collection of various studies representing the effects of the NO_X pollutant (at different concentrations) on some agricultural crops

Crop	Concentration	Effect
Rice	20–25 ppb	37–51% yield reduction
Rice	12 μl L^{-1}	37 and 42% yield reduction in two cultivars
Wheat	20–25 ppb	33–46% yield reduction
Common bean	<1.03 mg m^{-3} for 10–22 days	Growth suppression, increase in green color, and distortion of leaves
Soy bean	0.1–0.5 μl L^{-1}	23 and 50% reduction in the net photosynthetic rate after 5 days of exposure of 0.5 μl L^{-1} and 24 h after termination of exposure

Table 12.3 Collection of various studies representing the effects of the SO_2 pollutant (at different concentrations) on some agricultural crops

Crop	Concentration	Effect
Tomato, var. BT-2	0.25, 0.5, and 1.0 ppm for different durations	Leaf number and leaf area injury of 61–95.83% and 52–82% at 1.0 ppm, respectively
Rice, var. M7, M9	131, 262, and 393 μg m^{-3}	Reduction in the total seed weight of M9 and S201 by 22 and 14%, respectively
Rice, var. ADT-36	0.63–2.37 μg m^{-3} concentration	18–20% reduction in the number of panicles per plant and 3–5% reduction in the number of filled grains
Wheat, var. PBW-343	11.75, 1.87, 17.90, and 2.23 μg/m^{-3} during winter and 11.03, 1.79, 18.56, and 1.91 μg/m^{-3} during summer	The number of grains per plant and weight of 100/1000 grains show significant reduction between sites 1 and 2 for both wheat and mustard
Potato cv. Norchip 0	0, 0.15, 0.34, and 0.61 ppm	Quadratic response with stimulation, followed by decline in the number, percentage of dry matter, and sucrose content of tubers

industrial processes (5%), and (iv) usage of biofuels (5%) (Jayara 2021). Studies have shown that plants typically use small amounts of NO_X in their nitrate absorption pathways when creating organic nitrogenous chemicals (Sheng and Zhu 2019) and that higher NO_X concentrations cause chlorosis and potentially death of the entire plant. This is because the amount of chlorophyll is decreased, accompanied by the acidification of the plant's cells and the generation of harmful ROS (Sheng and Zhu 2019). Nitrogen dioxide levels are seen to be the highest in the winter, thus affecting wheat and other winter crops (Druckenmiller and Hsiang 2018). Recent research has shown that at least two indirect paths are available for NO_X creation, and these studies emphasize the complexity of these processes. In this regard, NO_X have been found to be a crucial precursor for the creation of O_3 (Mills et al. 2018), with particulate matter aerosols being the precursors of NO_X. This can occur when increased concentrations of ammonium nitrate aerosols (NH_4NO_3) and ammonium sulfate aerosols are produced when atmospheric ammonia is present, as is frequently the case in agricultural areas where nitrogenous fertilizers such as urea are used (Proctor 2021; Ahsan et al. 2018).

3.3 Crop Responses to SO_2

Normally, plants absorb sulfate and use it to create important substances like glutathione, cysteine, methionine, and sulfur-containing acids. For healthy plant development, many biochemical and physiological activities, assimilation of sulfur, and the formation of sulfur-containing amino acids such as cysteine and methionine are essential. While the prominent primary natural source for sulfur dioxide is from erupting volcanoes (Maruyama-Nakashita and Ohkama-Ohtsu 2017), man-made sources of SO_2 arise from the burning of fossil fuels by factories, transportation, and power plants, together with metal separation from ores in the mining industry.

When plants are exposed to SO_2, uneven stomatal movement reduces chlorophyll concentration and water use efficiency as well as protein and cell membrane oxidative damage. In addition, an excess of SO_2 increases plant respiration while decreasing photosynthesis (Rahman and Husen 2022). There have been reports of crop production reductions of 10–50% in response to SO_2 concentrations in the range of 75–139 g m^{-3} (Yadav et al. 2019). It has been suggested that, in response to SO_2 stress, the stomata open more widely, causing a rapid loss of water and an uncontrolled exchange of gases from the crop cover, which lowers crop yield and quality (Allen 2013); however, crop sensitivity to SO_2 might vary due to the plant's capacity to detoxify and remove excess pollutants as well as its efficiency at absorbing gaseous pollutants. With time and vegetative growth, the majority of the sulfur taken up by the leaves is translocated to other parts of the plant, reducing its effective concentration, but, when the concentration of SO_2 and its derivatives exceed the plant's ability to detoxify them, the exposure becomes dangerous. Modest amounts of exposure to SO_2 can demonstrate a benefit in terms of the development and growth of plants, but it has been observed that harm arises with an increase in exposure levels, with the degree of damage being dependent on the exposure dose (Yadav et al. 2019). Stomatal alterations are typically brought on by an increase in SO_2, with long-term high SO_2 concentrations inducing closure of the stomata. Increased SO_2 may cause a sharp rise in O_2 and H_2O_2 concentrations within the plant, and this requires the presence of superoxide dismutase, an essential enzyme for antioxidant defense (Huang et al. 2015; Balal et al. 2016). According to Li and Yi (2012) when *Arabidopsis thaliana* was exposed to SO_2, ROS levels and antioxidant enzymatic activity increased, with their findings indicating that the rate of O_2 and H_2O_2 creation accelerated. The increased ROS production in plant cells caused by prolonged exposure to high SO_2 concentrations was associated to cell damage and an increase in malondialdehyde (MDA) levels (Sonwani and Maurya 2019).

It is well-known that photosynthesis is a primary physiological process that can be impacted when plants are exposed to air pollutants, with their photosynthetic capacity being hampered by decreased leaf area, stomatal closure, and damage to the photosynthetic machinery. High levels of SO_2, O_3, and NO_X cause stomatal closure, which all contribute to the reduction in the amount of carbon dioxide (CO_2) available for photosynthesis (Dhir 2016).

3.4 Crop Responses to Volatile Organic Compounds

Due to their mobility, plant volatiles are one of the key priming stimuli that can affect plant stress, since they can quickly reach the extremes of the plant. It has been suggested that plants effectively mount a faster and/or stronger defense response that defines the post-challenge primed state and results in increased resistance and/or stress tolerance (Mauch-Mani et al. 2017; Mahmood and Honermeier 2012). The genotypic and phenotypic diversity of volatile organic compound (VOC) mixture composition depends on the ontogenetic stage of the plant and environmental conditions (Brilli et al. 2016). Besides being species-specific, the amount and types of constitutive VOC emissions strongly depend on leaf age and plant developmental stage. Isoprene is mainly emitted by adult, fully expanded leaves (Brilli et al. 2016). VOCs have been thoroughly proved to be effective herbivorous insect defenses, with numerous studies showing that VOCs can stimulate responses against herbivorous insects, diseases, and loss of natural habitat (Cofer et al. 2018). The term "green vaccination" has also been used to describe a plant's defense preparation against diseases (Luna-Diez 2016; Mahmood et al. 2022). In this regard, it has been demonstrated that green leaf volatile (GLV) compounds, such as Z-3-hexenyl acetate, which are widely and quickly released after physical pressure to plant leaves, prime wheat plants' resistance to the fungus *Fusarium graminearum* and lessen maize plant damage when they suffer from cold stress (Cofer et al. 2018). Interestingly, organic pollutants may actually aid in reducing herbicide use and thereby increase agricultural output through more efficient nutrient, water, and light acquisition (Puig et al. 2018; Naqve et al. 2021). In addition, other volatiles, including monoterpenes and methyl salicylate (MeSA), have been shown to actively participate in the pathways that result in systemic acquired resistance (SAR) within plants (Riedlmeier et al. 2017).

4 Effects of Air Pollutants on Crops

Crop reactions to a range of air pollutants can differ significantly and can depend on a number of parameters, including genetic makeup, physiological activity, plant growth, nutritional status of the plants, and the exogenous influence of environmental factors. The morphological and physiological traits noted in polluted plants include changed LAI, stomatal opening and closing, breadth of leaf and petiole variations, and reduced width of leaves. In parallel, there can be higher concentrations of proline, soluble sugars, a, b, and total chlorophyll, and carotenoids (Weyens et al. 2015).

In the management of the effects of pollution, the physiological changes noted above can be used as early warning signs of any negative effects on forests (Panda 2015). The major pollutants in this regard are sulfur and nitrogen dioxides (SO_2 and NO_2, respectively), which both react with oxygen and water vapor to form acid rain. Because H^+ can replace Mg^{2+} in the chlorophyll molecule, the elements that reach the plants via acid rain cause the remodeling of chlorophyll to pheophytin.

Carbon dioxide, together with a range of hazardous air pollutants, are predicted to be released into the atmosphere at a rate that is expected to rise as the world's population and the effects of industrialization grow. It has been noted that elevated CO_2 levels decrease stomatal conductance at a proportionately smaller rate than the amount of transpiration per unit leaf area and that gaseous pollutants (O_3, SO_2, NO_X, and H_2S) largely harm plants by entering through the stomata. Consequently, the leaf of a plant is the component that is the most vulnerable to damage from air pollution. In addition, the leaf is involved in the majority of critical physiological processes, and this accounts for its contribution to the sensitivity to gaseous pollutants. As a result, the leaf serves as an excellent sensor for air contaminants affecting a plant throughout all of its developmental stages.

An example of this growing problem is caused by the increasing level of pollutants from motor emissions, which can directly affect plants by piercing their leaves, harming individual cells, and reducing their ability to produce food. These harmful heavy metal emissions from internal combustion automobiles have an adverse effect on the morphology and growth traits of plants, with cadmium levels of 5 mg L^{-1} being the danger limit to root and shoot growth. The pollution from cars is felt in CO_2 levels, light intensity, temperature, and precipitation, all of which have a long-term effect on plants (Achakzai et al. 2017; Mahmood et al. 2021).

By limiting the interchange of gases required for photosynthesis and leaf formation, air pollutants have a detrimental effect on leaf length when compared to non-polluted sites. It has been observed, for instance, that due to the excessive levels of the air pollutants, NO_2, SO_2, and CO_2, the observed leaf length of *Ficus bengalensis* growing in polluted places is continuously decreasing (Swami 2018). Atmospheric pollutants injure the photosynthetic tissues and cause reduction in leaf size after entering through the stomata of leaves. In this regard, crop production depends on photosynthetically functional leaves, and work in a contaminated environment has shown that the growth of both *Thevetia nerifolia* and *Cassia siamea* leaves have been significantly inhibited (Shafiq et al. 2009). Wider investigations have indicated the generality of this issue as a range of leaves collected from polluted sites exhibit a loss in length, width, and area when compared to leaves from unpolluted places (Öztürk Çalı and Karavin 2020). It is clear that pollutants endanger not only the health of humans and animals but also the region's trees and crops, with the buildup of hydrogen fluoride and carbon monoxide causing a considerable reduction in the number of epidermal tissues, pores, and rhizomes per unit area (Armstrong and Drew, 2002). Gaseous pollutants pass through leaves using the same diffusion mechanisms as CO_2, and investigated plants in polluted areas have leaves that a show deformed stomata, which may have resulted from mechanical damage inside the leaf, a change in the turgor relations of the stomatal complex, or a reduction of pH in the guard cells' cytoplasm. Microscopic particles block the stomata, a mechanism that interferes with gas exchange, respiration, water absorption, and general crop production (Kushwaha et al. 2018; Rehman et al. 2018).

Fluorides are one of the many types of air pollutants that plants absorb through their leaves, being largely taken up by the stomata and cuticles in its gaseous state and assimilated by the entire leaf surface when in aqueous solution (SantAnna-Santos et al. 2014). Plants exposed to potassium fluoride (KF) experience changes in their morphology, anatomy, physiological makeup, and biochemistry (Dubey et al. 2020). It has been shown that, following tissue penetration, KF is primarily concentrated in the chloroplasts, causing cells to deform and parenchymal tissues to collapse, which has visible consequences like the formation of reddish patches on the leaf surface or the emergence of apical and marginal necrosis (Rodrigues et al. 2018). Contamination by these pollutants can also change the nature of photosynthetic pigments, reduce photosystem II's quantum efficiency, and produce reactive oxygen species (Rodrigues et al. 2017). The stresses arising from air pollution frequently have significant effects on plant growth, with the quantities of sugar and pigments (chlorophyll a, b, and carotenoids) being significantly lower in areas evidencing higher pollution loads. Plants that grow in polluted areas frequently display signs of numerous ailments, brittleness, and early aging, showing that pollutants seriously harm plants and plant cells both internally and externally (Sukumaran 2014).

5 Plant-Based Remediation of Air Pollutants

In light of the growing levels of atmospheric pollution, phytoremediation is being increasingly regarded as an economical and environmentally responsible method of assisting in the reduction of air pollutants. Airborne contaminants can be absorbed through the leaves of plants and subsequently destroyed by metabolic processes (Kim et al. 2020), where pollutants are broken down by plant enzymes such as oxidase and dehalogenase (Rachmadiarti et al. 2019). It has also been claimed that during the course of their development, plants can help remove dangerous substances such as metallic materials and chemical molecules, together with carbon emissions, which include CO_2 and methane (CH_4) (Wei and Wang 2020). Recently, the impact of plants on air pollutant blends has been the subject of extensive study (Papazian and Blande 2020), and there have been investigations on how well-suited plants are for both indoor and outdoor environments, with respect to absorbing air pollutants (Khare and Shukla 2020). Air pollution is now regarded as the leading global environmental issue, contributing to roughly 4.2 million premature deaths annually, with 0.4 million of those cases occurring in Europe alone (WHO 2016). It is hoped that, by eliminating various types of organic pollutants, plants and crops can help boost the quality of the atmosphere. In addition, the use of phytoremediation to filter indoor air has steadily gained importance (Teiri et al. 2018), and plant-specific traits such as exterior roughness, width, cellular structure, varnish content, LAI, and structure have a significant impact on the filtering capacity for particulate matter (Weyens et al. 2015). The key issues with plant-based research for the reduction of air pollutants in both outdoor and indoor environments have been reviewed in detail, along with potential future obstacles (Leung 2015). The success of phytoremediation is confirmed by analysis of currently available data regarding the assimilation and cleansing of contaminants by the leaves and roots of plants and trees while being influenced by various circumstances such as their pore characteristics and planting patterns. It has been suggested that since air pollutants have a negative impact on a plant's chlorophyll content, it is possible to estimate a plant's potential to reduce pollution by looking at its chlorophyll concentration (Yang et al. 2022). Plants can metabolize, sequester, or expel air pollutants after they have accumulated in the phyllosphere and rhizosphere whilst microbial biodegradation additionally helps phytoremediation to break down, detoxify, and sequester contaminants, thus promoting plant development (Weyens et al. 2015).

6 Conclusions and Future Perspectives

The current research has suggested that natural vegetation and productive crops are both crucial elements needed for maintaining the natural environment. It is, for example, known that the presence of indoor potted plants not only improves the aesthetics of an area but, importantly, also reduces the level of interior air pollution. In addition, depending on their placement and growing density, urban plants can remove some of the airborne pollutants around the transport corridors, which are produced by car and truck traffic. Indeed, in a similar manner to a wall or other physical barriers, larger plants are also seen to serve as a physical barrier to the spreading of pollution. This ability of plants to bind pollutants in confined spaces can be profitably used to evaluate the adsorption effects of plants in research.

The current research's disadvantages that are connected to the majority of remediation methods being used to mitigate air pollutants, whether they involve plants or other methods, are the relatively small surface areas available to measure exchange ratios (concerning all of the chemicals of interest) and the high rate of airflows (Khan and Ghoshal 2000). In this regard, decreasing the rate of air movement and increasing the surface area-to-volume ratio of leaves will allow better exchange; thus, the effects of these remediation solutions are more pronounced and obvious in enclosed spaces with poor ventilation. This scenario could provide significant potential for using crops and plants to actively remove air pollutants from internal environments. The majority of studies are now concentrating on research related to indoor atmospheric remediation by removing gaseous substances, whereas those involved with outdoor pollutants concentrate on the study of leaf absorption of particulate matter. In the latter situation, the quantity of PM 2.5 that can be collected on leaves has been found to be positively associated with the trichome density. Since outdoor environments have air circulation and exchange, only extremely local and short-term controls on pollution concentrations can be achieved by plants. Since ventilation rates often dominate the pollutant removal processes, they must be measured in every field of investigation. However, it is not possible to fully evaluate the cleansing effects of crops on air pollutants in actual environments using the available observational evidence. Future research should be focused on enabling experimental illustration and modeling of the real environmental circumstances to determine whether plants and crops can have a major impact on pollutant levels. It is clear from the evidence to date that more research must be conducted to fully address the efficiency of crops in outdoor contexts in order to more fully understand the fundamentals of phytoremediation of polluted air.

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Chapter 13
Water Stress and Crop Productivity in the Water-Limited Environment

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Abstract Drought is a serious restriction as it impacts the food security and lives of over two billion people who lives in arid areas. Water shortage is a limiting factor for plant growth. Drought is a natural condition that cannot be avoided; however, actions can be taken to mitigate its impacts. Drought stress affects water status, plant development, respiration, phenology, nutrient interactions, and photosynthesis. Drought stress affects floral growth, stem elongation, and rhizosphere, along with reduced plant water interaction and increased water-use efficiency. Closure of stomata, imbalances membrane functions, and disturbed mechanism of several enzymes, mainly the enzymes that are involved in carbon dioxide absorption and adenosine triphosphate production, all limit CO_2 uptake by leaves. Damage to macromolecules by reactive oxygen species (ROS) is one of the most significant growth inhibitors due to drought in plants. To deal with drought stress, many management solutions have been developed. Several strategies to mitigate adverse effects of drought stress on plants proper functioning have been developed, including breeding techniques, functional genomics, seed priming, and use of plant growth promoting bacteria.

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1 Introduction

Insufficiency of water resources leads to drought, which is a deleterious threat for the global food protection (Aamir et al. 2020). Due to soil water deficiency, the crop yield reduces by these three mechanisms: (1) reduction in absorption of active radiations by canopies, (2) decreased regulation of radiation-use, and (3) decreased grain ratio (Gholamhoseini et al. 2013). Improvements in the resilience mechanism through the use of modern genetics and traditional breeding forces have hampered due to slow revealing rate of tolerance mechanisms against drought (Xiong et al. 2012). However, the plant mechanisms and adaptations against water shortage are somewhat known, yet the plant responses alter under multiple stresses (Zahoor et al. 2017). Under changing environment, it is crucial to enhance the tolerance mechanisms for better crop yield against drought stress. Now a days, it is the need of economically applicable practices that can facilitate the crop yield under drought stress. However, the occurrence of tolerance mechanisms against drought stress helps to fulfill the food requirements. Knowledge about genetic standards of trait factors during various stages of development and various physiological mechanisms are required to increase drought resistance in crops. Valuable applications have been taking place regarding tolerance mechanisms against drought stress in crop plants (Gao et al. 2016). This chapter is a summary about the ongoing deleterious impacts of drought and tolerance mechanisms in the higher plants, along with some crucial mechanisms to tolerate the impacts of drought stress, mainly in the field crops (Villani et al. 2022).

2 Drought Stress in Drylands

All predictions related to climatic changes show that most of the area of our earth will become drier and hotter (Ganguli and Reddy 2014). There is a need to deal with increasing population, their needs, increasing poverty, food shortage, and severe natural resource limits, which are the results of water shortage in various drylands. Biophysical techniques are seemed as most urgent interventions required to cope with these issues, their success depends on institutional and policy transformation, which ensure the adaption of novel strategies to boost and regulate food production during drought. Regardless of these difficulties, dryland agricultural system is crucial for ensuring food security in many poor nations; thus, it must be a top priority for academics, decision makers, and funders of international development. The Integrated and Sustainable Agricultural Production Systems for Improved Food Security and Livelihoods in Dry Areas CGIAR Consortium Research Program

(CRP), directed by ICARDA, was launched in 2012 (Apgar and Douthwaite 2013). It involves 80 partners and targets farming methods in dry locations throughout the world. This strategy involves water, soil, livestock, trees, crops, and rangeland. It is considered that a wider, perspective would have a greater overall impact on the outcomes and will enhance human lives in sustainable ways, enabling them to realize their potential (Shen et al. 2014).

3 Impact of Drought Stress on Plants

Whatever stage of plant growth the water deficiency occurs, the drawbacks of drought can be depicted at all stages (Fig.13.1; Hussain et al. 2018a, b). The impacts caused by drought stress are depicted here.

3.1 *Growth and Yield of Crops*

The primary negative impacts of water shortage are poor establishment and impaired germination (Ledger et al. 2012). The reports have shown that drought stress reduces seedling stand and germination (Petrović et al. 2016). Additionally, polyethylene

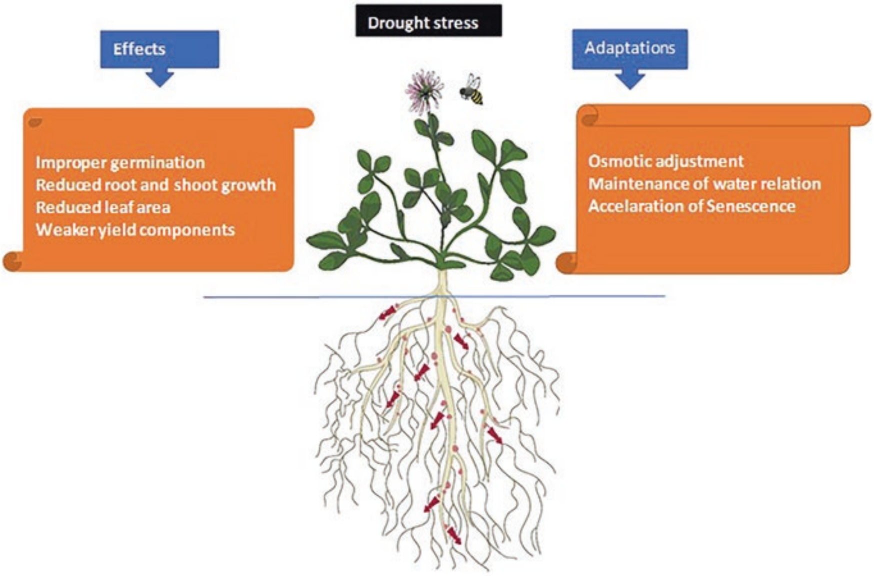

Fig. 13.1 Description of possible mechanisms of growth reduction under drought stress and adaptations (Hussain et al. 2018a, b)

glycol-induced water deficiency (*Medicago sativa*) reduced hypocotyl length, germination potential, and roots and shoot fresh and dry weights while increasing the root length (Zheng et al. 2016). Therefore, in rice, the effects of drought stress on plant growth and development were very negative during the vegetative stage (Samantaray et al. 2020). Plant growth is achieved through cell enlargement, cell division, and cell differentiation. It also contains complex interactions between genetic, morphological, ecological, and physiological events. Quantity and quality of plant germination depends on the stages that are inhibited by drought stress. Due to low turgor pressure, development of the cell is a physiological process which is vulnerable to dryness (Ullah et al. 2016). Under dry conditions, cell elongation, impaired mitosis, and expansion lead to decreased plant size, surface area of leaf, and growth (Hussain et al. 2018a, b). Water shortage triggers a variety of physiological reactions in plants that affect production. Many of these physiological mechanisms are intricately integrated by yield (Alghabari and Ihsan 2018).

3.2 Water Relations of Plants

Water potential, water content, and transpiration are among the major factors that affect plant water relations. Wheat leaves had higher relative water content when they were first developing than they had as they grew older and drier (Farooq et al. 2012). Clearly, wheat, and rice plants under water stress exhibited lower relative water contents than stressed plants. When these plants were subjected to drought stress, the relative water content, transpiration rate, and leaf water potential all significantly dropped, while floral temperature increased (Farooq et al. 2017).

In reality, stomatal opening and closure is more significantly impacted by decreased water availability than other plant water relations components. Additionally, changes in leaf temperature may have a significant role in maintaining the water level of the leaves during drought stress (Yigit et al. 2016).

3.3 Nutrient Relations

Reduced total nutrient intake and reduced tissue concentrations in crop plants are typically consequences of decreased water availability during droughts (Huda et al. 2013). Water scarcity has a significant impact on how nutrients are taken up by the root and transferred to the shoots. Reduced transpiration flow, disruption of the nutrient intake and unloading system, and lower inorganic nutrient absorption are all possible outcomes (Ashraf et al. 2013).

However, the response of different plant species and genotypes to the uptake of minerals during drought stress can vary. Generally, moisture causes a rise in nitrogen, a decrease in large proportion of phosphorus, and very little impact on potassium (Khalid et al. 2022). Drought inhibits transpiration (Arend et al. 2016).

Although it may not always have a similar effect on nutrient uptake. Lower level of energy for assemblage of phosphate and sulfate, which must be transformed into energy-dependent mechanisms prior to these ions, can be used for plant growth may also have an impact on how drought affects plant nutrition (Naik et al. 2022).

Application of fertilizer is anticipated to boost the effectiveness of crops in utilizing available water because of the strong relationship between nutrient and water requirements. This suggests that soil moisture deficiencies and fertilizer uptake interact significantly. Studies demonstrate that under arid and semi-arid climates, crops respond well to increased soil fertility. Presently, it is clear that increasing plant nutrient efficiency in conditions of low moisture availability can significantly increase agricultural yields (Garg et al. 2016). The uptake of nitrogen and potassium shows hurdle in cotton plant growth under drought stress (Jochum et al. 2019). Moreover, phosphorus and phosphate contents in the tissues of plant lower during drought stress, possibly because of lower concentration of phosphate mobility results in the lowering of moisture content (Carsjens et al. 2014).

3.4 Photosynthesis

The process of photosynthesis drastically reduces due to drought stress, which ultimately inhibits photosynthetic machinery, premature floral senescence, and leaf expansion decreases (Chaudhry and Sidhu 2022). In addition to CO_2 uptake, other processes are also damaged. The uptake of CO_2 through the leaves is limited due to induced effect of drought stress on stomata. Many changes occur as a result of drought in photosynthetic components and pigments (Huang et al. 2013), reduction in the functioning of enzymes of Calvin cycle, which leads to decreased crop yield (Chowdhury et al. 2016), and damage in photosynthetic apparatus (Huang et al. 2011). Decrease in the equilibrium among antioxidant and reactive oxygen species (ROS) production inhibits the photosynthetic abilities and growth of the plant (Ganguli and Reddy 2014), which causes accumulation of ROS, which decreases oxidative stress in cellular components, for example, proteins and lipids (Lei et al. 2016).

3.5 Stomatal Oscillations

Stomatal closure is considered to be first protective mechanism of all the plants against water deficiency to decrease the water loss through transpiration (Ram et al. 2020). This results either due to decreased leaf water potential and/or turgor pressure (Istanbuli et al. 2020) or due to an atmosphere with reduced humidity level (Damalas 2019). Drought mainly reduces metabolic impairment or decreases the rate of photosynthesis via stomatal closure (Istanbuli et al. 2020).

In the past, under drought conditions generally stomatal closure was considered as the determinant for reduced photosynthesis (Tamiru et al. 2015). Closing of stomata is the first response under the conditions of moderate or severe limiting availability of soil water (Lombardini and Rossi 2019). This reduces the uptake of CO_2 through the leaves by saving numerous electrons for ROS generation. It is concluded through different experiments that response of stomata is closely linked with moisture content of soil than the water level in the leaf. This suggests that stomata show response to the chemical signals such as abscisic acid (ABA), which is synthesized by dehydrating roots while water level of leaf is kept constant (Blum 2017). Environmental conditions enhance the transpiration and pH of the leaf sap, which promotes the accumulation of ABA that suppresses the conductivity of stomata (Davies and Wilkinson 2012). It is inferred that stomatal closure gradually occurs as the severity of drought increases, following a decrease in the net photosynthesis. The proportion of stomatal conductance, on the other hand, is influenced not only by the soil water availability but also by the intricate interplay of dependent and independent variables (Havko et al. 2020).

3.6 Nutrients Assimilation

Assimilating translocation in the sinks is key factor for physiology and development of plant seed. Seed set and stocking can be reduced by the storage or usage, for example, by restricting the potential source or sink (Xu et al. 2015). Water stress frequently increases the allocation of dry matter content into roots, which can improve water intake (Cui et al. 2021). Drought stress slows down photosynthesis and disrupts leaf carbohydrate metabolism and sucrose levels, resulting in slower export rates. This is probably due to the increased activity of acidic invertase induced by drought stress (Jeong et al. 2010). Restricted photosynthesis and sucrose build up in the leaves can slow sucrose export to sink pool and influence reproductive development. In addition to limitations of source, the capacity of biological sink pools to reproduce apply anabolic components is also disrupted during drought conditions and also regulates reproductive abortion (Anjum et al. 2017).

4 Physiological Mechanisms

Tolerance against drought stress is based on scavenging, antioxidation, osmoprotection, and osmotic adjustment. Physiological mechanisms of genetic diversity in drought stress responses are unclear, in part because of complex systems.

4.1 Antioxidant Defense

Plant cells have defense systems may be due to antioxidants of enzymatic and nonenzymatic in nature. Enzymes include ascorbate peroxidase, peroxidase, catalase, and superoxide dismutase. Nonenzymatic components include ascorbic acid, cystine, and glutathione (Gong et al. 2015). Drought tolerance requires high oxidative activity of enzymatic and nonenzymatic component concentration. Antioxidant enzymes are the most effective strategy against the oxidative stress in plants (Jaleel et al. 2009). The ascorbate-glutathione cycle, primarily cuts up superoxide radicals and H_2O_2, involves four enzymes. These include glutathione reductase, dehydroascorbate reductase, and ascorbate peroxidase (Bhat et al. 2022). The chloroplast stroma, peroxisomes, and mitochondria contain the majority of ascorbate-glutathione (Powers et al. 2020). Plant antioxidant ascorbate peroxidase is produced under drought stress conditions to mitigate the effects (Chourasia 2017). However, glutathione reductase sustains the glutathione peroxidase pool under stress (Keyvan 2010). Two glutathione reductase congruent deoxyribonucleic acids are recognized; one encodes cytosolic isoforms (Young et al. 2017), but the other produces chloroplast- and mitochondria-targeted enzymes (Suárez-Vidal et al. 2019).

4.2 Cell Membrane Stability

Abiotic stressors affect biological membranes. Maintaining membrane integrity during water shortage is a crucial component of tolerance mechanism against drought stress in plants (Rao et al. 2012). The stability of cell membrane is a physiological indicator used to evaluate drought resistance (da Silva et al. 2011). It's genetically linked, as QTLs have now been identified in rice experiencing water shortages at various stages of development (Munjal and Dhanda 2016) discovered that the most important drought tolerance trait was leaf membrane stability. Drought and temperature stress reduced the stability of cell membrane in kentucky bluegrass (Bu et al. 2014). Potassium feeding boosted maize's drought resistance by stabilizing cell membranes (Inès et al. 2022). Greater cell layer stability under dry conditions is distinct among genotypes and is closely correlated with lower relative growth rates under stress (Pourghayoumi et al. 2017). Drought tolerance in holm oak (*Quercus ilex)* embryos was increased by hardening via reducing stomatal control, osmotic potential, new root formation capability, and cellular membranes stability (Habben et al. 2014).

4.2.1 Regulators of Plant Growth

Low dosages of growth regulators for plants and phytohormones impact plant physiology (Morgan 1990). Both words are used interchangeably for gibberellins, auxins, ethylene, abscisic acid, and cytokinins (Ahanger et al. 2016).

During a drought, exogenous auxin, gibberellin, and cytokinin levels fall, whereas abscisic acid and ethylene levels rise (Liu et al. 2017). Phytohormones increase plants tolerance to drought. Auxins stimulate new root growth by reversing cytokinin-induced apical dominance. When abscisic acid and ethylene levels rise, drought stress reduces endogenous auxin synthesis (Ngumbi and Kloepper 2016).

4.3 Molecular Mechanisms

Reduced soil moisture might cause plant water shortage. Under specific conditions, expression of genes (up- and sweep) happens. Transcriptionally triggered genes are considered to function in drought resistance (Chourasia 2017). Stress can either directly or indirectly trigger gene expression via strictness and damage. Drought tolerance is a complicated phenomenon involving several genes (Kumar et al. 2018).

4.3.1 Aquaporins

Aquaporins control water exchange across membranes. They are highly conserved membrane proteins (Zhang et al. 2015). Aquaporins are prevalent in plant plasma and vacuolar membranes. The structure of aquaporin shows nutrient membrane water transport. The relationship between aquaporins and the tolerance mechanism against drought stress in plant is still unclear (Llorens et al. 2019). They may alter membrane hydraulic conductivity and improve water permeability 10- to 20-fold (Abbasi et al. 2015). Years have been spent studying aquaporins and plant water interactions. Mercury blocks aquaporins. Several studies on have revealed that the aquaporins shares an important role in total root water absorption (Grant 2012) and osmoregulation of root cells (Jang et al. 2013).

4.3.2 Stress Proteins

Production of stress proteins deals with stressors like water deprivation. Many of the proteins are water-soluble, they hydrate cellular structures to increase tolerance against drought stress (Farooq et al. 2009). The production of stress protein and factors involved in transpiration takes place during drought tolerance (Ahanger et al. 2016). Dehydration-responsive genes play a role in abiotic stress signaling. Hybrid plants might be made stress tolerant by altering DEB genes (Tiwari et al. 2021). A transcriptional factor that binds to a dehydration-responsive element boosted groundnut growth (Nakashima et al. 2014) and rice drought tolerance (Kudo et al. 2017).

4.3.3 Signaling and Drought Stress Tolerance

Redox signals, cell growth gates, and nucleotide sequences repaired pathways are all examples of general stress responses (Taylor et al. 2012). Stress sensing and activation of defensive and acclimatization pathways may include superoxide radicals, calcium, calcium-regulated enzymes, mitochondrial kinase pathways, and cross-walks between the transcriptional regulators (Son et al. 2012). Plant hormones, calcium, reactive oxygen species (ROS), and induced stress tolerance by activating genomic reprogramming (Brotherton and Joyce 2015). Mitogen-activated protein kinases are enzymes that link environmental stimuli to cellular responses (Tekle and Alemu 2016).

5 Drought Mitigation Strategy in Dry Lands

The most suitable plant genotypes and agronomic approaches may reduce drought stress (time of sowing, plant density, and soil management). This ensures that vulnerable crop stages occur during low-drought periods. Producing suitable plant types and improving high-yielding cultivars may be crucial to achieving this goal (Chen et al. 2016).

5.1 Selection and Breeding

Traditional breeding is yield based (Weber et al. 2012), quantitative variables having minimum heritability and significant interaction between genotype and environment are crucial in terms of yield (Almeida et al. 2013). Physiological and molecular knowledge may assist target yield-limiting characteristics. This may complement traditional breeding strategies and boost productivity (Jamil et al. 2018). Physical drought stress in the target area makes screening harder due to unpredictable drought responses. Underregulated stress and shelters for inclement weather, screening is easier. Natural stress response to selection is connected with controlled stress selection response (Dixit et al. 2017) Classical breeding focuses on progeny testing in many locations in conditions mimicking the target environment's drought stress variance (Prince et al. 2015).

5.2 Functional and Molecular Genomics

Approaches numerous abscisic acid- and strain proteins and transcription factors have now been discovered via molecular and biochemical studies during the 1990s (Xiong et al. 2006). Certain stress-responsive genes may reduce stress damage via unknown ways (Nakashima et al. 2014).

Transgenic expression of stress-regulated genes increases drought and other stress tolerance, according to lab and field research (Oddo et al. 2014). These transgenic methods are the standard for bioengineering crop drought tolerance (Subbaramamma and Manjusha 2017). Enhanced expression of these genes often causes growth retardation, limiting their practical use (Ye et al. 2016). Simpler and more sensitive approaches are needed to detect stress-responsive genomic networks. Whole genomics and associated technologies provide the capabilities to discover drought-responsive genes and connect their regulation to adaptive processes (Boyer et al. 2013).

5.3 Drought Resistance Induction

Various ways may boost drought resilience. Exogenous application of economic expansion and other chemicals have proven beneficial in the establishment of drought tolerance in several plants.

5.3.1 Priming of Seeds

Priming of seeds is a short-term, pragmatic way to reduce drought stress. Seed priming partially hydrates seeds, allowing metabolic processes related to germination to begin but not radical emergence (Jaleel et al. 2009). Priming of seed increases the rate of germination, consistency, and occasionally overall germination percentage (Farooq et al. 2017). This method reduces drought stress in several crop species (Jongen et al. 2013).

5.3.2 Plant Growth Regulators in Use

When applied foliarly, natural and synthetic plant growth regulators boost growth resistance to abiotic stresses. Gibberellic acid restores drought impact on hypocotyl length and weight. Gibberellic acid improves seedling hydration status and synthesis of proteins (Anjum et al. 2016). Under drought stress, gibberellic acid increased rate of photosynthesis, transpiration rate, and photosynthetic efficiency in silk (Singh et al. 2015) and pollination and fruit cone development in Coniferous trees (*Picea sitchensis*) (O'Brien et al. 2014). Drought tolerance can be increased by delaying senescence (Brown et al. 2015).

5.3.3 Application of Osmoprotectants

Mannitol, glycine betaine, proline, fructan, trehalose, and others are osmoprotectants in plants (Ma et al. 2012). They protect stressed subcellular structures and mediate osmotic adjustment (Omidi 2010). Not all plants accumulate enough of these chemicals to withstand drought (Nikalje et al. 2019). Traditional breeding and genetics are used to develop different cultivars having a natural ability to produce these compounds in large amounts in response to these stresses (Rehana and Naidu 2021); the exogenous application of these compounds produce tolerance ability against drought stress (Saleem et al. 2022).

In many agricultural plants, spontaneous glycine betaine accumulation is insufficient to mitigate dehydration from environmental abiotic stress factors (Ghatak et al. 2022). Glycine betaine improves drought tolerance exogenously (Shemi et al. 2021). Glycine applied foliarly increases the development of water-deficient plants by maintaining leaf hydration status and enhancing photosynthesis, principally owing to the higher efficiency of rubisco carboxylation and stomatal conductance (Kaushal and Wani 2016). Exogenous glycine betaine reduces the deleterious impacts of drought on sunflower achenes per capitulum (Jaganathan et al. 2015). Glycine betaine in the vegetative stage reduces drought damage (Ullah et al. 2021). Glycine betaine boosts antioxidative enzyme activity when dehydrated (Huang et al. 2017).

6 Conclusion

The growth and development of the plants are disturbed due to water stress. Duration, length, intensity, and development determine a plant water deficiency response. Enzymes involved in carbon absorption and ATP production are hindered by drought. The drought tolerance mechanism encompasses biochemical and physiological processes at different levels. Drought tolerance is aided by abscisic acid, cytokinins, salicylic acid, and ROS scavenging. Suitable plant varieties, seed anchoring, plant growth regulators, antioxidant capacity, and silicon may all help to alleviate drought stress. Further research is needed to establish the physiological basis of assimilating partitioning from source to sink, plant phenotypic plasticity that leads to drought tolerance. Exogenous glycine betaine, proline, and other suitable solutes act as drought tolerance inducers. Genomics, proteomics, and transcriptomics must be used to better understand plant drought tolerance and increase water-use efficiency. Mutant or transgenic plants with differing ROS generation and removal capacities might clarify this topic. Molecular data of mechanisms of response and tolerance might lead to drought-tolerant plants with high yields. Thus, it is concluded that use of aquaporin, application of fertilizers, and use of plant growth regulators minimize the drought stress effects and enhance crop productivity in drylands.

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Chapter 14
Climate Change and Nutrient Use Efficiency of Plants

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Abstract Modern agriculture faces significant challenges in order to secure crop production for an expanding population. Somehow minimizing the environmental impact of agricultural techniques. Moreover, the expenses involved with them, these all can be intensified by the high rate of abiotic stresses which can be imposed by climatic change. The agricultural use of land for crop yield can result in the extraction of soil nutrients on a continuous basis. Soil nutrient availability may decrease in the absence of adequate nutrient replenishment. Ultimately a decrease in the yield. Yield restriction could also occur as a result of relatively low nutrient levels in soils. It is of greatest importance to increase agriculture resilience to climate change by planned adaptation because climate change is likely to get across the issues of future food security due to exerting pressure on agriculture. As a result, in 2010–11, ICAR launched a significant network project, the National Initiative on Climate Resilient Agriculture (NICRA), to conduct planned research on mitigation and adaptation, fill critical gaps of research, illustrate technologies on farmers' fields to deal with contemporary climate change variability, and build the capacity of various stakeholders.

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1 Introduction

Seventeen elements or important nutrients are required by plants for proper growth and development. These nutrients may include copper (Cu), manganese (Mn), zinc (Zn), iron (Fe), boron (B), molybdenum (Mo), chlorine (Cl), and nickel. They also include hydrogen (H), oxygen (O), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and sulfhur (S). Additionally, cobalt (Co) is frequently mentioned as a crucial micronutrient in publications. Co increases plant growth in some cases, although it is not regarded as essential by Arnon and Stout (1939), who defined essentiality.

Essential nutrients can be defined as, those nutrients that are directly associated with plant metabolism that cannot be replaced by other elements and are necessary for plants to complete their lifespan (Fageria et al. 2002; Rice 2007). Epstein and Bloom (2005) have enlisted two requirements for the importance of nutrients. These requirements are; (1) the nutrient is a component of a molecule that is innate to a plant's structure or metabolism and (2) when the required nutrient is removed from the growing medium, the plant grows and develops irregularly as compared to a plant that is not. Plants absorb carbon, hydrogen, and oxygen from the air, as well as water and other essential nutrients from the soil solution (Javaid et al. 2022c). Within plant cells, each of these basic chemical components carries out a distinct biochemical or biophysical activity. Therefore, a deficiency in any of these nutrients can impair metabolism and prevent normal growth (Ahsan et al. 2018).

Nutrients are separated into macro- and micronutrients based on the quantity needed. Plants require a greater amount of macronutrients than micronutrients. Micronutrients are also known as minor or trace elements because their concentrations in plant tissues are minimal or trace in comparison to macronutrients. Because they constitute the majority of the proteins, lipids, and carbohydrates in plant cells, macronutrients have a higher quantity demand for plants, whereas micronutrients mainly help plants activate their enzymes.

Light, heat, and water must be supplied in sufficient quantities for plants to utilize these nutrients in an efficient manner. Crop production is also influenced by cultural practices and disease and insect control. Each plant is unique, with an optimal nutrient range and a minimum requirement level. Plants begin to exhibit nutrient deficiency symptoms below this minimum level. High nutrient uptake can also result in poor growth due to toxicity.

Therefore, the accurate amount of application and placement of nutrients is absolutely essential. To assess the nutrient content of soil and plants, soil and plant tissue tests have been developed. By analyzing this information, scientists can figure out the need for the nutrient for a given plant in a given soil. Aside from the levels of plant-available nutrients in soil, the pH of the soil also plays a significant role in nutrient availability (Javaid et al. 2022b).

1.1 Carbon, Hydrogen, Oxygen

The essential building blocks of carbohydrates, proteins, and lipids are carbon, hydrogen, and oxygen, which are also essential for nearly every metabolic process. The osmotic equilibrium is maintained by hydrogen, while respiration requires oxygen.

1.2 Nitrogen

As an essential nutrient for starch synthesis in leaves, the production of amino acids for the synthesis of proteins, and ultimately crop yield, N is one of the nutrients that crop plants fundamentally need for vegetative growth. P is an important factor of enzymes, cellular membranes, and nucleic acids. It is necessary for a number of different cellular functions, including signaling, redox-homeostasis, energy production, photosynthesis, and carbohydrate metabolism.

1.3 Phosphorus

P controls water content, lessens the negative effects of salts on plants, and activates more than 60 enzymes in plants. Sulfur is fundamentally necessary for the synthesis of amino acids such as methionine and cysteine, just as it functions as a cofactor or prosthetic group in the Fe-S center, S-adenosyl methionine, thiamine, and various primary and secondary metabolites (Wirtz and Hell 2006; Khan et al. 2010; Koprivova and Kopriva 2014).

1.4 Potassium

Potassium has a role in the metabolism of carbohydrates as well as the breakdown and transport of starch. Both photosynthesis and efficiency of water use are increased. It is required for protein production and is pivotal for fruit development. It switches on enzymes and regulates how quickly they react. It raises fruit and seed quality as well as winter hardiness. Additionally, it improves disease resistance.

1.5 Calcium

Calcium is used for ongoing cell creation and division. It helps to the metabolism of nitrogen. It reduces plant respiratory rate and speeds up the photosynthetic transfer from the leaves to fruiting organs. Fruit set is increased. It is necessary for peanuts to form nuts. Additionally, it enhances microbial activity.

1.6 Magnesium

One of the essential components in the formation of chlorophyll is Mg. It increases phosphorus's mobility and use. It is an enzyme activator and a part of numerous plant enzymes. It improves plants' ability to use iron. It affects maturity uniformity and earliness.

1.7 Sulfur

In the environment, sulfur is mostly found in oxidized inorganic forms. Most of sulfur in living things is found in reduced form of thiols and organic sulfur. S assimilation, which involves absorbing inorganic sulfate from the soil, converting it to sulfide, and producing a variety of biomolecules and this is only possible in plants, algae, fungi, and bacteria (Davies et al. 1996; Maruyama-Nakashita et al. 2004; Koprivova and Kopriva 2014).

1.8 Zinc

Likewise, Zn is essential for proper growth of plant because it effects various biological processes, such as cell division, P–Zn interactions, and glucose metabolism (Rehman et al. 2012). Only Zn is needed for all six kinds of enzymes (isomerases, hydrolases, oxidoreductases transferases, lyases, and ligases.) (Coleman 1998). Even though it helps to maintain the structural integrity of some regulatory proteins (Berg and Shi 1996), its high concentration is noxious to cells (Sresty and Madhava Rao 1999; Xu et al. 2013).

1.9 Copper

Several plant processes are catalyzed by Cu. Photosynthesis and the development of reproduction are two major functions. It indirectly contributes to the synthesis of chlorophyll. Fruits and vegetables' sugar content is raised, their color is intensified, and their flavor is enhanced. Like the majority of cations, copper primarily affects enzyme activity. There are a number of enzymes that are specifically impacted by copper deficiency.

1.10 Iron

Micronutrients such as Fe and Zn play an essential role in agricultural plant physiological processes. Despite the fact that they are only required at low levels. Chlorophyll production and chloroplast structure and function maintenance both require Fe. It is often more abundant in soil, but in aerobic and neutral pH settings, its bioavailability is restricted (Colombo et al. 2014).

1.11 Manganese

Manganese performs a specific purpose in a number of enzyme systems. It aids in the production of chlorophyll. Additionally, it makes calcium and phosphorus more readily available. Mn′s function in plant metabolism is not well understood. Manganese can replace magnesium in some enzyme systems because it has similar characteristics to magnesium.

1.12 Boron

Both biological processes and the formation of one of the RNA bases require the presence of boric acid. B has been determined to promote the growth of root. B is necessary for pollen tube growth and germination. B has been linked to lignin synthesis, enzyme activity, seed and cell wall formation, and transport of sugar.

1.13 Molybdenum

The least amount of all the necessary micronutrients is needed for molybdenum. In order to incorporate inorganic NO into organic N molecules, the enzyme nitrate reductase must be formed, which in plants lowers nitrates to ammonium. Mo shortage lowers nitrate reductase activity. It facilitates the development of nodules in legumes. It is necessary to transform inorganic phosphates into organic forms.

1.14 Chlorine

In some soils, chlorine increases the maturity of tiny grains while interfering with P uptake. There isn’t a lot of information available yet on its aim.

At every stage of plant development, a suitable ratio of each of these nutrients is required to optimum output. While plants only require modest levels of micronutrients like Fe, Zn, and boron, which are frequently cofactors in enzymatic reactions. Plants need a lot of P and N, which are essential nutrients since they are the components of basic biological compounds including nucleotides, amino acids, and proteins.

The majority of soils, however, lack one or more of these nutrients due to a variety of factors, such as sluggish diffusion rates, microbial activity in the rhizosphere, and the chemical and physical properties of the soil. Out of all the necessary elements for plants, P and N are the two that limit agricultural output, needing the application of significant amounts of fertilizer each year to increase crop yield.

2 Nutrient Uptake in Plants

The potential of roots to absorb nutrients and nutrient concentration at the root's surface are both factors in root nutrient uptake. For a plant, the primary surface for receiving different nutrients is its root system. The components of the root are mature zone near shoot and elongation zone near the cap or root tip. This elongation zone allows nutrients and water to freely flow into the xylem, the core of the root, and subsequently up into the shoot. A constraint known as a casparian strip makes it harder for nutrients to enter the root through the more established region of root. As a result, later in the growth season, nutrients in deep soil probably become more crucial, especially for deep-rooted plants. As plant grows, its roots expand out both laterally and vertically to access parts of the soil that contain more nutrients and water (Hussain et al. 2022).

2.1 Root (The Main Organ in Nutrient Absorption)

Organ of plant in vascular plants that exists naturally beneath the soil's top layer is known as the root. The radicle is the first root to emerge from a plant. The four main jobs of roots are to store food and nutrients, hold the plant body to the ground, absorb water and inorganic nutrients, and prevent soil erosion (Bouain et al. 2019). Roots also produce cytokinin in response to the concentration of nutrients, which serves as a signaling for how quickly the branches can grow. Food and nutrients are frequently stored by roots. Roots do not consciously move in the direction of a food source. The specific nutrient ion needs to be close to the root for nutrient uptake to happen. One or more of three processes can locate the nutrient ion.

2.1.1 Mass Flow

As water is absorbed, the soluble portion of nutrients that are in the ground water and aren't retained on to the soil component pass to root. The usual method of supplying nutrients like calcium, sulfhur, and nitrate-N is mass flow.

2.1.2 Diffusion

This generates a gradient in the soil solution, enabling nutrients to move from a highly concentrated zone to a low solution next to root. Most of the potassium, phosphorous, and zinc traveling to root for absorption is caused by diffusion. Plants take mineral and water substances from soil through their roots. These are the raw resources that plants use to produce not only food for themselves but also the majority of the world's food supply, together with CO_2 that is drained from air.

2.1.3 Mobility

The translocation of a nutrient within the plant system is determined by its property. Mobile nutrients such as K, P, N, Fe, and Mg are transferred from old leaves to new regions of growth in all circumstances. Under certain circumstances, Changeable mobile nutrients such as S, Zn, Mm, and Cu are moved from older leaves to the new growth zones. The xylem facilitates the relatively effortless movement of all nutrients from the root to the vegetative section of the plant.

It's interesting to note that, in cases of nutrient deficiency, some of the nutrients can also be migrated from older to younger leaves. When diagnosing nutrient deficits in plants, understanding the nutrients which are mobile (i.e., able to travel) is extremely beneficial, since if only lower leaves are harmed, then mobile nutrient is most probably the source of the problem. On the other hand, if just the higher leaves exhibit the deficiency, the plant is probably lacking a nutrient that cannot transfer from older to newer leaves. Depending on the level of insufficiency, sulfur is one of the elements that is both mobile and immobile.

2.2 Cell Membrane as the Site of Nutrient Transport

Knowing the process of nutrient absorption by plant roots requires an understanding of the structure of cell membrane. The membrane's structural layout only allows for the transportation of nutrients through integral membrane proteins. The specificity with which these transport proteins identify the molecules and ions for transport is strikingly similar to that of enzymes. H+ ATPase, an ATP hydrolyzing enzyme attached to the membrane, acts as the motor for the transport mechanism. The required mechanism is already established.

2.3 Nutrient Transporters

The absorption and the transport of mineral ions and water is one of the oldest issues in physiology of plant, and various studies have described these activities at both organ levels and whole plant (e.g., with excised roots). Later research used electrophysiology and extracted membrane vesicles to define membrane transport mechanisms. The plasma membrane is impermeable to some units due to its selective permeability property.

As a result, specialized proteins known as transporters are present to assist their entry through the plasma membrane. The ability to analyze transport mechanism in higher detail and to start understanding the connection between process of ion uptake that had frequently been identified at organ level is made possible by the latest cloning of genetic makeup for a vast number of transport proteins, as well as the accessibility of knockout mutants. Essential ions and metabolites must enter the cell through a selectively permeable barrier called the plant cell's plasma membrane (Fig. 14.1).

It enables cytoplasm to maintain intracellular homeostasis along with the vacuolar membrane (tonoplast). In order to maintain the cytosolic pH 1–3 units higher than that of cell outside or vacuole, which are predominantly composed of phospholipid bilayers with transmembrane proteins, must be able to pass through water, ions, and metabolites. Pure phospholipid bilayers are almost impermeable to the inorganic ions and other hydrophilic solutes like amino acids and sucrose, but permeable to gases like O_2 and CO_2. They are slightly water permeable. Organic solutes, inorganic ions, and protons must be delivered at high enough rates through plasma membrane and tonoplast to satisfy the cell's needs. Transport proteins of many sorts are present in membranes, including cotransporters, channel proteins, and ATPases or ATP-powered pumps (Lalonde et al. 1999; Sze et al. 1999).

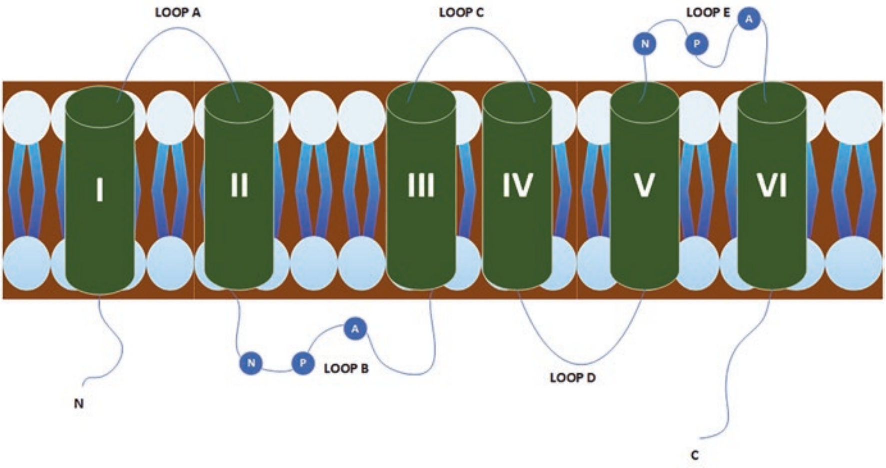

Fig. 14.1 Plasma membrane, as the site of nutrient transport (He et al. 2021)

Several separate groups of controlled transport activities have been identified by physiological study of ion uptake by roots of plant. These actions were divided into two mechanisms in Epstein's initial paper from 1966. H^+-ATPases in plant cells move protons across the tonoplast or plasma membrane to acidify the vacuole or extracellular matrix, correspondingly (Sze et al. 1999). The transport of ions and water along effectively advantageous ascent is facilitated by channel proteins.

3 Nutrient Use Efficiency

In the coming century, global warming is likely to occur, which will have an influence on crop productivity and food security. It is currently important to enhance the potency of agricultural land by using fertilizer resources for uses of crops (Handmer and Dovers 2012; Solomon et al. 2007). It is necessary to increase the availability of a nutrient in developing countries (Graham et al. 2001; Graham 2007). These challenges further underscore the need for NUE and the importance of plant nutrition in guaranteeing the sustainability of agriculture. To maintain food safety, agricultural output demands must rise (Cordell et al. 2009).

Additionally, the soil on agricultural lands lacks essential minerals for plant productivity (Lynch and Clair 2004). The usage of fertilizer is responsible for the increase in production. Furthermore, it has been claimed that the pace of fertilizer application directly affects crop output. If more fertilizer is applied than what the crop needs, it will be wasted through runoff and result in lower NUE (Vitousek et al. 2009).

However, climate change has an influence on nutrient inputs and activity owing to changes in wind patterns, temperature, sea level rise, and the hydrological cycle (Statham 2012; Raza et al. 2019). Nevertheless, certain agricultural lands continue to have severe nutrient deficiencies, which have a negative effect on agricultural output. The management systems used and the creation of novel strategies to deal with production failure are necessary for NUE improvement (McDonald et al. 2015).

NUE was defined by Ortiz-Monasterio et al. (2001) as the quantity of plant growth produced per unit of fertilizers or nutrient applied to the field. It consists of two components: first, a plant's ability to collect nutrients from the soil via its roots; and second, the plant's ability to extract these nutrients into grain, also known as utilization efficiency (Mcdonald et al. 2013). A physiological process known as plant nutrition involves plants absorbing and utilizing mineral element from the soil. These nutrients are utilized by the plant throughout its growth and development. While these elements are considered plant nutrients, the process is referred to as plant nutrition. As a result, only 60 of the 118 nutrients available to plants are actually used by them.

4 Factors Effecting Nutrient Uptake in Plants

Various steps occur in soil–plant system before a nutrient is taken or used by plant to make it available to plants. These include supplying nutrients to the soil or utilizing nutrients already present in the soil, moving nutrients from the earth to plant roots, having plant roots absorb nutrients, moving nutrients to plant tops, and lastly using nutrients produced by plants to produce useful parts or organs (Waheed et al. 2019). Climate, soil, and plant conditions, as well as their interactions, have an impact on all of these processes (Javaid et al. 2020).

Even within the same location, these elements differ from one place to another. As a result, the process of making nutrients available to plants is exceedingly complex and dynamic. However, figure provides a summary of biological, physical, and chemical changes that take place in rhizosphere and have a considerable impact on nutrient accessibility is given in Fig. 14.2. For a more comprehensive study on the topic, readers may look to the work of (Fageria and Baligar 2005; Epstein and Bloom 2005; Fageria and Stone 2006).

Food plant agriculture is necessary because of the world's rising population. Agriculture presently consumes more than 70% of fresh water worldwide (86% in developing nations), and it is predicted that this consumption will rise as the planet's climate gets drier and warmer in overall. As a result, it is crucial to comprehend the molecular processes underpinning plant drought stress response

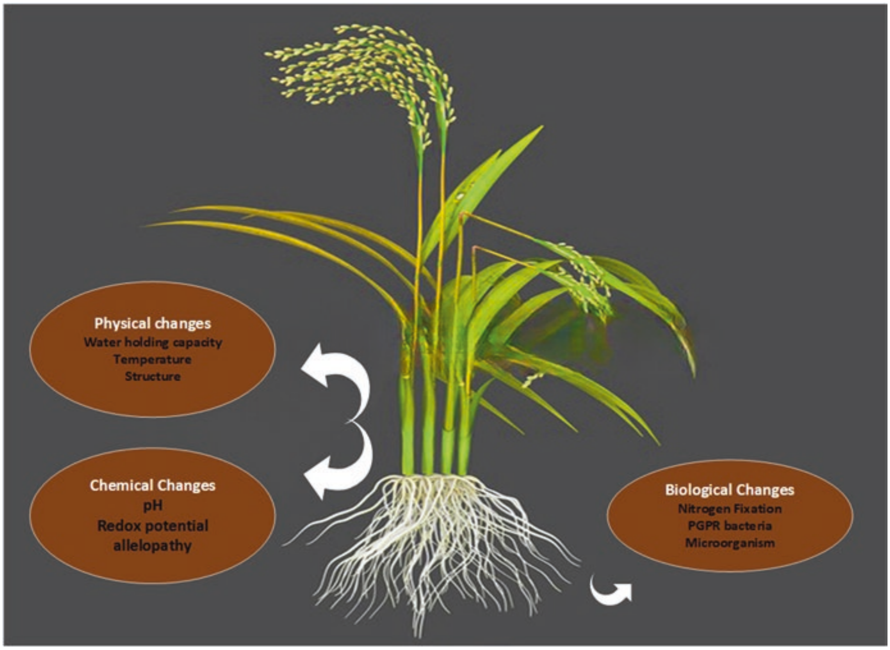

Fig. 14.2 Physical, chemical, and biological changes in the rhizosphere (Fageria and Stone 2006)

and to develop drought-resistant crops. Plant molecular biologists have discovered how plants respond to water stress by creating the phytohormone abscisic acid (ABA), reprogramming gene expression, adjusting osmotic pressure and closing stomata, ultimately resulting in adaptive growth and development, over the past 20 years.

4.1 Climate Change

Globally, the amplitude and regularity of utmost temperature (high and low temperatures) are increasing due to climate change. Crops subjected to unfavorable temperatures experience stunted development and growth, which limits their ability to be grown and lowers crop output (Javaid et al. 2022a, d).

4.2 Temperature Stress

Cellular membrane fluidity can be affected negatively and positively by cold and heat, respectively (Falcone et al. 2004; Zhu 2016). Calcium (Ca^{2+}) channels and receptor-like kinases (RLKs), which are membrane-anchored proteins, may be able to detect this shift in membrane fluidity (Gong et al. 1998; Zhu 2016). In mammalian cells, transient receptor potential vanilloid channels (TRPVs) have been shown to detect temperature stimuli (Venkatachalam and Montell 2007); however, no terrestrial plant homologs of these receptors have been found. Instead, it appears that several kinds of Ca^{2+} channels contribute to the signaling of temperature stress in plants (Ikram et al. 2019).

4.3 Salinity Stress

A big problem affecting worldwide land use and food production is soil salinity. According to estimates, salinity has an impact on about one-fifth of the world's irrigated farmland (Morton et al. 2019). Large tracts of marginal land, including coastal regions, are also unsuited for crop development. The growing food needs of the human population could be lessened if these saline soils were used to grow crops (Tanveer et al. 2014). However, because most crops are glycophytic and sensitive to salinity, it is not possible to cultivate the cultivars that are currently utilized on these saline soils (Ali et al. 2013).

5 Climate Change Impact on Agriculture

The frequency of stress intervals, their influence on day-to-day life, and damage to agricultural crops are the key metrics used to evaluate the effects of climate change and environmental variation. Due to the fact that poor environmental conditions primarily affect agricultural yield in developing nations, intense temperatures, and excessive CO_2 buildup led scientists to discover novel solutions to less foreseeable problems (Rosenzweig et al. 2014). Food security is impacted by climate change in a very complicated manner (Hassan et al. 2021).

It reduces agricultural production both directly by altering the agro-ecological environment and indirectly by placing pressure on economic growth and distribution, which in turn increases demand for agricultural products. Several methods have been used to calculate the effects of climate change on food security (Intergovernmental Panel on Climate Change; IPCC 2007).

5.1 Impact on Crop

Abiotic stressors from both ways directly or indirectly have severe effects on plant productivity and are aggravated by sudden changes in environmental circumstances. As a result of the continuous destruction of forests and wasteful fossil fuel consumption, the environmental CO_2 content has risen from 280 to 400 μmol^{-1}. At the end of this era, the CO_2 concentration is predicted to increase by two, or up to 800 μmol^{-1}. The major causes of the earth's climate and rapidly increasing global average temperatures are toxic gases emitters, especially CO_2 (Vaughan et al. 2018).

Drought stress impacts wheat at every phase of its development, while kernel formation and reproduction are the most important. Wheat production declined under minor drought conditions at the flowering stage from 1% to 30%, but climbed to a maximum of 92% under extended moderate stress conditions during blooming and grain development (Araus et al. 2002; De Oliveira et al. 2013).

Drought has significantly impacted the productivity of vital legume crops. Stress has been recorded to have a 26% reduction in mash bean (*Vigna mungo* L.) output throughout the reproductive phase and a 31–57% reduction in the flowering phase (Baroowa and Gogoi 2014). Maleki et al. (2013) described that drought conditions significantly reduced soybean output, with a 42% decrease seen when the grain is being filled.

According to Schlenker and Roberts (2009), corn productivity is enhanced at an optimal range of 29 °C, but it decreased as the temperature rose. It was discovered that every 1 °C increase in warmth had a detrimental effect on corn yield. Similarly, it was discovered that for every 1 °C rise in heat over the ideal growing temperature, maize output reduced by 8.3% (Lobell and Field 2007). According to Brown and Plan (2008), every 1 °C increase in heat caused a 10% reduction in wheat yield. According to another study, every 1 °C rise in temperature is another reason for a 3–4% decrease in wheat output (Ray et al. 2015).

5.2 Impact on Plants

Plants frequently face a variety of stresses in the framework of the natural climate, such as waterlogging, drought, temperature, frost, and saltiness (Ashraf et al. 2018; Benevenuto et al. 2017). Additional abiotic factors that increase stress involve UV-B light illumination strengths, storms, greenhouse emissions, and both chemical and physical issues (Suzuki et al. 2014). Crop production is impacted by climate change through direct, indirect, and socioeconomic effects. According to Boyer (1982), the crop output has decreased by up to 70% due to atmospheric conditions.

Plants are suffering from certain climatic conditions that are limiting their capacity to successfully adapt in a variety of ways due to the high environmental variability (Zain et al. 2017). Plant movement is not the answer to this issue because there have been more periods of rainfall and temperature. Nevertheless, alterations to plant internal functions have proved advantageous in particular atmospheric situations, but climatic change might be dangerous for flora's (Becklin et al. 2016).

Abiotic stresses have significant influence on morphology of plant's, biology and biochemistry. Despite the fact that plant physiology responses are anticipated to spread swiftly with only slight variations in fruiting and blooming under anticipated weather conditions in the future (Damatta et al. 2010; Jan et al. 2016). 10–35 °C is the best temperature range for plant development.

When temperatures are raised to a certain amount, plants are able to produce excess energy, but when temperatures rise more, plant development is slowed and photosynthesis rates fall below lethal levels (Tkemaladze and Makhashvili 2016). Lack of water affects the function of the photosynthesis enzymes, lowers metabolic capability, and eventually destroys the photosynthesis mechanism (Zargar et al. 2017).

5.3 Impact on Plant Nutrients

The physiological functions of plants are temperature sensitive (Jamieson et al. 2012). Increased photosynthetic and respiration rates tend to increase with the increase in heat along with a range predicted by atmospheric change (IPCC 2014), enhancing plant developmental ratio and perhaps changing nutritional ratio in plant cells. In fact, certain species of plants experience an increase in protein content with rising temperatures (Dong et al. 2001; Domisch et al. 2002).

Because high temperatures (35–408 °C) increase respiration and reduce photosynthesis, these effects can also be nonlinear, resulting in slower plant growth rates (Norby and Luo 2004; Rennenberg et al. 2006). High temperatures can also decrease seed lipid content by up to 41% and frequently cause decreases in foliar carbohydrate levels (Williams et al. 1995; Zvereva and Kozlov 2006). Such impacts differ in sign and extent according to the variety of living organisms, kind of environment, and warming mechanism; therefore, they are not all equally prevalent (Weih and Karlsson 2001; An et al. 2005).

5.4 Water Availability

As climate change progresses, the amount of precipitation is not anticipated to alter globally uniformly (Javaid et al. 2022d). But a common pattern in many terrestrial ecosystems is an increase in the frequency of droughts, which now affect twice as much worldwide land as they did in 1970 (Jamieson et al. 2012). In drought-stressed plants, carbohydrate levels and protein concentrations typically rise due to lowers osmolarity and enabling plants to retain more water (Dijkstra et al. 2012; Yuan and Chen 2015).

Additionally, as drought stress increases, leaves typically lose some of their relative water content (English-Loeb et al. 1997), which may make it harder for plant dependents to get benefit from an increase in foliar protein (Huberty and Denno 2004; Scriber 1977). However, the impact of drought on plant nutrition varies by species, tissue type, growth stage, severity of the drought, and length of the drought (Kreuzwieser and Gessler 2010; Lenhart et al. 2015).

5.5 Carbon Dioxide

Elevated photosynthesis and respiration at the leaf level can be quickly impacted by rising atmospheric CO_2 levels, and these changes typically lead to an increase in foliar carbohydrate content over time (Stiling and Cornelissen 2007; Robinson et al. 2012). Additionally, although C_4 plants are less sensitive than C_3 plants, typically, rising CO_2 induces a decrease in the proportion of total protein in upper parts of plant (Yuan and Chen 2015; Ziska et al. 2016).

This occurs as a result of plants moving protein distribution from topsoil to ground plant organs (Cotrufo et al. 1998) and in leaf tissue, Rubisco proteins are dysregulated (Stitt and Krapp 1999; Leakey et al. 2009). Moreover, increased CO_2 concentrations might diminish seed concentration by more than 19% (Williams et al. 1995).

6 Impact of Climate Change on Nutrient Use Efficiency of Plants

6.1 Background

The quality and amount of plant nutrients are being significantly impacted by both direct and indirect climate change, which is endangering plant growth and productivity. It highlights the known data on the nutrient ratio in eatable plant components and the influence of atmospheric changes on plant nutrition. It focuses on the impact of stressors such as salt, waterlogging, drought, and increased CO_2 (eCO_2), as well as what we learn about their impact both directly and indirectly on nutrient supply (Javaid et al. 2022a).

The buildup of minerals and proteins in crop plants is impacted by climate change, and eCO_2 is the primary cause of the most of the remarkable changes. Type, severity, and length of the induced stress, genetics of the plant, and the phase of development all clearly influence the outcomes. All climatic variables and soil nitrogen (N), potassium (K), iron (Fe), and phosphorous (P) supply exhibit powerful bonds (both +ve & −ve) (P).

Different molecular functions, developmental processes, morphological traits, and fundamental physiological responses of plants are impacted by climate change in different ways. It is well known that eCO_2 boosts photosynthesis, which in turn enhance plant development and production while frequently increasing the efficiency of crop water consumption (Han et al. 2015).

Furthermore, greater plant development and growth in the presence of eCO_2 is in contrast to decreasing responses in seed trait that is being noticed along a variety of plant. That shows eCO_2 alters the balance between plant mineral absorption, carbon activity, and nutrient utilization effectiveness. Micronutrient deficits are a significant people related health issue with detrimental effects on both health and nutrition (Anandan et al. 2011).

Nutritional deficits in zinc (Zn) and iron (Fe) have drawn a great deal of attention recently, particularly in underdeveloped countries in which sizable fraction of the population relies on nutrients which are obtained from legumes and kernels (Myers et al. 2014). Micronutrient deficiencies have an effect on plant development and outcome by restricting the expression of precious energy or biosynthetic and metabolic pathways (Grusak 2001). Thus, plants that experienced vitamin deficiencies are typically more susceptible to abiotic stressors.

By contrasting edible crops in two various East African areas, Fischer et al. (2019) investigated the impact of nutritional deficiency buildup. Nutrient concentrations decreased in a result of severe drought, but increased due to a mild water stress. This demonstrates that the impacts on nutrient accumulation rely greatly on both the type and intensity of climatic change. The mineral contents of vegetables and legumes were significantly altered by water stress (Wijewardana et al. 2019).

Complications associated to soil waterlogging brought on by either natural or human sources, like extreme watering and poor sewage system, are another sign of a changing climate (Smethurst et al. 2005). Wei et al. (2018) explained that waterlogging decreases the quantity of O_2 that is available on the land surface, increasing the risk of phytotoxins building up, leaf chlorosis, and stomatal closure, and limiting crop yield by reducing land nutrient availability (Ashraf 2012).

Without alleviating and altering plans, the modification will eventually have a cumulative impact. As the outcome of enough and nutrient-dense food will face significant challenges from climate change in the coming decade which has resulted in the long-term escalation of agricultural systems (Pretty et al. 2018).

7 Climate Resilience

All agricultural sectors—agriculture, forestry, and fisheries—are already being impacted by climate change, which is decreasing output capacity and raising production risks. Because of their unique geographical characteristics, significantly vast communities, and the predominance of farming in their economies, most emerging nations are extremely sensitive to climate change. It is anticipated that millions of people in these nations would experience historic agricultural losses due to climate change (Kang and Banga 2013).

Food insecurity, poverty, and climate vulnerability are all closely related. Protests have been caused by a lack of food in nations on every continent. Only agroecosystems with significantly improved biological adaptation can contribute to raising agricultural productivity levels and supplying enough food in the future (Folke et al. 2004). Even today's production systems, which have fluctuating yields and produce less, are more fragile, inefficient, and shock-resistant than they should be. In order to determine how vulnerable systems reliant on particular crops are, several studies have looked at how sensitive such crops are to predicted climate changes.

Resilience is a system's capacity to withstand stresses and return to regular operation as soon as the global factors recover. Systematic adaptability is required to boost crop production's resistance to change in the atmosphere. Management strategies that boost farming productivity under poor environmental conditions appear to help in climatic change by enhancing flexibility and decreasing yield gaps in changeable climates and acute events.

8 Climate Resilient Technologies

Creating cultivars that are temperature and saline tolerance, as well as rainfall and drought resistance are some potential adaptation strategies, as are altering agricultural production strategies to bring betterment in water management, implementing modern agriculture methods like resource conserving technologies (RCTs), diversity of species, strengthening pest control, improving crop coverage and meteorology, and utilizing farmers local academic know-how. In light of the anticipated difficult climatic circumstances brought on by climate change, some potential ways to boost plant productivity and yield include, among others:

- Increasing resistance to multiple stresses, with a focus on various climate scenarios when crops are simultaneously exposed to heat, dehydration, saltiness, storm, and excessive CO_2 levels, and disease invade. Understanding the exact anatomy, metabolic activity, and transduction systems included in crop management will be necessary for this job, as well as knowledge of the interactions both beneficial and detrimental between various stresses. For this ambitious goal to be accomplished, ongoing collaboration and open multidisciplinary crosstalk between many academics will be essential.

- Increasing interactions between plant microbiota in the root exudates, phylosphere, and endophytes as well as by designing the root systems, microscopic pores, tissues, and biochemical and regulation processes. Genetic analyses of plants and microbiomes along with in-depth metagenomic studies and visualization might be crucial in this regard.
- Enhancing plant growth and grain germination in stressful circumstances. The ability of flowers to withstand heat and dehydration as well as the distribution of photons from leaves to flowers could be improved in order to accomplish this goal. Given that temperature was discovered to have a negative impact on blooming and fertilization, particular attention must be paid to heat stress.
- By reducing photorespiration and increasing the number of photosynthetic proteins, it is possible to increase the efficiency of photosynthetic light absorption and CO_2 assimilation. This objective also includes maximizing light absorption by a larger area of the plant canopy and modifying leaf pores and density control phenomenon.
- Artificial biology, nanoparticle technique, chemicals, and sophisticated intelligence systems will be used to build and integrate novel defensive and acclimatization approaches, which are not clearly active in plant genomes, into our toolset of climate change adaptation strategies.
- Establish, integrate, and enhance the usage of accuracy techniques that will allow farm owner to immediately begin reducing certain effects of climate change in their fields.
- This objective covers advances in robotics, drone, and imaging technology as well as the creation of novel irrigation and chemical application techniques. Environmental scientists, plant biochemists, microbiologists and physicists, veterinarians, economists, paleontologists, technologists and software engineers, bioinformaticians, and several other experts from around the world will need to work more actively together to develop these future technologies. Although there is a long and difficult road ahead, “climate time” has arrived.

9 Conclusion

Plants that are efficient in absorption and utilization of nutrients greatly enhance the efficiency of applied fertilizers, reducing cost of inputs, and preventing losses of nutrients to ecosystems. Inter- and intraspecific variation for plant growth and mineral nutrient use efficiency (NUE) are known to be under genetic and physiological control and are modified by plant interactions with environmental variables. There is need for breeding programs to focus on developing cultivars with high NUE. Identification of traits such as nutrient absorption, transport, utilization, and mobilization in plant cultivars should greatly enhance fertilizer use efficiency. Climate-resilient technologies are promising tool to guard a farming system from climate variations. Impact study of these technologies is a prerequisite for guiding the adaptive research for better customization, for upscaling, and out scaling them.

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Chapter 15
Conservation Tillage for Sustainable Agriculture

Tahreem Arshad, Maria Naqve, Asif Mukhtiar, Muammad Mansoor Javaid, Athar Mahmood, Muhammad Ather Nadeem, and Bilal Ahmad Khan

Abstract Remarkable structural changes take place in the community due to different modes of distribution occurring in the root zone diazotrophic community because of tillage. The transformation of conventional tillage system concealed a significant concentration of soil organic carbon. One of the most important purposes of agricultural conservation is to ameliorate the growth and development of plant along with soil structure and without any damage to the environment. The conservation tillage systems is the basis of conservation agriculture for conserving the resources and to increase the crop yield without compromising the soil structure, soil health, and sustainability of crop system. The conservation tillage can be defined as a crop system resulting in the conservation of natural resources and the sustainability of agricultural system regarding the applications of agricultural instruments and other practices that ensures the conservation of soil and water as economically viable, technically appropriate, socially acceptable, and environmentally nondegraded. Cultivation tillage promotes the temperature of soil against the conservation tillage systems. However, CT improves the concentration of C: N ratio, nitrogen, potassium, phosphorus, and the plant yield while at the same time it lowers the pH of soil. The decayed

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crop residues enable the conservation tillage to promote the soil structure and health and have many ways to reduce compatibility. It was reported that shifting from conventional tillage to the no-tillage resulting in C sequestration rate of 367–3667 kg CO_2 ha^{-1} $year^{-1}$. The CT promotes pathways of worms and suppressing the macro porosity. The weeds population is also controlled by the application of agricultural practices with CT.

Keywords Organic carbon · Conservation · Crops · Agriculture · Root zone

1 Introduction

In order to produce crops, the soil must be mechanically functioned, which has a substantial impact on soil properties like evapotranspiration, water retention, soil temperature, and infiltration (Leskovar et al. 2016). Ploughing intentionally alters the soil in order to grow crops, which has an influence on the environment. With increase in population, food demand increases and requires the use of greater land for food production (Fernandez et al. 2010; Ali et al. 2013). In order to meet rising demand, production gains must be sought out while minimizing soil degradation and preparing land to act as a sink rather than a source of air pollution. As a result, conservation tillage has become a feasible way to assure continuous supply of food and protect environmental sustainability. It can be used in conjunction with complementary strategies like crop diversity and soil cover (Corsi et al. 2012). It shows the relationship between the conservation tillage and conservation agriculture (CA). The CA is helpful in maintaining the ecosystem and increasing the production likewise increasing the livelihood for people and conservation of natural resources (Corsi et al. 2012; Javaid et al. 2022). Three fundamental tenets for CA are crop variety, permanent organic cover, and mechanical disturbance of soil. An ecological method of managing soil surface and preparing seedbeds is conservation tillage. When done according to the CA principle, replacing conventional tillage with conservation tillage may improve structure of soil, reduce temperature fluctuations, and improve soil quality and its ability to regulate the environment. An essential and renewable resource is crop residue. Crops residues should not be removed, burned, or ploughed under since these actions can hasten erosion, deplete soil fertility, and cause environmental contamination when they are burned. Soil may be protected from rainfall and sunshine by crop remains, soil aeration, and water circulation are improved by conservation tillage (Yvan et al. 2012). Therefore, the purpose of this chapter is to investigate how conservation tillage affects the soil, crops, and overall environmental impact (Yvan et al. 2012). This might give land users and other farmer's knowledge about the benefits of conservation tillage approach for sustaining crop output increase with little harm to the ecosystem and soil.

2 Types of Conservation Tillage (CT)

The conservation tillage is a broad term including different tillage techniques, such as minimal-till (MT), no-tillage (NT), counter tillage (CnT), ridge tillage (RT), and mulching. In NT soil disturbance is negligible and occurs only during the time of crop planting. Minimum soil is the cultivation of soil with little to no soil manipulation, usually through ploughing with primary tillage tool (O'Brien et al. 2022). Mulch tillage involves preparing or tilling the soil, which allows plant wastes to cover up the soil surface. But in case of ridge tillage, plants are sown in rows either on top or along the ridges. CnT is carried out in a straight angle to the slope.

3 Conservation Tillage and Soil Properties

Tillage effects are visible on biological, chemical, and physical qualities though in varying magnitudes. Soil erosion and runoff are two additional impacts of tillage on soil ecosystem (Derpsch et al. 2014).

3.1 Soil Physical Properties

Conservation tillage affects the soil characteristics in different ways which vary depending on the system used. The NT system has dramatically altered the soil properties, especially in the first few millimeters, which intact the high coverage of soil surface (Busari et al. 2015). With no tillage system, soil physical qualities are typically better than with tillage-based one (Stavi et al. 2011). Several studies have demonstrated that because of pore continuity, NT significantly improves saturated and unsaturated water conductivity (Pelosi et al. 2014) with the aid of limited numbers of larger pores (Ramzan et al. 2019). The NT technologies have helped in reducing the erosion losses, disturbance in crop residues, soil reducing, and moderate soil evaporation (Reicosky 2015). No-tillage is more beneficial for arid regions than water saving. It has been found that more water is retaining in untilled plots than in tilled plots (Kargas et al. 2012). The MT results in an increase in the storing holes (0.5–50 mm) due to which the soil porosity by increases (Valboa et al. 2015). The topsoil under no-tillage contains higher moisture content than it does after ploughing (Blanco-Canqui et al. 2017).

3.2 Soil Chemical Properties

Tillage practices effect the chemical characteristics of soil such as exchangeable cations and pH, etc. (Furtak and Gajda 2018). When using the no-till method, the surface layer's soil chemical characteristics are typically better than when using the tilled soil (Matloob et al. 2015). The soil's structure and chemical qualities, especially the soil organic carbon (SOC) content, increase by NT, which refers to the use of the no-tillage system on an ongoing basis over a lengthy period of time. Plant residues remain on the soil during annual no-tillage increase the organic contents in the soil (Crittenden et al. 2015; Tanveer et al. 2012), and NT-treated soil has a substantially greater SOC than untilled soil (Puget and Lal 2005). Additionally, less total nitrogen loss was seen with NT compared to CT (Somasundaram et al. 2017). By deterioration of the soil structure after tillage, higher mineralization or leaching rates may be to blame for the decrease in organic carbon and total nitrogen beneath tilled plots. Though no-till systems have been demonstrated to have lower soil pH than CT, tillage technique never effects soil pH (Wortmann and Dang 2020), and NT plots had significantly higher soil pH levels than tilled plots did (Roper et al. 2010). Soil pH may not be directly impacted by tillage, but it may be impacted by other factors such as soil type, management practices, and the local climate. When compared with the ploughed soil, exchangeable cations were significantly greater when soil is subjected to no tillage (Abu-Hamdeh et al. 2019). The minimum levels of soil organic matter, nitrogen, phosphorous, potassium, calcium, and magnesium were found in traditional till plots, which are related to leaching as well as upper soil inversion after plowing, which results in less fertile subsoil to the surface (Fig.15.1; Mitchell et al. 2019). Zero tillage soil in southwest Nigeria had a significantly

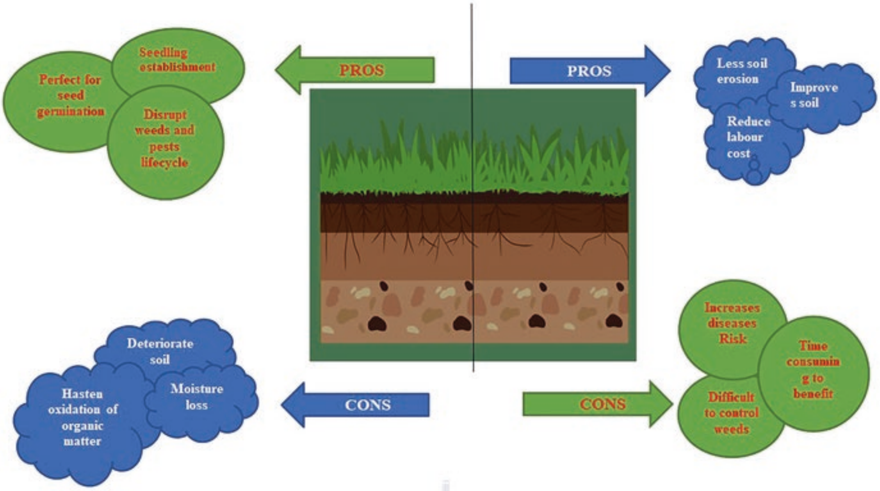

Fig. 15.1 Depicting the comparison of the physical characteristics between tilled and non-tilled soil (Mitchell et al. 2019)

higher pH at the end of the first year following tillage, but that the pH had dramatically decreased compared to CT soil by the end of the second year following tillage (Busari and Salako 2013).

3.3 Soil Biological Properties

The SOC content is the biological component of soil that is most impacted by tillage (Sutherland et al. 2017). The activities of soil organisms are significantly being affected by the soil organic matter, and these activities in turn affect SOC dynamics. Earthworms make up a significant portion of the soil as macro fauna improving the dynamics of soil fertility because their burrowing activities increase soil aeration and water infiltration. A plough less tillage study has shown that tillage practices have an impact on the number of earthworms (Roper et al. 2013). Earthworm populations were shown to be substantially higher under no-till soil during the course of a six year (Kakabouki et al. 2014). Less intensive ploughing boosted the activity of surface-feeding earthworms (Gómez-Rey et al. 2012).

3.4 Residue Distribution Within the Soil Profile

The stratification of the soil strata varies depending on the type of tillage practice. The surface, topsoil, and subsoil layers are the three divisions of the soil. The seedbed is corresponding to the top layer. Crop remnants are found in a tilled layer that ranges in thickness from 5 to 40 cm (Picone et al. 2002; Balal et al. 2014). Shallow ploughing is the minimal tillage technique that leaves the fewest residues on the surface. Additionally, compared to chisel tines, disc harrows contain more crop leftovers. The primary effects of various tillage techniques on seedbed quality result from modifications in crop residue thickness, inversion depth, and mixing intensity brought on by the implement. The degree of residue breakdown, such as straw length, affects how much residue is incorporated (Shahid et al. 2015).

3.5 Chemical and Biological Properties

Depending on the interactions with climate and soil type, the amount of soil organic matter in the entire topsoil varies (VandenBygaart and Kay 2004). Soil organic matter and activity of microorganisms are stratified in the soil profile in conservation tillage in accordance with the depth at which crop residues and manures are buried (Needelman et al. 1999; Balal et al. 2016). However, numerous writers have demonstrated that varied tillage strategies do not significantly improve the overall amount of soil organic carbon (C) in the topsoil as a whole. Comparing conservation tillage to conventional tillage, organic C, SOM, and level of soil microorganisms enhance in tilled layer while remaining constant or decreasing in the layer underneath. However, in conservation tillage, there is an increase in concentration in the topsoil (also known as the tilled layer), rather than a significant increase in the topsoil as a whole (Lognoul et al. 2017). Additionally, the authors thought that soil NO_3 was susceptible to denitrification loss, especially in moist, fine-textured soils. However, compared to traditional tillage, less N is anticipated to be lost through runoff and leaching (Veras et al. 2016).

3.6 Aggregate Stability

Reduced soil erosion is one of conservation tillage's primary goals (Blubaugh and Kaplan 2015). With conservation tillage, soil organic matter is concentrated on the soil surface and, in particular, organic matter promotes microbial activity and increases the stability of soil aggregates and enhances soil structure (Miller et al. 2019). Similar to this, fungal hyphae, which are more prevalent in the soil surface in conservation tillage, are crucial for stabilizing and aggregating soil structure. Additionally, crop remains on the topsoil prevent crusting on the upper surface in the absence of tillage (Rücknagel et al. 2017). This increased penetration rate that tends to increase aggregate stability, which in turn leads to reduced runoff consisting dissolved nutrients and adsorbed phosphorus (Javaid et al. 2021). In order to maintain the structure of the soil, organic matter is crucial. Soil composition in more than 90 arable areas that were managed using organic and conventional methods (Abdollahi et al. 2015). The structure of the soil improves with the addition of organic matter than the conventional soil (Javaid et al. 2022). For fine-to-medium textured soils, it takes around 3–5 years after the adoption of conservation tillage to enhance the fertility of the top soil layers (Kadžienė et al. 2011).

3.7 Compaction

Topsoil and subsoil structures can deteriorate due to compaction, which is mostly brought on by vehicular traffic, tillage method, and grazing intensity as well (Mcleod et al. 2016). Compaction is of following types: (1) short-term compaction, (2) long-term compaction of the topsoil brought on by persistent physical degradation; and (3) long-term compaction of the subsurface (Botta et al. 2018). To avoid long-term topsoil and subsurface compaction issues, tillage needs to be controlled. Due to the concentration of decaying crop residues, conservation tillage enhances surface soil structure and has the potential to minimize compatibility (Garbout et al. 2013). Following the implementation of conservation tillage, soil structure may change depending on biological activity, weather, organic matter content, and structure-forming activity, which are all related to clay content and mineralogy (Sheehy et al. 2015; Mahmood et al. 2022).

4 Conservation Tillage and the Environment

4.1 Soil Environment

The major benefits of conservation tillage come from the decrease in runoff, which often carries with it any leftover agricultural chemicals and soil sediments (Gill and Kukal 2017). For instance, the decrease in runoff that zero-till plots typically experience is a fantastic chance to lower surface water contamination and even water table pollution. Due to the drastic runoff and the speed with which the herbicides are converted into harmless compounds by soil organisms (that are typically abundant under zero tillage), the potential of surface water pollution is extremely low under ZT (Derpsch et al. 2014). Such agrochemicals go farther outside the vadose zone when applied to intensively ploughed soil than they would in plough less soil (Bhatt and Arora 2015). Intense tillage causes significant erosion by losing the soil, burying agricultural waste, and exposing it to high wind and rainfall intensities (Srinivasarao et al. 2014; Rasheed et al. 2021). In order to prevent soil erosion caused by wind and water, conservation tillage techniques like NT and MT are created (Arai et al. 2018).

4.2 Atmosphere

According to a survey, variations in agriculture and forest use, especially devastation in tropical areas, are responsible for nearly one-third of the world's greenhouse gas emissions, 74% of which come from developing nations (Bhatt and Arora 2015). Agriculture's direct emissions in 2010 supplied 10–12% of the world's greenhouse gas emissions (Tubiello et al. 2013). In light of this, the UNEP 2013 report named agriculture as one of the four areas which are assisting in the achievement of national objectives and have demonstrated their ability to effectively cut greenhouse gas emissions. The report placed emphasis on the need to promote no-tillage methods if agriculture is to play its proper part in lowering greenhouse gas emissions. One of the benefits of no-tillage has been noted to be high carbon sequestration (Lal 2010). It has been observed that switching from conventional tillage to no-tillage results in a C sequestration rate of 367–3667 kg carbon dioxide ha^{-1} $year^{-1}$ (Tebrugge and Epperlein 2011). Conservation tillage techniques reduced the amount of unmineralized organic materials that were exposed to microbial activities, which in turn slowed the rate of SOM degradation and CO_2 release (Baye and Bogale 2019; Hassan et al. 2021). Aside from carbon dioxide (CO_2), it has been claimed that tillage practices have an impact on other greenhouse gases (GHGs), particularly methane and nitrous oxide (Alvarez et al. 2011). While methane is regarded as the most powerful greenhouse gas after carbon dioxide, nitrous oxide from soils accounts for around 38% of emissions to the atmosphere (Hassan et al. 2018). Areas that have been tilled significantly emit more N_2O than sites that have not been tilled (Regina and Alakukku 2010). Since tilled soil has greater aeration, there may be more oxygen available, which could lead to greater aerobic soil turnover and greater capacity for emission of gases (Chatskikh and Olesen 2007).

4.3 Soil Function

In organic farming, soil mineralization frequently limits yields, and one of the main ways to improve organic farming efficiency is through modifying the nitrogen status (Jilling et al. 2020). The balance between immobilization and mineralization during the turnover of organic matter determines how much nitrogen is released for crop uptake. Numerous parameters, such as soil moisture and aeration, favor the timing of mineralization (Hou et al. 2018). By boosting microbial activity, adding fresh organic matter with a higher SOM component speeds up mineralization. The tillage system has an impact on the SOM mineralization. The SOM is exposed by conventional ploughing, which also speeds up its degradation (Nunes et al. 2016). This phenomenon is brought on by an increase in the warmth and aeration of the tilled layer, an increase in microbial activity brought on by the absorption and mixing of carbon inputs (Roger-Estrade et al. 2010). Net mineralization is influenced by the frequency and depth of conventional tillage activities, or instance, when tillage occurs during times of high soil temperature more N is released (Vakali et al. 2011). A larger proportion of soil nitrogen from bacterial metabolism on the surface is present under conservation tillage, especially no-till (Galdos et al. 2019). Additionally, the decomposition of carbon and nitrogen in soil is also impacted by soil compaction (Hamza et al. 2011). Therefore, topsoil compression in conservation tillage changes the composition and distribution of soil gases (carbon dioxide and molecular oxygen) and soil water, which in turn influences the habitat of soil microorganisms and subsequently their activity (Munkholm et al. 2013). For instance, increased denitrification may take place (Giarola et al. 2013), which would reduce the amount of accessible N to the crops. Because of increased microbial activity is a prerequisite for many of the advantages of conservation or no-till, for general use, these strategies are most effective in semi-humid or subtropical locations (Huang et al. 2012). On organic farms, experimentation with tillage compared to ploughing shallow tillage produces less mineralized nitrogen (Travlos et al. 2018). Organic farming has the potential to raise SOM content, but the loss of mineral nitrogen input may cause a delay in the provision of accessible N to crops.

4.4 Nitrogen Supply and Crop Rotation

Crop rotations can be used in organic farming to control the crop N supply (Ball et al. 2018). Peas and other crops with lower N requirements should be planted later in the fertile stage. Utilizing crops with a lengthy N absorption phase, such spring barley and potatoes, maximizes the release of available nitrogen over a long period of time (Delgado 2010). Growing legumes and intercropping are other ways to improve resource utilization. These novel crops use results in rotations that must be designed to take other agronomic factors into consideration. Although potatoes grow successfully by planting them into residues with tillage used just to create ridges, conservation tillage is typically utilized with nonroot crops.

4.5 Emergence and Root Growth

For a particular environment, the effect of soil structure on crop emergence temperature, surface layer moisture, and the lack of organic manure at the soil surface are all dependent on the quality of the seedbed conservation tillage could hinder crop emergence since it raises residues and lowers soil surface layer temperature. Wheat, maize, and sugarbeet may all experience delayed crop emergence as a result of short-term topsoil compaction (Behaeen et al. 2013), which will ultimately reduce yields (He et al. 2017). In barley and oats, switching to minimum tillage on a topsoil (55% clay) resulted in a reduction in rooting density at a depth of 15–25 cm (Andruschkewitsch et al. 2013). Conservation tillage enhances worm pathways while reducing total macro porosity. Therefore, in order to make up for the lack of the mechanical macro pores generated by the plough, root growth in conservation tillage relies on the natural macro pores in the soil (Catania et al. 2018).

4.6 Soil Water Storage and Infiltration

In conservation tillage, soil water absorption can vary significantly depending on the overall permeability and distribution of pore size (Melander et al. 2017). The continuity of biological pores and micro porosity was both improved by residue cover at the soil surface under conservation tillage (Ali et al. 2020). Earthworm population during tillage improves filtration and water flow (Pandey et al. 2015).

5 Weed, Disease, and Pest Control

5.1 Weed Pressures

Tillage has an impact on weed population through changes in the distribution of weed seed within the top soil and through physical destruction of young weed seedlings (Peigné et al. 2007). In the soil surface layer, conservation tillage alters the micro-topography, light, water, and temperature conditions (Scursoni et al. 2014), which affects how quickly weed seeds germinate depending on the type of weeds and the weather (Derrouch et al. 2022). No-tillage practices tend to alter the 0–5 cm layer of soil by reducing particle size and improving overall porosity. Weed emergence may also be impacted by these changes. For instance, when using conservation tillage, crop residues may alter the seed–soil interface, making it less favorable for the sprouting of tiny undesirable plants (Bond and Grundy 2001). The effect of tillage strategies on dicotyledonous weeds relies on the variety (Manhas et al. 2015). For instance, when some annual dicotyledons perennial seeds come on the surface due to ploughing, such as *Chenopodium* sp. and *Papaver rhoeas*, conventional tillage tends to boost their populations. Unlike when the subsoil is inverted, conservation tillage prevents rapid and brief seed light exposure and changes in soil temperature. As a result, older and deeper located persistent weed seeds take longer to germinate (Crittenden et al. 2015). The lack of tillage favors weeds with climbing roots or rhizomes (Schutte et al. 2014). Conservation tillage using discs, especially with *Agropyrum repens*, can promote their growth by uprooting and scattering their rhizomes. The same is true for *Elymus repens,* a plant preferred by conservation tillage that could pose a serious issue in sustainable agriculture (Briones and Schmidt 2017). Organic farmers are frequently discouraged from implementing conservation tillage because of unfavorable effects in weed seed banks and weed emergence (Fitzgerald et al. 2020) and the impact on weeds of switching from conventional to organic production (Travlos et al. 2018). The ban of inorganic N fertilizers boosts leguminous plant species while reducing nitrophilous weed species (such as *Gallium aparine*). Traditionally planted perennial crops in organic agriculture rotations favor perennial weeds over long-lived annual weeds. Moreover, perennial dicotyledons like *Cirsium arvense* are more prevalent in organic fields (Gliński and Stępniewski 2018).

5.2 Weed Control

When organic farming adopts conservation tillage, weed control calls for the substitution of other methods for ploughing. Weeds can be managed using a variety of agricultural practices with conservation tillage (Briones and Schmidt 2017). All of these methods help crops compete more effectively with weed growth (Melander et al. 2005). Several elements affect how effectively cultural activities operate. Which included the basic weed seed bank, soil and climatic factors that affect the effectiveness of weed management, and crop growth stage (Melander et al. 2017).

6 Conclusion

It is not sustainable or environmentally friendly to disturb the soil by conventional tillage since this causes the soil to act as a source of contaminants rather as a sink for them. However, rather than advocating no-tillage solely, it appears that international development groups are in favor of encouraging conservation agriculture generally. According to research studies, conservation tillage, especially MT, improves the soil's chemical composition more than CT. Soils with conservation tillage benefit soil fauna more than soils without it. The significance of switching to the NT system for reducing runoff and maintaining environmental quality is emphasized. Additionally, crops cultivated on tilled plots have the advantage of higher yields due to benefits of climatic adaptability (such as drought and high temperatures); whereas crops grown in reduced tillage have the advantage of higher yields because of breaking the compact soil mass and mild soil disruption. It is impossible to overstate the advantages of little or no tillage in conjunction with similar techniques. Therefore, conservation tillage is more crucial than ever in order to ensure sustainable nutrient supply with little negative impact on the soil. It is concluded that reduced soil erosion, reduction in runoff, and use of organic material proved to be beneficial in conservation tillage for sustainable agriculture.

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Chapter 16
Prospect of Underutilized (Minor) Crops for Climate-Resilient Agriculture

Oksana Sytar

Abstract A scoping chapter has been used on online scientific databases to specify the possibility of underutilized crops to provide (1) the nutritional potential of underutilized plants for food use, (2) the resistance of underutilized plants to adverse environments, and (3) an upgrade of agricultural sustainability under the changed environment with crop rotation via use of underutilized crops. Knowledge of sensing mechanisms, development of oxidative stress reaction, and genetic molecular parameters are important to advance climate-resilient crops. It is recommended to study the more detailed potential of underutilized plants described in the presented work for crop rotation under climate-resilient agriculture practices.

Keywords Climate-resilient agriculture · Underutilized crops · Minor crops · Environmental stress · Crop rotation

1 Introduction

The manufacture of agricultural products is responsive to climate change. One of the serious worldwide challenges for human beings is climate change, as temperatures keep rising, provoking the development of extreme weather effects such as flooding, drought, and heat stress (Feulner 2017). Such climate-affected questions are shown promptly, with socioeconomic instability and health insecurities occurring, notably in marginalized districts (Schmidhuber and Tubiello 2007). There is a rising indication of unintended connections between changed environmental conditions and the increase in the percentage of malnutrition, weak health due to hunger or starvation, in addition to water and food insecurity (Webb et al. 2018). Climate

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change-associated challenges exceed the usual coping abilities of a supposed nearly 500 million family farms (FAO 2016; Frimpong et al. 2020). If regional knowledge is not related to modernized technologies (Padulosi et al. 2013; Wheeler and von Braun 2013; Li and Siddique 2020) farmers may have a decrease in the average annual harvest by up to 25% by 2050, with loss in some years of the whole harvest (Skytt et al. 2021).

Climate-resilient agriculture is a way of sustainably using current natural resources through crop and livestock production systems to obtain greater productivity and farm incomes under climate changeability in the long term. It is discussed that climate-resilient agriculture can decrease hunger and poverty for upcoming generations in the face of global warming (FAO 2017). For climate-resilient agriculture it is crucial to establish strategies and technologies for adaptation to climate change. Climate-resilient agriculture is not just related to botanical and zoological backgrounds, but also the use of water and soils by animals and plants to support the function of normal nutrient cycles (especially carbon–nitrogen–phosphorus–potassium cycles) (Dhankher and Foyer 2018). The natural development of environmental changes such as aridness and drought may result in the physical scarcity of water. With the impacts of all human activities, water storage and desertification may also cause water scarcity (Pereira et al. 2009; White 2014). Based on the current scenarios, farmers are enforced to cultivate their crops in soils under conditions of salinity and heat or drought stress during the vegetation season.

Wheat, soybean, rice, and maize contribute two-thirds of human caloric intake and distressed yield and production of these crops under climate-change factors (salinity, heavy metals, temperature, drought, etc.) may cause serious problems (Zhao et al. 2017). At the same time, alone, these crops cannot contribute the full range of nutrients for optimal development and existence of humans. For this reason, a far more variable diet is recommended, which a great number of people from developing countries in the world are not able to get (Powell et al. 2017). Such an absence of agricultural variability also has little impact on the natural environment and global biodiversity (Roe 2019).

Minor crops have low visibility as neglect and abandonment from the research community because of very limited or no investigation into experimental and genetic development. Minor crops, known by local people and widely established by farmers, are remarkably rich in nutritional composition, valuable for medicinal use, and well-accustomed to sub-optimal cultivation conditions (Sibhatu et al. 2015; Scarano et al. 2021). Furthermore, marginal conditions have infertile soils represented by ultimate weather conditions such as water deficit, heat, the salinity of soil and water, and erratic rainfall (Sibhatu et al. 2015). In the case of the appearance of extreme climatic circumstances and extended degradation of land, minor crops are starting to obtain refreshed consideration as alternate crops for dietary variety in marginal environments and, by continuation, around the world. Increased realization of a healthy lifestyle via the quality of food products is also a main point with regard to the renewed attention given to orphan crops (Talabi et al. 2022).

In fact, most commonly cultivated plant species and varieties used in food production heavily rely on substantial external inputs to thrive across a wide range of environments, including both local resources and the ability to withstand external stresses. Therefore, today is the right time to shift to some of the other promising food crops (nearly 5000) known generally as neglected and underutilized species (Li et al. 2020).

The current chapter uses scientific databases to specify the possibilities of neglected crops to provide (1) the worthwhile and nutritional potential of neglected plants for food use, (2) the resistance of underutilized plants to adverse environments, and (3) the development of agricultural sustainability under the effects of global warming. For instance, certain underappreciated crops within existing monoculture cropping systems might endorse the adoption of more nutritious, sustainable, and diverse food systems in marginalized agricultural settings (Mabhaudhi et al. 2019).

2 Neglected and Underutilized Plant Species

The particularly significant role of underutilized crops in sustaining and enhancing biodiversity was expressed for a vast range of diverse species. The production of a principal monoculture (placed on a few main crops such as wheat, maize, soybean, cassava and rice, rye, potato, etc., depending on specific regional circumstances) has one main problem, the genetic destruction of plant diversity and identical biodiversity of life cycles in the soil and plant cultivation management (plant diseases, pests, novel components of genetically modified organism sequences in the plants, etc.). Furthermore, the high addiction of humans in the world to a minor quantity of plant species for human groceries is a tendency that remains (Mugiyo et al. 2021). Therefore, it is essential to describe the attractive characteristics of novel plant crops regarding consumer demands and interests. It is also crucial to define plant potential and cultivation parameters for their possible domestication (Piperno 2011). In the meantime, addiction to high-yielding plant varieties (green revolution), which need fertilizers and pesticide inputs causes the enhanced liability of farmers (Pingali 2012). Therefore, last year's functional plant biodiversity is rapidly developing. The functional plant biodiversity established on intensive crop rotations connected with underutilized crops optimizes the variability of alive organisms in the soil and has an effect on the qualitative and sustainable potential of cultured plants. It supports a favorable rationing of the soils of plant diseases and pests (Bavec et al. 2017).

Underutilized crops that are cultivated in their natural habitats are great indicators of soil parameters and the effects of climate change on soil (Bavec et al. 2017). As a result of the use of crop rotation the main crop + underutilized crop together with organic farming functional biodiversity is developing. Soil recovery, increasing organic matter, and the diverse presence of live microorganisms support the development of sustainable agriculture compared with the use for the cultivation of one major crop over a long period (Fig. 16.1).

However, even with the present knowledge of the cultivation needs of the major world crops, maize, wheat, and cotton related to environmental conditions, for many

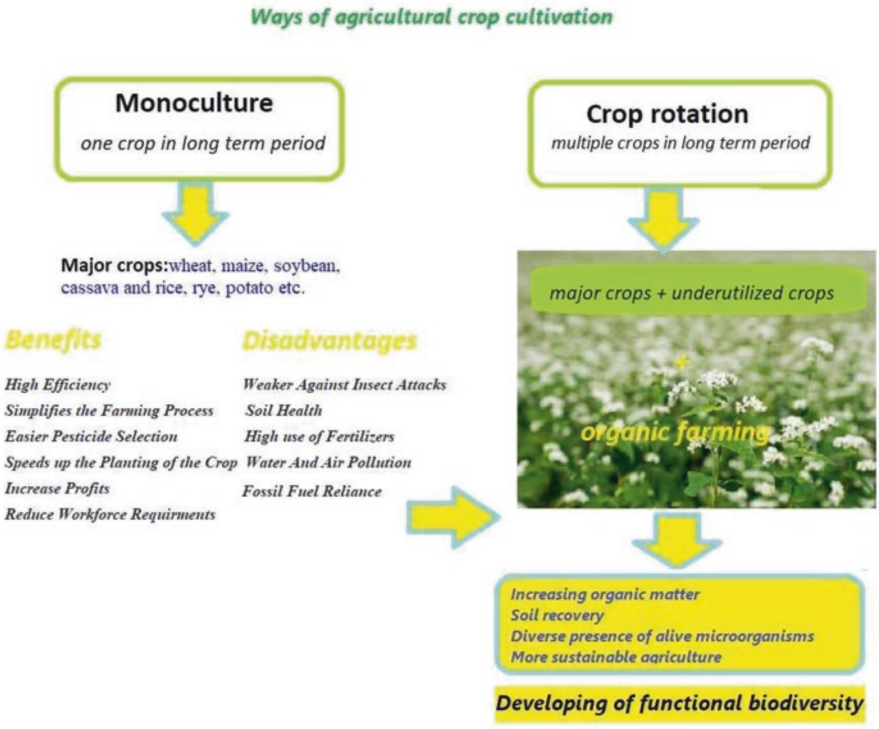

Fig. 16.1 Importance of underutilized field crops for increasing functional biodiversity

other plant crops, we have very little knowledge. For example, as the adequate temperature range of mostly all tropical and sub-tropical crops extends almost to the poles as a result of global warming, their climate extension can also be likely to move closer to the poles. Day length is likely a crucial factor in determining the specific seasonal requirements of many plant species, allowing them to effectively delineate their suitable cultivation areas. Understandably, cropping systems are under climate change all over the world, and the crops grown inside such systems will have to adapt to the advanced climatic conditions. In Table 16.1 the mostly known underutilized plant species for which attempts have been made to reuse them in Europe are described as an example. The environmental conditions required for growth, resistance to adverse environments, the nutritional potential of underutilized plant species, together with ethnobotanical usage, are presented.

It is important to admit their resistance to adverse environments and the conditions required for their growth. This basic knowledge may help to develop successful cultivation via crop rotation by choosing optimal underutilized crops for specific regions. For example, some regions have high concentrations of heavy metals, so it would be recommended to use for crop rotation the following neglected plants: *Brassica carinata*, *Cynara cardunculus*, *Fagopyrum esculentum*, *Vigna* sp., roquette (*Eruca vesicaria L. Cav.,* formerly *E. sativa* Mill.), milk thistle (*Silybum marianum* L.),

Table 16.1 Neglected and underutilized plant :attempted reuse in Europe

Neglected and underutilized plant species	Origin	Environmental conditions required for growth	Resistance to adverse environment	Nutritional	Ethnobotanical usages	References
Amaranthus caudatus	Originates in Latin America	Well-drained loam, any soil	Tolerates drought	Gluten-free, rich for minerals Fe and Ca, betacyanins, high flavonoids, phenolic and proanthocyanidin, antioxidant potential	Mainly consumed as grains	Silva et al. (2019), Jimoh et al. (2019)
Basella rubra	Originates in tropical Asia and Africa	Any soils, seemingly without regard to fertility	Water stress resistance	Gallic acid, ferulic acid, caffeic acid, lutein, zeaxanthin, and β-carotene. Vitamins, minerals, phenols and dietary fiber	Mainly consumed as leaf vegetable	Kumar et al. (2021), Adenegan-Alakinde and Akinnubi (2015)
Brassica carinata	Hybrid between *Brassica nigra* and *Brassica oleracea*	Susceptible to adverse environmental conditions	Tolerant to drought, salinity, heavy metals	Rich in glucosinolates and erucic acid	Mainly consumed as leaf vegetable. Seeds also used	Ashraf and Mehmood (1990), Hagos et al. (2020)
Buckwheat (*Fagopyrum esculentum*)	Originates in the Tibetan plateau, domesticated food plant raised in Asia, widespread in Europe, North America	Rich soils in marginal areas	Tolerant to soils polluted with heavy metals and UV-radiation	Flavonoids rutin and quercetin, phenolic acids, amino acids	Mainly consumed as grains, also inflorescence as tea	Sytar et al. (2016), Domańska et al. (2021), Germ et al. (2019)

(continued)

Table 16.1 (continued)

Neglected and underutilized plant species	Origin	Environmental conditions required for growth	Resistance to adverse environment	Nutritional	Ethnobotanical usages	References
Cajanus cajan Pigeon pea	Native to India and West Africa	Cultivated on marginal land	Tolerant to drought, salinity	High levels of protein and the important amino acids methionine, lysine, and tryptophan. Plus vitamins, minerals	Mainly consumed as seeds	Solomon et al. (2017), Tayyab et al. (2016), Sinha et al. (2016)
Chenopodium quinoa	Originates in the Andean region of northwestern South America	Cool climates, dry soils	Resistant to dry soil, salinity	Rich in protein, vitamins, minerals Mn, P	Mainly consumed as grains	Hinojosa et al. (2018), Angeli et al. (2020)
Cichorium intybus	Originates in Europe, and is now common in North America, China, and Australia	Fertile, well-draining soil	Resistant to drought	Rich in phenolic acids, flavonoids, fatty acids. Chicory root contains essential oils, inulin	Mainly consumed as leaves and roots. Use in traditional medicine and last years as a possible energy crop	Ghanaatiyan and Sadeghi (2017), Sytar et al. (2019)
Cynara cardunculus Cardoon	Originates from the western and Central Mediterranean region	Cultivated on well-drained soil	Resistant to drought, salt, and heavy metal stresses	High level of fatty acids, phenolic acids (5-*O*-caffeoylquinic and 3,5-*O*-dicaffeoylquinic acid)	Mainly consumed as the flower buds, stems	Pappalardo et al. (2020), Petropoulos et al. (2018)
Echinochloa frumentacea Indian barnyard millet	Originates in South Asia, widely grown as a cereal in India, Pakistan, and Nepal	Cultivated on marginal lands where rice and other crops will not grow well	High degree of tolerance to salinity; tolerance to heavy metals	Rich in protein, carbohydrate, fiber, minerals (Fe and Zn)	Mainly consumed as grains. Sometimes grains are fermented to make beer	Senthil et al. (2019), Renganathan et al. (2020), Gorelova et al. (2022)

Eragrostis tef	Originates in Horn of Africa, notably to modern-day Ethiopia	Grows in various environments. It does not tolerate frost	Tolerant to drought, pests	Rich in protein (gluten-free status), starch, fatty acids	Mainly consumed as grains	Pichmony et al. (2020), Assefa et al. (2015)
Lablab purpureus	Originates from Africa	Grown on heavy soils	Drought tolerant, salt stress	High level of protein lectin. Lablab beans effectively block the infections of influenza viruses and SARS-CoV-2	Mainly consumed as beans	Liu et al. (2020), Kokila and Devaraj (2021)
Lathyrus sativus Grasspea	Originates from the Balkan Peninsula	Grows best in moist soils, improves the nitrogen content of soil	Drought salinity resistance	High protein level. A neurotoxic amino acid β-N-oxalyl-L-α,β-diaminopropionic acid in the seeds	Mainly consumed as seeds. It is not recommended for use for long periods	Jiang et al. (2013), Khosravi et al. (2022), Rao et al. (1964)
Leopoldia comosa (L.) Parl.	Turkey and the Mediterranean area	Temperate areas, rocky grounds	Resistant to cold	Rich in flavonoids, phenolic acids, and fatty acids, antioxidant and hypoglycemic properties	Consumption of bulbs in local dishes	Scarano et al. (2021)
Lupinus mutabilis L.	Originates in Central Peru, at present in the eastern side of South America, from Colombia to the North of Argentina	Soils in marginal areas	Tolerant to cold, needs in low input agriculture on marginal land	High level of oil and protein content similar to soybean	Mainly consumed as grains	Gulisano et al. (2019)

(continued)

Table 16.1 (continued)

Neglected and underutilized plant species	Origin	Environmental conditions required for growth	Resistance to adverse environment	Nutritional	Ethnobotanical usages	References
Multicolored carrots (*Daucus carota* L.)	Originated from Central Asia, spread across Middle East, North Africa, Europe, China	Moist and calcareous soils	Resistant to cold	Rich in minerals, phenolics, anthocyanins, β-carotene, etc.	Mainly consumed as fresh product (roots)	Scarano et al. (2021)
Nigella sativa Black caraway	Originates from Eastern Europe (Bulgaria and Romania) and Western Asia (Cyprus, Turkey, Iran, and Iraq)	Grows in various environments	Some ecotypes tolerant to drought stress	Rich in protein, various alkaloids, linoleic acid, oleic acid, palmitic acid, and trans-anethole, as well as *p*-cymene, carvacrol, α-thujene, thymol, α-pinene, β-pinene and *trans*-anethole	Mainly consumed as seeds	Yimer et al. (2019), Alaghemand et al. (2019)
Panicum miliaceum Proso millet	Originates from Northern China	Grows in light or medium to heavy soil	Highly drought-resistant	Rich in protein with high content of essential amino acids (leucine, isoleucine, and methionine), phenolics, high Ca level	Mainly consumed as grains	Saleh et al. (2012), Ventura et al. (2022)
Purslane (*Portulaca oleracea* L.)	Uncertain	Temperate, subtropical and tropical areas	Synanthropic species	Rich in minerals, phenolics, omega-3-fatty acids, tocopherol, and vitamin C	Consumption of fresh or cooked leaves in local dishes	Scarano et al. (2021)
Roquette *Eruca vesicaria* L. Cav. (formerly *E. sativa* Mill.)	Widespread around the world	Rich soils in marginal areas	Tolerance to nitrates and heavy metals	Rich in vitamin C, carotenoids, glucosinolate, phenolics	Leaves used as leafy/ green salad	Scarano et al. (2021)

Salicornia spp. (L) Parl.	Originated between the Mediterranean and Central Asia during the Miocene	Saline environments, coastlines, tidal floodways, salt lakes	Salt tolerant	Rich in minerals, phenolics, vitamins, fatty acids, immunomodulatory potential	Livestock feeding, human consumption in local dishes (stew, leaves), glass and soap making	Scarano et al. (2021)
Solanum nigrum	Originates in Eurasia and introduced in the Americas, Australasia, and South Africa	Soils rich in organic matter, water, and fertility	Tolerant to Cd, drought, salinity	Rich in protein, alkaloids, flavonoids, phenols, minerals Fe, Zn, Cu, Mg	Mainly consumed as berries, flowers, leaves	Xu et al. (2012), Weber et al. (2014), Khateeb et al. (2019), Padmashree et al. (2014)
Silphium perfoliatum	Originates in the ancient Greek city of Cyrene, in North Africa	Slightly drained soil	Drought and frost resistant, heavy metals	Rich in protein, fatty acids	May be used for biogas production	Peni et al. (2020), Kowalska et al. (2020), Nescu et al. (2022), Lopushniak et al. (2022)
Milk thistle (*Silybum marianum* L.)	Mediterranean area, then widespread over the world	Warm environment, dry soils	Tolerant to dry soils or polluted with heavy metals	Rich in flavolignans (especially silybin), flavonoids, tocopherol	Oils and tea from fruits; consumption of cooked leaves and stems in local dishes	Scarano et al. (2021)
Triticale	Originates from Africa	Warm environment, dry soils	Tolerant to dry soil, salinity, low pH, defined mineral toxicity	Rich in protein, vitamins, minerals Ca, Mg, P, Cu, and Zn	Mainly consumed as grains	Blum (2014), Bona et al. (2014)

(continued)

Table 16.1 (continued)

Neglected and underutilized plant species	Origin	Environmental conditions required for growth	Resistance to adverse environment	Nutritional	Ethnobotanical usages	References
Trigonella foenum-graecum Fenugreek	Originates from transcontinental region in Western Asia	Wide variety of soils but clayey loam is better	Tolerant to frost and freezing weather	Rich source of protein, dietary fiber, vitamins B, minerals, Mg, Fe, alkaloid trigonelline, coumarins, cinnamic acid, and scopoletin	Used as a herb (dried or fresh leaves), spice (seeds), and vegetable (fresh leaves, sprouts, and microgreens)	Ouzir et al. (2016), Mirmiran et al. (2018)
Vigna spp.	Originates in Asia and Africa	Grows well in semiarid and arid environments	Tolerant to drought, salinity, Al	Rich in protein, phenolics, tannins, linoleic and linolenic acid	Mainly consumed as grains	Iseki et al. (2018), HanumanthaRao et al. (2016), Singh et al. (2015), Tresina et al. (2014)
Talinum triangulare Ceylon spinach	Originates in tropical Africa	Grows best under humid conditions at temperatures of about 30 °C	Tolerant to salinity, heavy metals, crude oil-polluted soil	Rich in vitamins, including vitamins A and C, and minerals such as Fe and Ca, flavonoids	Fruit and vegetable: in Southern Nigeria, the leaves and young shoots are widely eaten as a cooked vegetables, and they also help to thicken sauces. In Thailand, the leaves are fried or added to soup with minced pork	Montero et al. (2018), Kumar et al. (2012), Ekpo et al. (2013)

Solanum nigrum, and *Echinochloa frumentacea*. *Amaranthus caudatus*, *Brassica carinata*, *Cichorium intybus*, *Cajanus cajan*, *Cynara cardunculus*, *Lablab purpureus*, *Lathyrus sativus*, *Panicum miliaceum*, *Eragrostis tef*, *Solanum nigrum*, *Silphium perfoliatum*, and *Vigna* spp. were described as neglected plants with drought-tolerant potential (Jimoh et al. 2019; Hagos et al. 2020; Ghanaatiyan and Sadeghi 2017; Pichmony et al. 2020; Khateeb et al. 2019; Padmashree et al. 2014; Lopushniak et al. 2022; Singh et al. 2015). *Brassica carinata*, *Cajanus cajan*, *Chenopodium quinoa*, *Cynara cardunculus*, *Echinochloa frumentacea*, *Lablab purpureus*, *Lathyrus sativus*, *Salicornia* spp. (L) Parl., *Solanum nigrum*, *Triticale*, *Vigna* spp., and *Talinum triangulare* are neglected plants with salt-tolerant potential. Some neglected plants are able to handle the effect of a few stress factors: heavy metals, drought, and salinity. Depending on the region and the needs of the soil of the region, it is recommended to choose optimal neglected plants for crop rotation to support climate-resilient agriculture.

3 Prospect of Minor Crops and Underutilized Crops for Climate-Resilient Agriculture

Climate change has many impacts on plants, be it heat waves, increased flooding, or droughts. Some areas may lose many species because of fast changes occurring owing to global warming, and other species from nearby warmer environments may colonize these areas (Harrison 2020). The increasing concentrations of carbon dioxide and temperatures directly influence plant reproduction and growth. The stress response reaction of various plants may vary depending on the plant's metabolism. Defensive adaptations in plant metabolism may change the physiological responses of the whole plant. Prevalent among the defensive mechanisms are oxygen radical scavenging, the balance of water, the upkeep of ion uptake, and reactions modifying the allocation of carbon and nitrogen, that decrease power alleviation (Bohnert and Sheveleva 1998). Secondary metabolites are active compounds in defense responses to changes in biotic and abiotic stress. Accumulation of secondary metabolites often arises in plants subjected to stresses, especially for different signal molecules or elicitors (Ramakrishna and Ravishankar 2011). The participation of secondary metabolites in plant tolerance and bio-fortification is shown in Fig. 16.2. Environmental stresses include excess light, pathogen attack, UV irradiation, injury, nutrient deficiencies, temperature, and concentration (Dixon and Paiva 1995). A low iron level may stimulate the enhanced release of phenolic acids from roots (Chalker-Scott and Fnchigami 1989). Nutrient stress showed a significant influence on phenolic levels in plant tissues (Chalker-Scott and Fnchigami 1989). The content of different secondary compounds is strongly related to the growing conditions with further influence on the metabolic pathways responsible for the accumulation of the specific natural compounds. For example, current studies have shown the potential capacities of *Cynara cardunculus* (cardoon) to be cultivated in changed climate

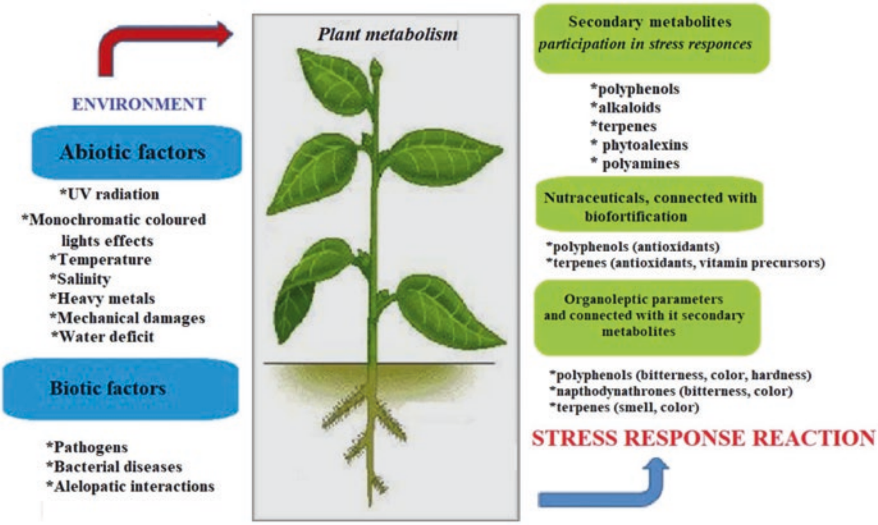

Fig. 16.2 The role of secondary metabolites in the formation of plant tolerance and bio-fortification

conditions, which is related to the greater biosynthesis of specific secondary metabolites in *Cynara* plants. The enhanced level of secondary metabolites, which is related to environmental stresses (salt, heat, pollution, and drought stress), may characterize many of the world's marginal areas that are affected by the climate changes (Pappalardo et al. 2020). Exposure to drought or salt stress causes many common reactions in plants but adaptation reactions may differ between genotypes as well. It was discovered that between two neglected plant genotypes, *F. tataricum* is more intolerant to water stress than *F. esculentum*. At the same time, *F. esculentum* showed limits of drought prevention, whereas *F. tataricum* showed tendencies toward drought tolerance (Aubert et al. 2021). *F. esculentum* (common buckwheat) and *F. tataricum* (tartary buckwheat) cultivars of various origins from different countries of the world may vary in the abundance of phenolics and flavonoids (Sytar 2015; Mikulajová et al. 2016). Plant morphology and biomass production, photosynthetic pigments, stomatal conductance, potential and effective photochemical efficiency, and UV-absorbing compounds were negatively affected by increased UV-B radiation in common buckwheat. This effect was highly visible in watered plants but less evident in plants grown under water limitation. A combined effect of two abiotic factors on phenolics of buckwheat species at two experimental points – 3 and 6 weeks – was confirmed (Germ et al. 2013), but more detailed formation during the vegetation period was not present. The same was observed for chicory plants (Ghanaatiyan and Sadeghi 2017; Sytar et al. 2019). In *Lupinus angustifolium* under drought stress an increase in the alkaloid quinolizidine was observed (Christiansen et al. 1997). Salinity stress intensifies solasodine accumulation in *Solanum nigrum* L. (Bhat et al. 2008). An unchanged level of specific pigments betacyanins in the tissues of stressed *Amaranthus hypochondriacus* plants has been observed (Casique-Arroyo et al. 2014). The free phenolic acid composition in seed extracts isolated from *Amaranthus caudatus* and *Amaranthus paniculatus* showed significant differences (Klimczak et al. 2002), which confirm the different biochemical composition between genotypes of one species. Plant biodiversity supports metabolomic biodiversity and various adaptation reactions.

Energy crops such as *Brassica* spp., *Chicory* spp., and *Silphium* spp., which are also underutilized plants, showed tolerance to the few environmental stresses – drought, salinity, heavy metals (Peni et al. 2020; Hagos et al. 2020). In *Chicory* spp. changes in the phenolic acid composition were observed under the effect of colored light (Sytar et al. 2019). Drought stress influences increased the levels of phytol, trans-2-hexenal, and δ-tocopherol in *Brassica oleracea* (Podda et al. 2019), glucosinolates in *Brassica carinata*, and *Brassica napus* (Jensen et al. 1996; Schreiner et al. 2009). Special interest has been developed during recent years in *Silphium perfoliatum* as a plant with a long flowering period. The soil coverage of *Silphium* is also ecologically beneficial (Gansberger et al. 2015). It has strong interest as a well-adapted, fast-growing crop with competitive forage quality. Many underutilized plants, which are presented in the Table 16.1, are examples of this.

The known abiotic stresses may cause cellular dehydration, IIh in paraIlel induces osmotic stress and water elimination from the cytoplasm to vacuoles. Development of an original breeding strategy for drought tolerance by introducing drought-tolerant, neglected crops into production systems to improve their resilience to water deficiency is especially current nowadays (Rosero et al. 2020). Bryant et al. (1983) have suggested that plants under stress might be able to create a replacement between carbon to biomass production or the formation of protective secondary compounds. A stress plant reaction is confirmed when plants identify stress at the cellular level.

Various plant species display different sensitivities to the stresses occurring in global warming. The herbaceous species react faster to environmental stresses than the woody plant species (Sun et al. 2021). Plant stress responses define the suite of molecular and cellular activities that are generated by plant detection under some kind of stress. The known abiotic stresses are heavy metals, salinity, drought or excess light, and biotic, such as various pathogens and herbivores (Zhang et al. 2022). Defense against active suppression of growth under stress and stress effects are two correlative tactics by which plants react to unfavorable growth conditions (Zhang et al. 2020).

New sensing mechanisms to the different stresses have been studied, especially salt sensing by glycosyl inositol phosphorylceramide sphingolipids, heat sensing by the photoreceptor phytochrome B, and drought sensing by the specific calcium influx channel OSCA1. High temperatures are premeditated by light receptors. Under temperature stress, the effect of membrane fluidity is not a sensor of temperature. It does confer the acclimation response. Two analogous calcium channels can regulate osmotic stress-dependent calcium influxes (Lamers et al. 2020).

Knowledge of sensing mechanisms together with the development of oxidative stress reaction and genetic, molecular parameters are acceptable for improving climate-resilient crops via the outcome of mechanisms of plant tolerance to stress combinations (Rivero et al. 2022). The plant reaction to stress combinations is specific and could not be guessed by studying single stresses that are part of the stress combination. For that case in practical use, until more detailed studies of plant tolerance to stress combination are developed, the use of crop rotation technology can be recommended.

In climate-resilient agriculture, a crucial part may be taken by crop rotation via the use of underutilized crops. In a crop rotation, the grower regulates the availability of nutrients and organic matter in the soil by an assortment of various crop residues, use of cover crops, cycling among crops with diverse nutrient needs, and incorporation of organic soil amendments (Hayat et al. 2020). An interesting fact is that many minor or underutilized plants are tolerant to stress, as we see from Table 16.1. This capacity of underutilized crops such as *Brassica* spp., *Chicory* spp., and *Silphium* spp. (biogas production crops) (Abdelsalam et al. 2019) may be used for crop rotation with more sensitivity to some stress crop plants (Crotty et al. 2016; Sytar et al. 2016; Björn et al. 2021). The tolerance potential of some plants may relate to their origin and metabolism as a consequence of biochemical characteristics and antioxidant potential.

4 Conclusion

The present chapter has shown the current situation with the possible use of underutilized plants in climate-resilient agriculture. It discussed the possibility of the biofortification of underutilized plants under the effects of various abiotic and biotic factors. Knowledge of sensing mechanisms, development of oxidative stress reaction, and genetic, and molecular parameters are significant for developing climate-resilient crops. Crop rotation is an important technology to replace major crops with underutilized plants for functional biodiversity and climate-resilient agriculture. It is recommended to study the more detailed potential of underutilized plants described in the present work for crop rotation under climate-resilient agriculture practices.

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Chapter 17
Crop Protection for Sustainable Agriculture in the Era of Climate Change

Sana Khalid, Areesha Nadeem, Shabnum Shaheen, Ruhangiz Mammadova, and Allah Bakhsh

Abstract Habitats of major crops are unceasingly disturbed underneath the continuous climate change. This situation aggravates many biotic and abiotic stresses, viz., plant pathogens (viruses, bacterial, and fungal) and temperature, heavy metals, irradiations, etc., thus causing reduced crop yield/productivity. Therefore, to meet the food demands of increasing global population, scientists made efforts and designed strategies to mitigate the outcomes of these stresses and manage to maintain the sustainable agriculture. This chapter highlights the molecular approaches (host plant resistance, RNA interference, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas9) coupled with in silico tools), biological control methods including proteinase inhibitor, phyto-antifeedants, induced resistance and defense priming, plant growth promoting rhizobacteria, synergism, and botanical pesticides. Moreover, chemo-ecological plant response and biophysical methods followed by the establishment of nano-fertilizers are also discussed in this chapter.

Keywords Crop protection · Biotic/abiotic factors · Molecular methods · Biological control · Chemical/biophysical approaches · Nanotechnology

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1 Molecular Approaches

1.1 Host Plant Resistance (HPR)

Researchers focus on the development of resistant varieties (host plant resistance, HPR) because of several limitations of chemical methods usage, viz., insect pest renaissance, insecticide resistance, nontarget species hostile (natural enemies and pollinators), and environmental pollution. Pest management by HPR varieties is ecofriendly and economic and it hinders the survival of insects (Peris et al. 2020). Development of transgenic plant is a novel and important biotechnological tool that introduces not only an improved species by toting beneficial or unique trait and modifying the genetic characters but subjugates the key limitation of traditional plant breeding. This technology improves crop yield, is cost-effective, and cuts chemical usage (Alemu 2020). Moreover, structural variations, amplification, and upregulation in genes are the key factors to detect insect resistance. These provide timely management against disease (Clarkson et al. 2018).

1.2 RNA Interference (RNAi)

In the biological process of RNA interference (RNAi), RNA counterbalances the mRNA molecule (targeted) which constrains gene expression. It involves a. siRNA (small-interfering RNA) and b. miRNA (micro-RNA). Earlier, this process was called quashing, PTGS (post-transcriptional gene sequencing) and co-suppression. Now, this technology is applied in development of disease and pest-resistant transgenic plants and manufacturing of insecticide base with RNAi. These small RNAs block translation by destroying mRNA (messenger RNA) through enzymes (PTGS), thus leading to gene silencing (local or systemic). Dicer breaks dsRNA into siRNA, amassed with RISC (RNA-induced silencing complex) besides argonuate protein to target specific mRNAs (Jalaluddin et al. 2019).

1.3 Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas9)

To improve the crop quality, the most versatile technology named CRISPR-Cas9 technology is adopted successfully. It can edit the specific gene that makes it nifty in crop breeding. Many crops with preferred agronomic performance have been developed by using this technology. The best thing about CRISPR is that it does not involve the integration of exogenous genome and inheritable mutations and has minute chances of off-target endeavors (Liu et al. 2021). It was first observed as an immune mechanism in *Escherichia coli* in 1987 against attacking plasmid DNA and

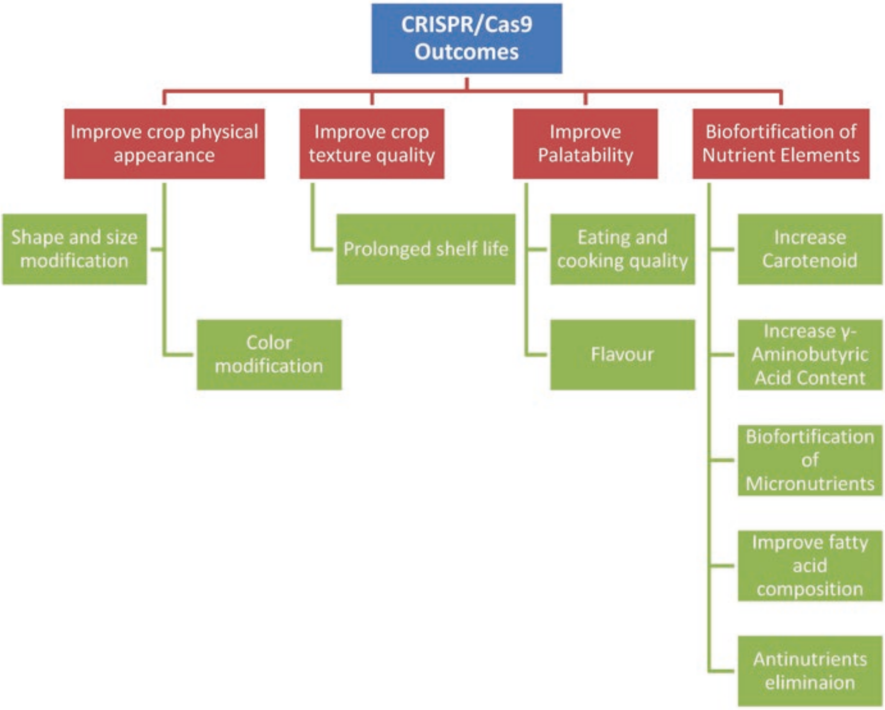

Fig. 17.1 Illustration of CRISPR/Cas9 outcomes

viruses (Ishino et al. 1987). In order to improve the crop, this technology is labor/cost effective, straightforward, and progresses the desired trait considerably (Lino et al. 2018). Some of the outcomes of CRISPR/Cas9 are illustrated in Fig. 17.1. Mostly, genetic engineering tools involve the single nucleotide polymorphism, substitution of large fragments, and insertions/deletions. However, four SDN (site-directed nuclease) families are reported to have nucleotide-excision mechanism as shown in Table 17.1. In plants, CRISPR/Cas9 was applied in 2013 and reported in many crops until now as shown in Fig. 17.2.

1.4 Bioinformatics Tools Used for Crop Protection for Sustainable Agriculture

For sustainable agriculture, it is mandatory to create the equilibrium of the insect population below the threshold level to avoid economic losses. It is noticed that with the passage of time, pests create resistance against applied insecticides. Application of bioinformatics tools is one of the best options to identify the factors of insect evolution, gene expression, and adaptation. For instance, some dry lab tools are mentioned in Table 17.2.

Table 17.1 Illustration of four site-directed nuclease (SDN) families involved in nucleotide-excision mechanism

Families	Description	References
Homing endonucleases or mega-nucleases (HEs)	Two DNA damage repair systems are used by endogenous repair system of plants to fix DSBs automatically, viz., NHEJ (nonhomologous end joining): Frequent introduction of small indels nearby cleavage sites. Error-prone system HDR (homologous directed recombination): Use repair template/flanked homologous sequences to repair breaks Fragment replacement Large insertions	Wyman and Kanaar (2006)
Zinc-finger nucleases (ZFNs)	First generation of genome-editing nucleases Generated by combining zinc finger DNA-binding domain with FokI endonuclease domain	Kim et al. (1996)
Transcription activator-like effector nucleases (TALENs)	Consist of a FokI cleavage domain and a specific DNA-binding domain from TALE proteins Comparing with ZFNs, TALENs technology shows a higher target binding specificity and a lower off-target probability It was widely used as a gene-editing tool in rice, wheat, maize, and tomato However, both of them require a complex construction process, which has constrained their large-scale application in plants	Joung and Sander (2013), Shan et al. (2013), Wang et al. (2014) and Čermák et al. (2015)
CRISPR-associated protein (Cas)	Specificity editing by guide RNA complementarity nucleotide to a target sequence without complex protein engineering. Gene function analysis by CRISPR/Cas	Lino et al. (2018)

2 Biological Control

2.1 Proteinase Inhibitor

Storage tissues principally have some defensive proteins against pests, namely, plant proteinase inhibitors (PIs). They inhibit the gut protease activity of larva. Insects create resistance against pesticides rapidly, so PIs play a very important role as biopesticides against range of insects. Furthermore, transgene PIs expression singly of with defense genes cemented to get the goal of crop protection for the development of sustainable agriculture (Swathi et al. 2021).

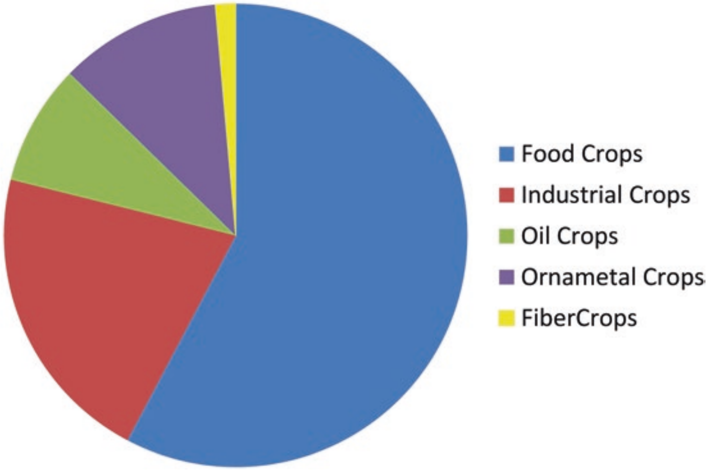

Fig. 17.2 Summary of crops genetically edited by CRISPR/Cas9

Table 17.2 Depiction of some computation tools used to create sustainable agriculture

Bioinformatics tools	Functions
DIRProt	Analysis of insecticide resistance proteins An ACE tool for insect resistance mutations To detect gene arrangement accountable for adaptation
OffTargetFinder software	Provides species-specific RNAi design to manage insect pests, sterile insect technique with RNAi and InsectBase platform for comparative genomic analysis on gene families, pathways, and orthologs
ConFind (conserved region finder)	For conserved sequence analysis and interpretation CryGetter automates the retrieval of cryoprotein
CRISPR	Using the gene disruption techniques Clustered regularly interspaced short palindromic repeats (CRISPR) Population suppression techniques

2.2 *Phyto-antifeedants*

Primary and secondary metabolites in plants perform the key physiological functions and protect from herbivore injury correspondingly. Phyto-antifeedants are secondary metabolites found in mainly Labiatae, Asteraceae, Meliaceae, and Leguminosae reported among 43 families. From plant source, steroids, coumarins, flavonoids, alkaloids, and terpenes act as antifeedants. Until now, 1000 antifeedants have been extracted from plants. Azadirachtin A is most important extracted from *Azadirachta indica* and used against many insects. Some insects possess midgut detoxification enzyme P450 to nullify the effect of antifeedants. Scientists use water oil-based formulation and latex-based application of antifeedants. However, their ineffectiveness in the field conditions and restricted broad-spectrum count as major limitations of this application. So, further research is required to make it eco-friendly herbal medicine for pests (Barik 2021).

2.3 *Induced Resistance and Defense Priming*

In this method, plants attain heightened defensive capacity due to dealing with resistance-induced agents to strongly respond the stresses, viz., abiotic and biotic (Conrath et al. 2002). It is attained at defense activation twitch to lessen the lag time or cut the trade-off and defense activation rate (Ahmad et al. 2010). Most often, chemical compounds from natural origin are found as priming stimuli. However, mineral elements, i.e., silicon and heavy metals, are also used for this purpose.

In plants, terpenoids and GLVs (green leaf volatiles) are produced following insect damage (natural enemies), aiding in the development of tritrophic relationships (Gully 2019). Primim is a very promising technique for biological control, together with other elements like endophytes and endosymbionts.

2.4 *Plant Growth Promoting Rhizobacteria (PGPR) as Biological Fertilizers*

PGPR is a group of beneficial rhizobacterial strains from the genera *Rhizobium*, *Pseudomonas*, *Azotobacter*, *Bacillus*, *Azospirillum*, *Burkholdaria*, *Enterobacter*, *Flavobacterium,* and *Erwinia* (Rodriguez and Fraga 1999). PGPR have shown potential both as biofertilizers and free living (Podile and Kishore 2007). Many research and surveys revealed that PGPR inoculations promoted plant growth, enhanced yield, and N and other element uptake (Sheng and He 2006; Glick et al. 2007). Some actions of PGPR have been illustrated in Fig. 17.3.

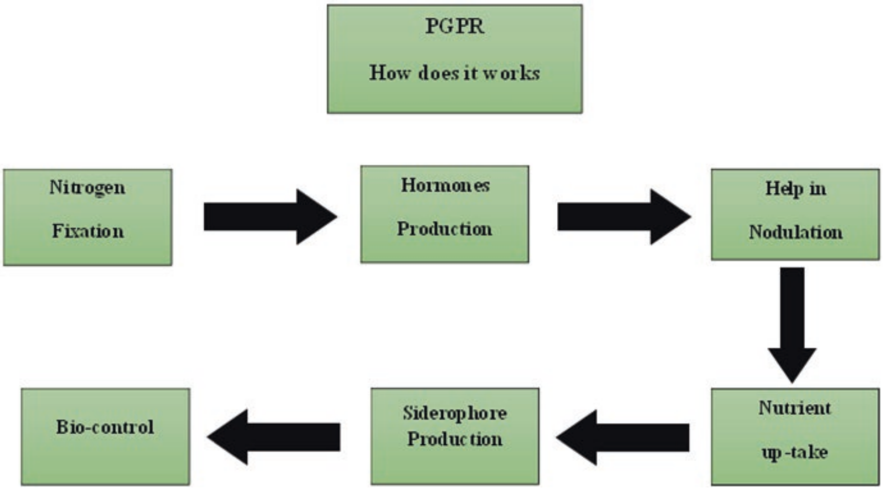

Fig. 17.3 Illustration of action of PGPR

Furthermore, PGPR treatments encourage root growth, resulting in roots with more root hairs and a larger surface area (Mantelin and Touraine 2004). For instance, massive amounts of artificial fertilizer are sprayed to restore soil N and P, resulting in high cost and environment hazards. Plants cannot access the majority of the P in insoluble compounds. Agricultural plants benefit from N2-fixing and P solubilizing bacteria (PSB) because they increase N and P uptake and functions PGPR in biofertilization (Zahir et al. 2004; Zaidi and Mohammad 2006). The use of such bacteria as environmentally friendly biofertilizer, instead of pricey phosphatic fertilizers could help save money.

Phosphorus biofertilizers increase the availability of stored P (via solubilization), the efficiency of biological N2 fixation, and the availability of Fe, Zn, and other elements by producing chemicals that stimulate plant development (Kucey et al. 1989). Rare reports for co-inoculating wheat with rhizobium and PSB exist, and little research has been done along these lines. It is, therefore, critically necessary to conduct comprehensive study on the impact of single and dual inoculations of N2-fixing and P-solubilizing bacterial species on crop yields. Agronomic yields are significantly increased when arable soils are treated with PGPR inoculants, according to recent research. *Pseudomonas alcaligenes* PsA15, *Bacillus polymyxa* BcP26, and *Mycobacterium phlei* MbP18, three PGPR strains, showed significant stimulatory effects on plant growth and N, P, and K uptake by maize in nutrient-deficient calcisol soils (Egamberdiyeva 2007).

PGPR increased various agronomic yields by producing growth-promoting phytohormones, mobilizing phosphate, producing siderophores and antibiotics, inhibiting plant ethylene synthesis, and inducing plant systemic resistance to diseases (Han et al. 2004; Zahir et al. 2004; Ramazan et al. 2005; Wua et al. 2005; Zaidi and Mohammad 2006; Turan et al. 2006; Kohler et al. 2006). According to Kavino et al. (2010), *P. fluorescens* strain CHA0 combined with chitin increased banana plant growth, leaf nutrient content, and yield under perennial cropping systems. This suggests that, given the environmental issues brought on by excessive fertilizer use and high fertilizer production costs, PGPR may represent a potential soil microflora to be used for sustainable and eco-friendly agriculture.

2.5 Synergism: The Key to Sustainability

Planning and operating a farm holistically is necessary for sustainable farming. One must endeavor to grasp the greater whole to understand its components, not the other way around because complete systems contain attributes and characteristics that are not present in any of their constituent parts. Through the process of synergism, systems acquire value in and of themselves. The arrangement of something's elements captures the essence of the whole. Arrangement is a feature of the whole world, not of the components that are organized. The fundamental sources of usefulness or economic worth are time, place, form, and possession. However, creating value is more than altering the form of objects through physical processes of manufacturing. Some simple examples may serve to demonstrate the fundamental nature of potential synergetic gains from holistic farming system management in general. The time, place, form, and possession features of production systems are obviously interconnected and are only discussed individually in these cases for demonstration purposes (Ikerd 1993).

2.6 Botanical Pesticides in Sustainable Agriculture

Plant diseases such as mildews, rusts, blast, and blight are mentioned in the Bible and other early writings. Pest management with locally available plants is an outdated technology in many places around the world. During the prehistoric time, some plants, such as Nicotiana, Ryania, and Derris, were employed to battle agricultural pests. Botanical pesticides were widely employed up until the 1940s, when they were partly displaced by synthetic pesticides that seemed to be simple to use and durable for a long time. Some botanical pesticides are listed in Table 17.3. Higher plants include a variety of chemicals that enable resistance to harmful pathogens. The selection pressure exerted by diseases and herbivores during evolution was most likely acute and severe, resulting in a great chemical variety in higher plants.

Secondary compounds from plants, unlike synthetic compounds, are nearly certain to have biological action, defending the plant from pathogens, herbivores, and competitors. In general, plant secondary metabolites are thought to have coevolved with herbivory. Knowing which pests are resistant to secondary compounds produced by plants may provide useful leads in forecasting which pests may be controlled by compounds from a specific plant species. This method has resulted in the identification of various plant insecticides. Pesticides derived from neem leave no residue on the crop. They also function as systemic insecticides since they are absorbed by the plant, distributed to all tissues, and eaten by insects that feed on plants. South Africa has created a push-pull or stimulus deterrent diversionary approach to reduce maize stem borer insect damage. This strategy involves selecting plant species that serve as trap crops to keep stem borer insects away from maize fields or employing some plant species as intercrops to keep insects at bay. Certain semi chemicals found in insect trap and repellent plants draw or deter insects. Push-pull control of *Heliothis* sp. is also used in cotton fields. An indigenous and easily accessible method for managing insect populations in field crops is the push-pull strategy, which takes advantage of the chemical ecology of plants. Pests can be managed in or around the primary crop by planting particular vegetables and flowers, such as marigolds. In pest control, a similar tactic is sometimes known as “companion planting” (Dubey et al. 2010).

Table 17.3 Some botanical pesticides used in agriculture

Botanical pesticides	
Insecticides	Larvicides
	Growth regulators
	Ovicides
	Antifeedency
	Sterilant
Fungicides	Suppress mycelial growth
	Delay sporulation
	Reduce pathogenicity
	Reduce severity
Bacteriocides	Growth inhibition
	Incidence reduction
	Inhibit severity
	Cause mortality
Nematicides	Reduce reduction
	Suppress gall formation
	Reduce motility
	Cause mortality
Virucides	Induce systematic resistance
	Inhibit transmission
	Reduce symptoms
	Inhibit penetration
	Suppress proliferation

3 Chemical and Biophysical Methods

3.1 *Chemoecological Responses of Plants*

Plants produce volatile organic compounds (VOCs) utilizing the lipoxygenase, isoprenoid, and shikimic acid pathways for crop protection with the aim of building sustainable agriculture to strengthen defense system against insect and pathogen (Brilli et al. 2011).

3.2 *Biophysics Methods Applicable in Agriculture*

The previous century was an era of sophisticated chemical use in agriculture as well as other and diverse aspects of contemporary living, and the detrimental impacts on food products and the environment are well documented. As a result, many scientists anticipate that this century will be the age of biophysical technique application to attain sustainable agriculture as shown in Fig. 17.4.

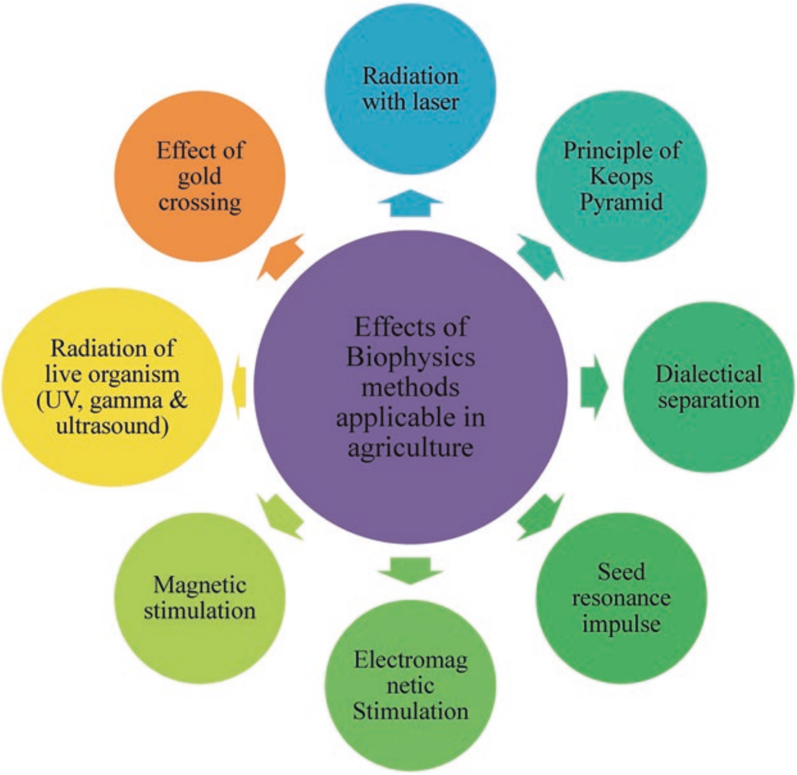

Fig. 17.4 Biophysical methods applicable in agriculture

Physical factors affecting living things have an impact on the dielectric characteristics of bio-membranes. The ability to polarize and so cross from a lower to a higher electrical level under various physical, chemical, or mechanical forces is a fundamental property of dielectrics. In addition, the influence of physical elements on living organisms is based on the increase of energy balance through the transformation of energy, regardless of its source, into electrical and resulting in an increase in the electro potential of bio-membranes. The simulative influence of physical elements is lowered on enhancing the energy balance of living organisms, intensifying material exchanges, and activating growth and development processes (Vasilevski 2003).

The survival of modern science required a “cosmic” assessment of all processes on our planet. It is vital to identify the interrelationships between forces and materials, connecting and developing astrophysical and astrochemical phenomena with biophysical and biochemical processes of cosmo-biological forces. It is possible to select numerous research results of the application of different biophysical approaches on plant production from current and accessible literature sources. It is very important to note that biophysical stimulation techniques do not alter the genetically determined course of physiological processes (Injushin 1990). Because of this, the recommended amounts for seeds and plants during application do not cause genetic damage. These techniques will allow for more intensive and higher quality agricultural production, as well as environmental conservation. Although it is unlikely that these approaches will be adopted more widely, one thing is certain: the results obtained through their use are undeniable and are paving the way for their wider adoption in agricultural production.

4 Nanotechnology

In agriculture, nanotechnology rank first position in establishing productivity with dwindling resources. Pesticides have negative direct and indirect effects on the environment and biota. This method not only increased crop productivity but also controlled arthropods and guards against a variety of abiotic and biotic challenges in the field. Nanopesticides have been made using a variety of nanoparticles, including Ag, Mg (OH)2, Au, and others. Nanopesticides have several beneficial properties, including component loading, controlled and gradual release, low dosage, and biodegradability. A pesticide or insecticide based on bio-conjugated nanomaterials is the most realistic choice for achieving the desired precision farming (Kumar et al. 2019).

4.1 Nano-fertilizers

The use of nano-fertilizers in agriculture has a big impact on productivity growth and abiotic stress resistance. Thus, it is important to consider the possible uses of nano-fertilizers in the horticulture and agri-food biotechnology industries. Furthermore, in the current atmosphere change situation, the potential benefits of nano-fertilizers have sparked considerable interest in increasing agricultural crop output capacity. The primary economic advantages of using nano-fertilizers are the decreased leaching and volatilization that come with using conventional fertilizers (Duhan et al. 2017).

In addition, the well-known benefits to yield and product quality have a significant potential to boost growers' profit margins when this technology is used. Despite several intriguing outcomes in the field of agriculture, the importance of nano-fertilizers has not yet been focused toward commercial viability. Prior to commercially distributing nano-fertilizers, it is crucial to carefully research the unknowns pertaining to how nano-materials interact with the environment and any potential negative effects on human health. In order to open up this new sector of sustainable agriculture, future research must concentrate on producing complete information in these unexplored regions (Prasad et al. 2017). As a result, research on the toxicity of various nanoparticles utilized in the creation of nano-fertilizers as well as the safety of their application must be given top importance. Besides that, before recommending a specific nano-fertilizer for a specific crop and soil type, an extensive evaluation of the effect of nano-fertilizers in soils with varying physio-chemical properties is required. Biosynthesized nanoparticle-based fertilizer and nano-biofertilizers should be researched further as a promising technology for increasing yields while maintaining sustainability (Al-Mamun et al. 2021).

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Chapter 18
Biofertilizers and Biofortification in Future Agriculture

Vikas and Rajiv Ranjan

Abstract Agrochemical pollutants in soil water and air, rapid rate of biodiversity loss, ill health of the ecosystem, desertification and salinity of soil, and increasing rate of infertility of soil are global challenges agriculture face today, and to some extent conventional agriculture is responsible for these outcomes. Hidden hunger is another global challenge, also known as micronutrient deficiency, which can be eradicated by feeding the global population rich micronutrients food. Approximately half of the population on earth is affected by micronutrient malnutrition. There are two sustainable approaches that offer the best chance of solving the above challenges: biofertilizers and biofortification. This chapter will focus on the types, techniques, pros and cons, needs, and impact of biofertilizers and biofortification in modern agriculture and global welfare.

Keywords Biofertilizers · Biofortification · Agrochemicals

1 Introduction

Agriculture has a number of challenges to face today and tomorrow. These include climate change, global warming, soil erosion, greenhouse gas emissions, biodiversity loss, agrochemical pollutants, malnutrition, and ecosystem sustainability as well as feeding healthy food to the expected growing population of 9.7 billion people by 2050 (FAO 2017; Calicioglu et al. 2019; Steensland 2019; WPP 2019; Shahzad et al. 2021). Chemical fertilizers, pesticides, and weedicides are heavily used in conventional agriculture, which worsens the situation (Mylonas et al. 2020; Meena et al. 2020; Singh et al. 2020; Mandal et al. 2020). Using biofertilizers and biofortification is one of the most effective approaches to solve almost all of these challenges in modern and future agriculture (Bouis et al. 2011; Khush et al. 2012; Panwar and Jain 2016; Atieno et al. 2020; Singh et al. 2022).

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2 Biofertilizers

Biofertilizers include the words “Bio” from the Greek word bios meaning life, and fertilizer from the Latin word fertilis meaning fruitful or productive (Venter 2019; ten Have 2021). The biofertilizers are the microbial consortia or specific species or materials that contain microbes when applied to the field or to crops, they make macro and micronutrients more mobile and also improve nutrient uptake by the plants (Du Jardin 2015; Bindraban et al. 2015; Odoh et al. 2020; Behera et al. 2021). Mycorrhiza as a biofertilizer also helps in coping with the disease, flood, drought, and salinity (Borde et al. 2017; Diagne et al. 2020). Based on the type of microbe, there are various types of biofertilizers displayed in Fig. 18.1.

3 Global Challenges and Agrochemicals

Global warming, soil, water, air pollution, climate change, biodiversity loss, ecological disturbance, etc., are some of the biggest challenges and obstacles facing agriculture today. Agrochemicals contribute to some of these problems (Koli et al. 2019). By-products (NH_3, NOX and N_2O) of nitrogen fertilizers act as greenhouse gases (Xuejun and Fusuo 2011; Malyan et al. 2019). Compared to

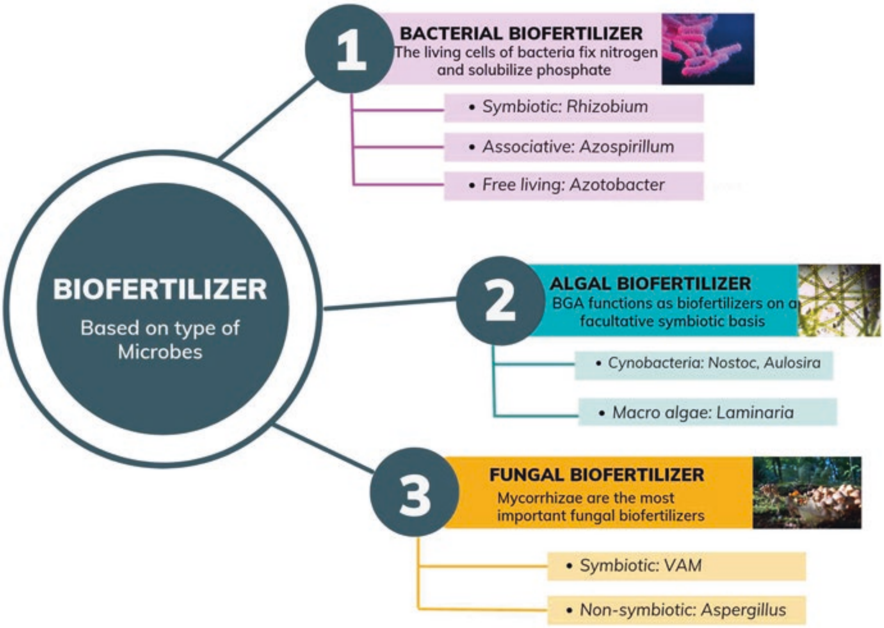

Fig. 18.1 Classification of biofertilizers based on microorganism

Table 18.1 Agrochemicals and their negative impact

Agrochemicals	Active ingredients	Major impact on environment and Human health
Insecticides	Carbaryl, Malathion, Atrazin, Aldicarb	Toxic residues in food, water, air and soil, biodiversity loss, poisoning, mental and physical illness
Herbicides	Dacthal, Sethoxydim, Bensulide	Adverse effects on birds, animals, and microorganism, disturbing ecosystem, muscular and neurological symptoms
Fungicides	Anilazin, Captan, Ferbam, Ziram	Acute toxicity in human, highly toxic for aquatic life, soil microorganism, and earhworm
Rodenticides	Coumatetralyl, Difenacoum, Brodifacoum	Super toxic for human, animal, and aquatic ecosystem
Nematicides	Ethoprophos, Terbufos	Adverse effects on male reproductive system, negative impact on nontargeted organisms
Chemical fertilizers	Nitrate and ammonia-based fertilizers	Emission of greenhouse gases, soil erosion, loss of soil carbon, microbial population disturbance
Soil conditioner	Slate, gypsum, glauconite, polysaccharides.	There is no significant impact but residues of soil conditioner can adversely impact soil microflora
Plant growth regulators	1-Naphthyl, ancymidol, daminozide, 4-indol-3-ylbutyric acid	Detrimental to human health as they are potentially neurotoxic, hepatotoxic, and carcinogenic and affects flower fruiting and root growth in plants

CO_2, CH_4 and N_2O have equivalent masses of 23 and 296 times higher, respectively, and have greater potentiality of global warming (Jungkunst and Fiedler 2007; Dijkstra et al. 2012). The use of improper fertigation can increase soil salinity, deposit heavy metals, cause eutrophication of water, and accumulate nitrate in the atmosphere, which is considered pollution (Savci 2012). About 60% of ammonia emission is due to anthropogenic activity, particularly agriculture, and CO_2, CH_4, and N_2O are produced during the processing of nitrogen-based fertilizers. These emissions contribute to climate change (Sistani et al. 2011; Kumar et al. 2019). Various agrochemicals can cause a number of severe side effects on the environment and human health as shown in Table 18.1 (Brittain and Potts 2011; Sánchez-Bayo 2012; Kaur et al. 2019; Zaller and Brühl 2019; Regnery et al. 2019).

4 Biofertilizers: A Solution to Major Challenges of Environment

We find climate change, biodiversity loss, pollution, food security, and poverty among farmers and water scarcity among the great global challenges of environment, food, and water (Ramanathan and Feng 2009; Tscharntke et al. 2012;

Matyssek et al. 2013; Bunn 2016). Biofertilizers can help solve these problems to a certain extent. Greenhouse gases including CO_2, NH_3, and N_2O are emitted either in processing of chemical fertilizers or as a by-product when applied in agricultural fields (Brar et al. 2012; Kantha et al. 2015; Hadi and Nur 2017). The use of biofertilizers can relieve the burden of greenhouse gas emissions from cropping fields as well as reduce the deposition of heavy metals in crops (Brar et al. 2015). Ultimately, it aids in the fight against climate change and global warming.

Along with chemical fertilizers, chemical pesticides increased agricultural productivity but also drastically affected non targeted organisms (Kumar et al. 2021c). They are one of the main reasons for insect and bird population declines. Butterflies, bees, natural enemies, amphibians, and aquatic animals are adversely affected by agrochemicals (Glare et al. 2012). As biopesticides, living microorganisms that are capable of producing bioactive compounds naturally, which act as toxins on pests (Kumar et al. 2021b). A biopesticide not only enhances crop productivity naturally but it also preserves biodiversity and strengthens ecosystems.

The use of chemical fertilizers replenished soil fertility and increased production, but overuse polluted air and water, degraded soil, and affected not just the environment but also microflora of soil animals and humans (Kumar et al. 2019). Excessive use of chemicals in fertilizers alters the soil's pH and electrical properties and deposits heavy metals (Brar et al. 2012; Bhatt et al. 2019). These pollution and deteriorated quality can be improved by using biofertilizers. Further, bacteria, cyanobacteria, fungi and azolla help in removing heavy metals (zinc, copper, chromium, arsenic, cadmium, nickel, and lead) from soil and contaminated water bodies.

Biofertilizers and biofortification share synergies (Kumar et al. 2021a) in providing healthy food to the global population. The use of agrochemicals in conventional agriculture leads to a global epidemic of unhealthy food (Hendges et al. 2019; Singh et al. 2020; Raimundo et al. 2021). Biofertilizers are eco-friendly (Kumar et al. 2021d) and naturally occurring fertilizers (Riaz et al. 2021) that not only boost productivity but also improve the quality of food (Nosheen et al. 2021). Aside from their numerous benefits, biofertilizers are also cost-effective, convenient, and a best choice from the farmer's perspective (Al abboud et al. 2014; Mazid and Khan 2015; Pal et al. 2015).

Agriculture sector is the main consumer of water resources for irrigation, approximately 80% of the water is used for irrigation purposes across the globe. The consumption of hydric resources in developing countries reaches upto 90% while developed countries consume 60% of the hydric resources (Velasco-Muñoz et al. 2018). The increasing food demand in developing countries requires 50% more irrigation water, while in developed countries it requires 16% more (Fischer et al. 2007). Increasing population growth, economic development, and water demand are leading to water scarcity. During this time when food productivity should increase and water resources are scarce, biofertilizers like mycorrhiza are crucial (Huang et al. 2020; Seutra Kaba et al. 2021).

5 Can Biofertilizer Feed the Growing Population?

We begin demonizing agrochemicals when we evaluate the detrimental effects of these products critically. In the context of food security, chemical fertilizers definitely increase agricultural yields beyond expectation, and we are unable to feed the growing global population without agrochemicals. G7 commitment made at Schloss Elmau in 2015 to alleviate hunger and malnutrition by 2030 for 500 million people in developing countries (von Braun et al. 2021). Can we really feed the whole world full stomach and nourished food only using biofertilizers at this current level of efficiency? The answer to this question leads to research and development in biofertilizer efficiency and to the discovery of new strains and combinations of consortiums. In addition, emphasis on how chemical fertilizers can be used sustainably and integrated with biofertilizers in agriculture to feed the growing population.

6 Future Perspective of Biofertilizers

Biofertilizers are cost effective and eco-friendly solutions in nature. Chemical fertilizers can be replaced with this natural alternative, which colonizes plant root systems. The market has many varieties of biofertilizers today, including potassium-solubilizing, phosphate-solubilizing, and nitrogen-fixing ones. Due to the fact that strains of the same microbial species have similar characteristics, a technological process developed for one strain is adaptable to another strain of a few species with only slight modifications. Biofertilization is limited due to poor quality of inoculants produced, lack of a committed strategy, and lack of knowledge of inoculation technology by extension staff and farmers.

Further researches are needed to enhance potential of biofertilizers:

- Isolation and characterization of new microbes
- Genetic modification and development of more efficient strains from existential one.
- Development of new media which can support large number of bacteria and increase viability
- Research and development in the field of complementarity between the two or more microbial species or with microbes and associated crops
- Study in the synergy between soil, biofertilizers, and ecology

7 Biofortification

A biofortified food crop is one that has been enriched with micronutrients through selective breeding, genetic modification, or enriched fertilization (White and Broadley 2005; Garg et al. 2018). The process of biofortification increases the nutritional value of food by using genetic and biochemical processes (Wakeet et al.

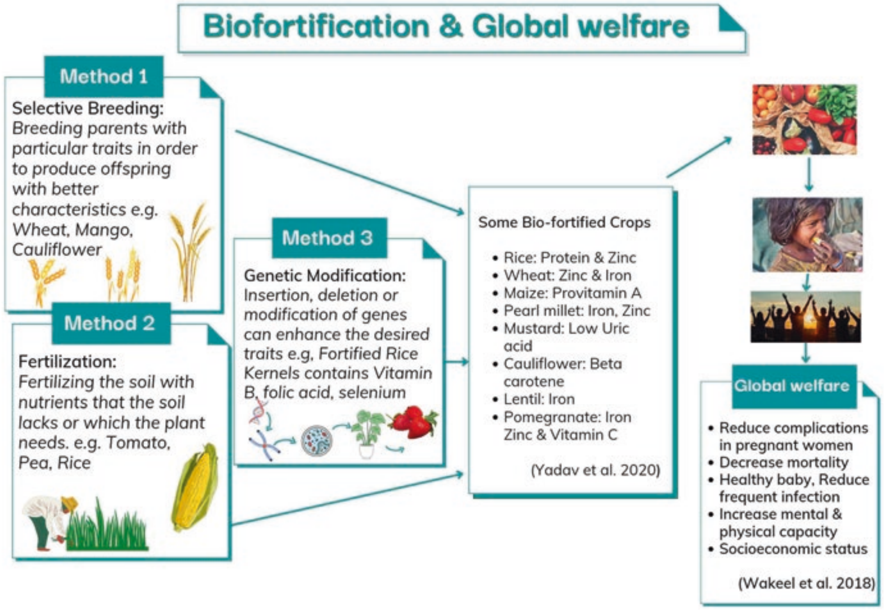

Fig. 18.2 Biofortification nexus in global welfare

2011) depicted in Fig. 18.2. A report published by the World Health Organisation (WHO) in 2007 estimated that approximately 20 million people die each year from malnutrition in the world (WHO 2007). As a result of biofortification, fatal and morbid mortality rates associated with micronutrient deficiency are reduced in developing nations and it also ensures quality food of unprivileged populations throughout the globe (Majumder et al. 2019; Meenakshi et al. 2010). The world's population is estimated to be malnourished by 800 million people, around 98% of whom reside in developing countries (Sinha et al. 2019). Despite the fact that all plants can synthesize and store micronutrients, including zinc, iron, vitamins, and folate, some staple crops contain inadequate amounts of micronutrients, so biofortification of major crops is a potential way to combat nutritional deficiency (Beintema et al. 2018; Welch and Graham 2004; Nestel et al. 2006).

8 Conventional and Emerging Techniques for Biofortification

8.1 *Conventional Plant Breeding*

Historically, in order to increase food yield and nutritional value, conventional breeding is the most effective method. However, conventional plant breeding already implies natural crop variations; moreover, it takes years to make quantitatively or qualitatively improved variety. Therefore, it has some limitations (Saltzman et al. 2017).

8.2 Agronomic Approach

Farmers use manure and fertilizer to improve the health of the crop, leading to a higher yield and more nutritious food, and same strategy can be used to accumule micronutrients in edible part of the plants (Rengel et al. 1999). The cost of mineral fertilizers, however, is a burden on farmers and developing countries cannot accept such a strategy so readily.

8.3 Molecular Breeding

It is a modern biotechnology technique known as marker-assisted breeding. A marker can be detected in seedling tissue, so a crop can be developed much more quickly without having to wait for it to mature before finding out if the desired trait is present (Sheikh et al. 2020). This technique is used by both private and public seed producers to introduce new varieties. It is a biological breeding process, which avoids direct gene insertion from different groups of organisms like plant, animal, or microbes; therefore, it is also accepted by the organic farming community (Bouis and Saltzman 2017).

8.4 Mutation Breeding

Mutation is induced either by the chemical treatment or by irradiation. In chemical treatment, the most popular mutagen is ethyl methanesulfonate (EMS) due to its effectiveness and ease of handling (Jankowicz-Cieslak and Till 2016). EMS offers inexpensive and rapid high density variety within genes. Gamma irradiation is also popular in mutation breeding (Anne and Lim 2020). There have been over 2500 varieties developed through mutation breeding (Singh et al. 2016). It is a less expensive alternative to developing varieties of qualitatively rich crops.

8.5 Plant Tissue Culture

In a variety of techniques in plant tissue culture, the process of growing a whole plant from a single cell allows the production of disease-free plants or clones of high-quality crops. Combining tissue culture and embryo rescue techniques allows plant breeders to use wild varieties of a crop, which normally do not cross with the cultivated variety. Breeders can then incorporate valuable traits from weeds and wild relatives into the cultivated crop, increasing genetic variability.

8.6 Genetic Engineering

With genetic engineering or r-DNA technology, plant breeding can be done very quickly. Gene from any source including microorganism and animal can be incorporated in the host plant to obtain desired traits. Transgenic traits are added to plants without normal biological reproduction, but they become inheritable through normal reproduction once they are in the plant (Simkin 2019). Carotenoids, tocochromanols, coenzyme Q10, ascorbate, and flavonoids are already enhanced through genetic engineering in different types of crops (Zhu et al. 2013).

Other sustainable ways for the bio-fortification process are vesicular-arbuscular mycorrhiza (VAM) and plant growth-promoting rhizobacteria (PGPR). VAM and PGPR are mobilizes, micronutrients, and make bioavailability to plants therefore increasing the quality of food (Singh and Prasad 2014; Dhuldhaj and Pandya 2017).

9 An Overview of Malnutrition

Malnutrition is a very complex issue in society, especially in developing countries. Malnourish affects growth and development differently at different ages as shown in Fig. 18.2. Among the sustainable development goals (SDGs) of the United Nations, “zero hunger” by 2030 is aimed at ending all forms of hunger and malnutrition by 2030, ensuring all people—especially children—have adequate and nutritious food throughout the year. It is one of 17 sustainable goals (Fan et al. 2022). The number of children under five who died of malnutrition has decreased by half since 1990 (Adepoju et al. 2019).

Despite the improving malnutrition situation in the last few decades, the situation is still chronic in underdeveloped and developing countries. According to an estimate in 2012, approximately 26% of the children are stunted due to malnutrition. Forty-five percent of children who died under-fives were underweight and 3% of children were severely wasted. Southern Asia and Saharan Africa both have a high rate of these deaths (Kramer and Allen 2015). In resource poor community’s malnutrition is highly prevalent. Families with weak economies consume a lot of staples such as rice, wheat and corn (Kimani-Murage et al. 2015; Brown et al. 2009; Van de Poel et al. 2007). This is where biofortification comes into play. Across the globe, biofortification is the easiest way to combat malnutrition.

10 Challenges for Biofortification

Antinutrients: Some antinutrients such as phytic acid, lectins, phenolic compounds, and saponins (Thompson 1993) are found throughout the plant but concentrated in seed or grains of the plant (Singh et al. 2016). These are the edible parts in most of

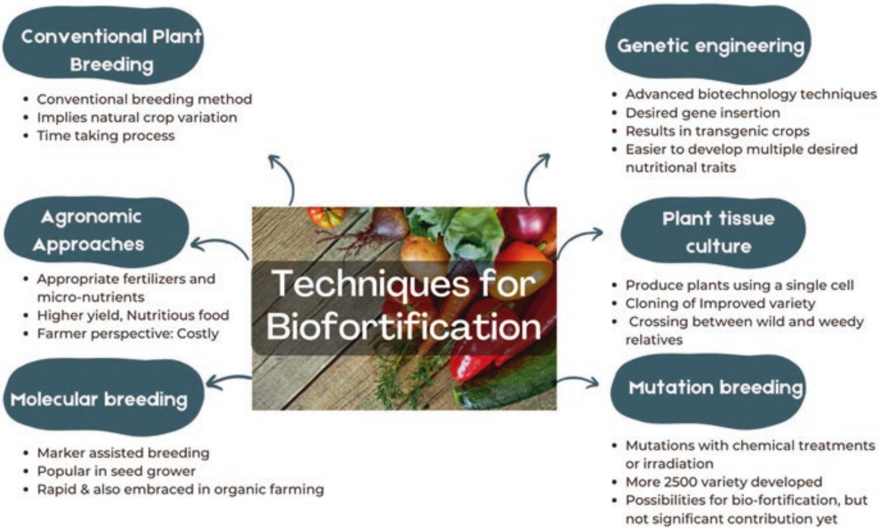

Fig. 18.3 Different techniques useful for biofortification

the crops, and these antinutrients prevent absorption of the few micronutrients such zinc, calcium, and iron in the gut (Bouis et al. 2016). Some transgenic plants have been produced through a breeding process that produces reduced amounts of phytate (Bänziger and Long 2000). For future perspective in research, the amount of antinutrients should be decreased in crops therefore absorption should increase. Phytochemicals such as $_{\beta}$-carotene, inulin, long-chain fatty acids, and amino acids (lysine, cysteine) are antagonists to antinutrients such as oxalic acid, phytic acid, polyphenols, and tannins. So enhancing these phytochemicals resulted in better uptake of micronutrients. In soil, micronutrients are not bioavailable or plants have difficulties absorbing them. Biofortification may improve if the biological system is enhanced in its ability to absorb micronutrients by physicochemical means. In terms of changing soil properties and providing nutrients to plants, biofertilizers have proven to be a very useful tool. A natural biofortification process can be achieved through the incorporation of biofertilizers into agriculture systems (Figs. 18.3 and 18.4).

11 Conclusion

Environmental awareness and health consciousness emphasize healthy lifestyle and as we consider that we are connected deeply to nature. The benefits of organic farming to the environment and human health have made it popular in recent years. Biofertilizers are the backbone of organic farming. In the near future, organic farming will boom, as will biofertilizers. The vision of a zero hunger and

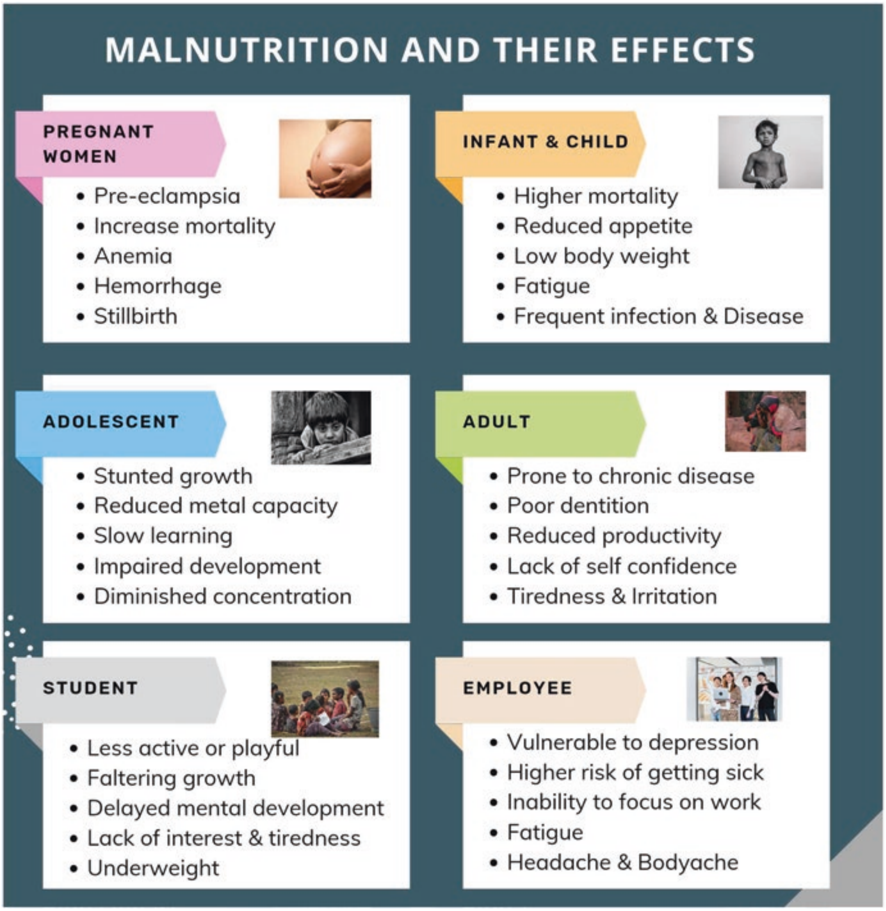

Fig. 18.4 Effects of malnutrition on different age groups and types of individuals

malnutrition-free world is being aimed for by 2030. Biofortification has the potential to eliminate malnutrition around the globe, but the process and methods of biofortification require extensive research. It is obvious that biofortification will never be out of style because of the growing population around the world. Biofertilizers and biofortification are currently at the infancy stage of research, development, and application. The future of a healthy environment and human health lies in these two areas.

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Chapter 19
Plant Secondary Metabolites in Stress Tolerance

Esra Koç and Belgizar Karayiğit

Abstract Secondary metabolites are natural defense elements that play a vital role in plant defense against adverse environmental conditions. The amounts of secondary metabolites increase significantly to adapt to harsh conditions. The increase in the synthesis and accumulation of plant secondary metabolites to cope with abiotic and biotic stress indicates a strong link between secondary metabolites and biotic and abiotic stress tolerance. In this chapter, the contribution of secondary metabolites to plant defense against biotic and abiotic stress factors such as salinity, drought, heat and cold, heavy metals, and UV is discussed.

Keywords Abiotic and biotic stress · Antioxidants · Oxidative stress · Phytochemicals · Plant secondary metabolites

1 Introduction

The lack of an immune system and active mobility of plants makes it very difficult for plants to resist environmental stresses (Meena et al. 2017). Therefore, plants develop a variety of defense responses, including secondary metabolites (SMs), to cope with the stresses that arise under variable growing conditions (Fig. 19.1). Although plant SMs do not directly affect plant metabolism and growth, they play an important role in the plant defense. Secondary metabolites are primary metabolite derivative compounds produced in plants when various physiological changes occur (Zandalinas et al. 2017). The SMs are substances produced by the plants to protect themselves in case of exposure to any stress condition (Isah 2019). Secondary metabolites play a role in alleviating biotic stresses such as fungi, viruses, and bacteria, as well as abiotic stresses (Jan et al. 2021). When plants are exposed to abiotic and biotic stress conditions, they can

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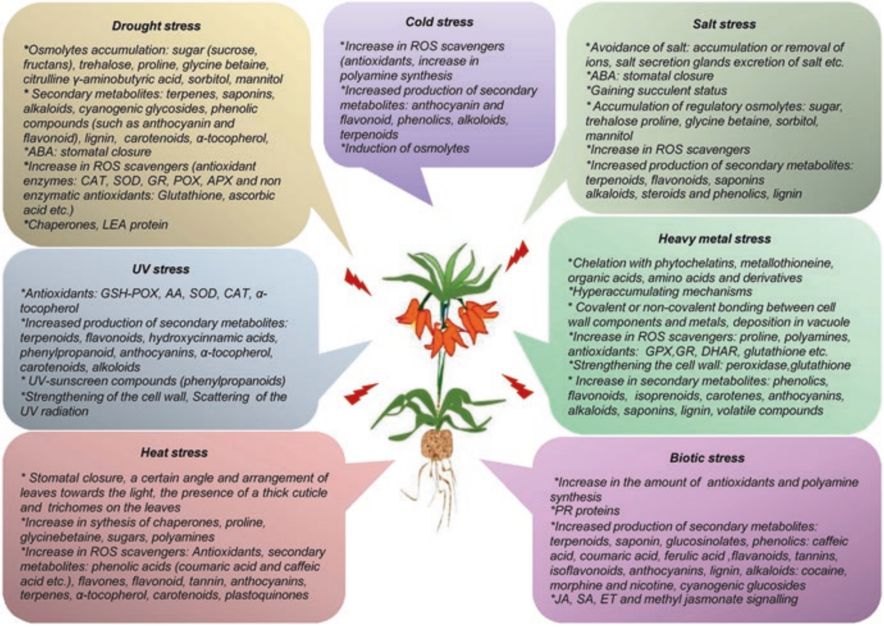

Fig. 19.1 Plant defense responses to stresses

produce more than one hundred thousand SMs through different metabolic pathways (Meena et al. 2017). The biosynthesis and accumulation of SMs vary depending on abiotic and biotic stress. In plants, SMs are classified as N-containing compounds, phenolic compounds (phenolic acids, lignin, flavonoids, stilbenes, coumarins, tannins), terpenes (sterol, carotenoids, glycosides, volatiles), and S-containing compounds (glutathione, glucosinolates, phytoalexins, thionins, defensins, alliin) (Fang et al. 2011; Ashraf et al. 2018; Jamwal et al. 2018; Isah 2019). Various SMs are synthesized by alternative mechanisms in plants. Mono-, di-, and tetraterpenes, phytol, plastoquinone, and carotenoids are synthesized from the methylerythritol phosphate pathway; sterols, sesquiterpenes, and triterpenes are synthesized from the mevalonate pathway; phenolic compounds are synthesized from the shikimic acid and malonic acid pathway; and N-containing compounds are synthesized from the tricarboxylic acid pathway (Jamwal et al. 2018). Additionally, SMs have different chemical structures such as aliphatic (polyamine, isoprene, ethylene), aromatic (phenolic acid), hydroaromatic (terpenoid, jasmonic acid), and heterocyclic (flavonoid) that enable them to perform different functions (Edreva et al. 2008; Ahanger et al. 2020). Phenolics are compounds synthesized in plants during normal development or when the plant is exposed to biotic or abiotic stress (Xiao et al. 2019). Phenolics are aromatic plant SMs that have a phenyl ring attached to one or more hydroxyl groups (Mathew et al. 2015). In plants, it generally accumulates in the vacuoles located in the center of epidermal cells and in the cells under the epidermis in the leaves and shoots. Some phenolic compounds are covalently bound to the plant cell wall, while others are found on the outer surfaces of the cuticle or plant organs. However, in some tree species, flavonoids accumulate in the nucleus, and this causes the formation of a DNA-flavonoid complex, which protects against oxidative damage (Falcone Ferreyra et al. 2012). The most well-known property of phenolics is the scavenging of reactive oxygen species (ROS). Phenolic compounds such as esters, flavonoids, lignins, and tannins act as antioxidants under abiotic stress conditions (Selmar 2008). Terpenes consist only of isoprene units, whereas terpenoids have isoprene units as well as additional units such as ketone, heterocyclic, and hydroxyl. Terpenoids are one of the important secondary metabolites that play a role in defense against both abiotic and biotic stress factors in plants (Porres-Martinez et al. 2016). Due to their antioxidant activities, terpenes can prevent abiotic-induced oxidative stress (Blanch et al. 2009). Like carotenoids, terpenoids protect plants against photodamage and oxidative stress by promoting photorespiration (Bartwal et al. 2013). ROS formed due to photoinhibition are scavenged by antioxidants such as tocopherols and carotenoids (Goh et al. 2011). It is assumed that the isoprene units in the structure of terpenes can alleviate stress conditions, as large protein complexes increase the interaction between themselves or with membrane lipids, providing the stability of the membrane structure (Sharkey and Yeh 2001). Phytohormones stimulate the synthesis of volatile terpenes as signal compounds in plant defense and stress responses (Wani et al. 2016). Phytoalexins are one of the compounds that play a role in the defense mechanism in plants. Diterpenes and sesquiterpenes function as phytoalexins (Hwang and Sung 1989). Most plant SMs contain nitrogen (N) in their structure. Alkaloids, cyanogenic glycosides, glucosinolates, and nonprotein amino acids are mainly nitrogen-containing SMs. Alkaloids have antifungal, anti-insecticidal, and antibacterial effects (Singh 2018). The inhibitory effects of alkaloids on glycosidase metabolism deter herbivores and provide protection owing to their singlet reactive oxygen scavenging properties (Mithöfer and Boland 2012). Cyanogenic glycosides are involved in plant defense against both herbivores and phytopathogens, while glucosinolates are involved in plant defense against biotic agents (Ballhorn 2011). Nonprotein amino acids have different roles, including antiherbivore, antimicrobial, and allelochemical activities (Mcsweeney et al. 2008).

Studies have shown that the amount of plant SMs generally increases during abiotic and biotic stresses. This demonstrates the importance of accumulation of secondary metabolites in improving stress tolerance. In this chapter, the role of SMs against various stress factors such as salt, drought, cold, high temperature, heavy metals, UV, and pathogens to which plants are exposed has been discussed.

2 Abiotic Stress and Secondary Metabolites

2.1 Secondary Metabolites in the Salt Stress Tolerance of Plants

Salt stress is one of the important abiotic factors limiting the growth and development of plants worldwide (Yang et al. 2018). Salinity causes osmotic stress, which causes dehydration, oxidative stress, ionic stress, and physiological drought in plant cells. This situation causes a decrease in cytosolic and vacuolar volumes, a decrease in photosynthesis and growth rate, the inability of plants to take water despite the presence of water, and a decrease in nutrient uptake (Ashraf et al. 2015). Plants exposed to salt stress accumulate sugar alcohols such as sorbitol, mannitol, pinitol, and carbohydrates such as fructose, glucose, sucrose, trehalose, raffinose, and stachyose. These osmolytes stabilize the cell membranes against lipid peroxidation and maintain turgor pressure (Slama et al. 2015). Trehalose has an important role in the regulation of ionic balance and redox state. Additionally, raffinose and galactinol accumulations were detected in the intercellular space of plants exposed to stress (Yan S et al. 2022). It has been reported that raffinose and galactinol protect cells against oxidative damage by scavenging the hydroxyl radical (Nishizawa et al. 2008). In addition to their osmolyte function, amino acids have cellular functions such as scavenging ROS and controlling the transport of ions. For example, proline not only acts as an osmolyte in plants under salt stress but also protects plants against oxidative damage as a ROS scavenger with its antioxidant property. A positive correlation was found between proline accumulation and salinity tolerance in *L. esculentum*, *M. sativa*, and *A. corniculatum* plants. An increase in phenolic levels was detected in *A. fragrantissima*, *C. annuum*, and *C. tinctorius* exposed to salt stress (Navarro et al. 2006; Verma and Shukla 2015; Golkar and Taghizadeh 2018). In addition to proline, increases in the levels of amino acids such as phenylalanine, aspartic acid, valine, arginine, cysteine, citrulline, alanine, arginine, and glutamine were determined in plants under salt stress (Cao et al. 2017). Glycine betaine, which is an osmoprotectant and also acts as a ROS scavenger, reduces lipid peroxidation by improving the activities of glutathione *S*-transferase (GST) and glutathione peroxidase (GPX) enzymes. It protects the 3D structures of proteins by preventing protein carbonylation (Hoque et al. 2007; Hasanuzzaman et al. 2014).

Plants provide a maximum tolerance to salt stress by increasing or decreasing the secondary metabolite production (Golkar and Taghizadeh 2018). Corn, wheat, rice, and potato plants exposed to salt stress produce secondary compounds such as terpenoids, flavonoids, alkaloids, steroids, and phenolics (Jan et al. 2021). It has been reported that high alkaloid and phenolic concentrations in plants are effective in scavenging ROS caused by salt stress. They are compounds with high antioxidant properties (Chunthaburee et al. 2015). Again, the increase in flavonoid levels under stress shows that their antioxidant properties are effective in increasing tolerance to oxidative damage as a ROS scavenger. The amounts of chlorogenic acid, caffeic acid, ellagic acid, ferulic acid, gallic acid, syringic acid, vanillic acid, and *p*-coumaric acid increase under salinity conditions to maintain redox homeostasis (Razieh et al. 2021). Similarly, the increase in terpene accumulation in plants under salt stress showed that these compounds act as ROS scavengers with their antioxidant properties against oxidative stress (Dahham et al. 2015; Porres-Martinez et al. 2016). Salt stress increased the concentrations of various alkaloids and essential oils in *Solanum nigrum*, *Catharanthus roseus*, *Rauvolfia tetraphylla*, *A. fragrantissima*, *Oryza sativa*, and *Datura innoxia* (Said-Al and Omer 2011; Chunthaburee et al. 2015; Verma and Shukla 2015). Again, in *S. nigrum* seedlings exposed to salt stress, increases in the expression of flavonoid genes and genes related to carotenoids were determined (Ben Abdallah et al. 2016). Hyoscyamine 6β-hydroxylase is known to act as the factor responsible for alkaloid synthesis in plants exposed to salt stress (Schlesinger et al. 2019). Salinity stress in *Matricaria chamomilla* increased the concentration of various phenolics such as caffeic, chlorogenic, and protocatechuic acid (Kováčik et al. 2009). Oliveira et al. (2020) reported that the accumulation of cellulose, lignin, and matrix polysaccharides in stem and root tissues of maize (*Zea mays*) under salt stress and the expression of genes from phenylpropanoid biosynthesis and the activities of enzymes were stimulated. Another study reported that *M. pulegium* and *N. sativa* increased the amount of phenolic compounds under salinity stress (Oueslati et al. 2010). Similarly, in *M. pulegium* exposed to salt stress, an increase was detected in the amount of pulegone, but no change was observed in the amount of another terpene, neomenthol (Karray et al. 2009). Additionally, in a study conducted on *H. annuus* L. exposed to salt stress, significant increases in the polyamine content of the roots of the plant were observed (Chiapusio et al. 2016). Some SMs produced in different plants exposed to salt stress are detailed in Table 19.1.

Many natural and synthetic metabolites have been used exogenously to increase plant tolerance to salt stress as osmoregulatory and ROS scavengers. Various amino acids (proline, glycine betaine, etc.), hormones (salicylic acid, methyl jasmonate, benzyl aminopurine, melatonin), sugars (trehalose), polyamines (spermine, spermidine, putrescine), and vitamins are among these metabolites (Patel et al. 2020). These exogenous applications are suggested as a promising approach to increasing tolerance to salt stress. Another promising approach to increasing salt tolerance is the manipulation of genes involved in the synthesis of SMs with protective properties.

2.2 *The Role of Secondary Metabolites in Reducing Drought Stress Damage in Plants*

Drought stress, which is one of the stresses that mostly affect agricultural productivity in the world, has been reported by the World Health Organization as a factor that will cause 700 million people to migrate to different regions by 2030 (WHO 2020). Drought stress occurs when the amount of water available in the soil cannot meet the needs of the plants and when atmospheric. This situation causes physiological, morphological, biochemical, precipitation is insufficient ecological, and molecular changes in plants by affecting many metabolic processes, such as the growth and development of plants, amount of biomass, photosynthesis and transpiration rate, stomatal conductance, and cellular dehydration (Xu et al. 2010; Mashilo et al. 2017). Drought stress causes the production of ROS such as superoxide, hydroxyl and singlet oxide, and hydrogen peroxide, which are quite toxic and reactive in plants. Reactive oxygen species, on the other hand, cause disruption of cellular homeostasis by damaging protein, carbohydrate, lipid, and DNA (Anjum et al. 2017; Ibrahim et al. 2019). However, plants induce an enhanced SM production,

Table 19.1 SMs accumulate in different plants under salts stress

Plant	SMs	Function	References
Matricaria chamomilla	Caffeic acid (hydroxycinnamic acid)	Antioxidant activity	El Mihyaoui et al. (2022)
Solanum lycopersicum	Polyamine	H_2O_2-mediated signaling	Raziq et al. (2022)
Olea europaea	Oleuropein (polyphenolic)	Antioxidant activity	Araújo et al. (2021)
Achillea fragrantissima	Alkaloid	Antioxidant activity	Elsharkawy et al. (2021)
Medicago sativa, Medicago arborea	Medicagenic acid and zahnic acid (saponins), hydroxycinnamic acids	Fortification of plant membranes, ROS scavenger, lignin formation	Sarri et al. (2021)
Cotton	Gossypol and tannin	With these metabolites, which increase with salt stress, slower growth of cotton aphids and reduction of reproduction rate	Ma et al. (2021)
Helianthus annuum	Chlorogenic acid (polyphenol)	ROS scavengers	Ma et al. (2020)
Solanum lycopersicum	Flavonoid	Antioxidant activity	Martínez et al. (2020)
Matricaria chamomilla	Chlorogenic acid (polyphenol)	Antioxidant activity (participate in the nonenzymatic detoxification of oxygen radicals and lipid peroxidation products)	Petrulova et al. (2020)
Apocynum venetum	Quercetin, kaempferol	Antioxidant activity	Xu et al. (2020)
Fragilariopsis cylindrus	Dimethylsulfoniopropionate, dimethylsulfoxide (dimethylsulfonium compounds)	Osmoregulators	Wittek et al. (2020)
Lycopersicon esculentum	Glycine betaine	Protective effect on the plant growth	Civelek & Yildirim (2019)
Datura innoxia	Hyoscyamine, scopolamine (alkaloids)	Antioxidant activity	Schlesinger et al. (2019)
Ocimum basilicum	Rosmarinic acid, caffeic acid, caftaric acid, cinnamyl malic acid, feruloyl tartaric acid, quercetin (phenolics)	Antioxidant activity, ROS scavengers, maintaining redox homeostasis	Scagel et al. (2019)
Datura innoxia	Hyoscyamine, scopolamine (alkaloids)	Antioxidant activity	Schlesinger et al. (2019)

(continued)

Table 19.1 (continued)

Plant	SMs	Function	References
Iranian licorice	Glycyrrhizin, betulinic acid, soyasaponins, and phytosterols (triterpenoids)	Antioxidant activity	Shirazi et al. (2019)
Salicornia brachiata	3,6-Dihydronicotine, portulacaxanthin II, papaverine, and secoberbine (alkaloids)	Antioxidant activity: ROS scavengers	Benjamin et al. (2019)
Salicornia brachiata (in root and leaves)	3-β-$_{D}$-Glucuronoside-28--glucoside, taxol, glycyrrhetinate (oleanolate) Desoxyhemigossypol-6-methyl ether, costunolide, heliespirone C (sesquiterpenoids)	Antioxidant activity, ROS scavengers	Benjamin et al. (2019)
Salvia mirzayanii	1,8-Cineole and linalyl acetate (increased), bicyclogermacrene (decreased) (terpenoids)	Antioxidant activity	Valifard et al. (2019)
Carthamus tinctorius	Proline	Antioxidant activity	Golkar and Taghizadeh (2018)
Solanum lycopersicum	Tomaditine (alkaloid)	ROS scavengers	Rivero et al. (2018)
Prosopis farcta	Caffeic acid (hydroxycinnamic acid)	Antioxidant: ROS scavengers	Sarker and Oba (2018)
Rauvolfia tetraphylla	Reserpine (alkaloid)	Antioxidant: ROS scavengers	Sytar et al. (2018)
Artemisia annua	Artemisinin (terpenoid)	ROS scavengers	Vashisth et al. (2018)
Chenopodium quinoa Willd.	Saponin	ROS scavengers, seed germination stimulant	Yang et al. (2017)
Triticum aestivum	Glycine betaine	Antioxidant, osmolyte	Tian et al. (2017)
Oryza sativa	Ferulic acid, p-coumaric acid (phenolic)	Antioxidant activity, ROS scavengers	Minh et al. (2016)
Citrus aurantium L.	Linalool, linalyl acetate, neryl acetate, geranyl acetate and α-terpineol, limonene and trans-β-ocimene	ROS scavengers	Eirini et al. (2017)
Catharanthus roseus	Vincristine ,vinblastine, ajmalicine (alkaloids)	Antioxidant activity	Fatima et al. (2015)
Gossypium	Tannic acid	Antioxidant activity	Wang et al. (2015)
Brassica oleracea	Sinigrin (aliphatic glucosinolate)	Plant water balance, involving aquaporins under salt stress, antioxidant activity	Martínez-Ballesta et al. (2015)

(continued)

Table 19.1 (continued)

Plant	SMs	Function	References
Solanum nigrum	Solamargine, solasonine (glycol alkaloids)	Salt stress enhanced production of total alkaloids	Muthulakshmi et al. (2013)
Plantago ovata	Saponins flavonoids	ROS scavengers	Zahra et al. (2012)
Capsicum annuum	Capsaicin	Reducing the negative effects of osmotic stress	Arrowsmith et al. (2012)
Fagopyrum esculentum	Rutin, orientin, isoorientin, vitexin	ROS scavengers	Lim et al. (2012)
Nicotiana tabacum	Proline, myo-inositol, GABA	Osmolyte, ROS scavengers	Zhang et al. (2011)
Glycine max	Abscisic acid	Stomatal closure	Gao et al. (2011)

phytohormonal response, and osmotic regulation to increase tolerance to drought stress (Larson 2018; Jogawat et al. 2021; Yadav et al. 2021a). Secondary metabolites reduce membrane lipid peroxidation with their antioxidant properties and serve as cell wall components to strengthen the cell wall against stress factors (Yang et al. 2018). Plants try to cope with drought conditions by increasing the amounts of SMs such as terpenes, saponins, alkaloids, and phenolics (anthocyanins and flavonoids) (Chen et al. 2011; Jaafar et al. 2012; Isah 2019). Generally, drought stress increases the concentrations of phenolic compounds by stimulating key genes in the phenylpropanoid pathway. Flavonoids, polyphenols, and terpenoids or isoprenoids are secondary compounds that are effective in scavenging increased ROS due to drought (Treml and Smejkal 2016). For example, increases in the levels of phenolic compounds were determined in *H. brasiliense*, *P. sativum*, *Chrysanthemum* sp., and *Salix* sp., which were exposed to drought stress (Dawid and Hille 2018; Hodaei et al. 2018; Larson 2018). In studies on cotton and potato, it has been determined that drought stress increases terpene and flavonoid synthesis (Payton et al. 2011; Zhang et al. 2014). In another study, it was determined that drought stress increased the amounts of glycosides, monoterpenes, terpenoids, and carotenoids in rosemary and grapes (Liu et al. 2014; Savoi et al. 2016). It has been reported that there is an increase in rosmarinic, ursolic, and oleanolic acid production in *P. vulgaris* and an increase in betulinic acid content in *H. brasiliense* (Chen et al. 2011; Jaafar et al. 2012). Razavizadeh and Komatsu (2018) found significant increases in the amounts of thymol, γ-terpinene, proline, and carbohydrates in seedlings exposed to mannitol-induced drought stress. Wang et al. (2019) found significant increases in the amounts of flavonoids, proanthocyanidins, and phenolics and in the activities of antioxidant enzymes in *Matteuccia struthiopteris* (L.) Todar. and *A. multidentatum* (Doll.) exposed to drought stress. Drought stress significantly increased the lignin and pectin content in the roots of soybean (Al-Hakimi 2006). Mazloom et al. (2020) reported that the treatment of lignin-based hydrogel reduced electrolyte leakage while increasing the water content and proline amount. The other groups of SMs produced in response to drought stress are N- and S-containing compounds. Increases in the amounts of alkaloids such as catharanthine, vindoline, capsaicinoid, vincristine, and vinblastine were determined in *C. roseus* under drought stress (Phimchan et al. 2012; Zhang et al. 2012). Cyanogenic glycosides act as antioxidants in water deficiency conditions, and the released hydrogen cyanide increases the amount of endogenous salicylic acid (SA) (Sun et al. 2018). Amino acids such as citrulline γ-aminobutyric acid, β-aminobutyric acid, β-alanine, and ornithine act as both antioxidants and osmolytes (Vranova et al. 2011). Glutathione and thionine are compounds that serve to scavenge ROS as powerful antioxidants. For some SMs produced in different plants exposed to drought stress, refer to Table 19.2. All these studies have shown that genes responsible for the biosynthesis of SMs can be used to increase drought tolerance. For example, overexpression of chalcone synthase in tobacco plant increased the amount of flavonoids (Zhao et al. 2019), and overexpression of the *GH4CL7* gene in *G. hirsutum* and increase in lignin biosynthesis increased resistance to drought stress (Sun et al. 2020). In another study, it was determined that overexpression of *IAA5*, *IAA6*, and *IAA19* genes in *Arabidopsis thaliana* stimulated glucosinolate accumulation (Salehin et al. 2019). It has been reported that overexpression of phosphoenolpyruvate carboxylase and an increase in anthocyanin biosynthesis in transgenic rice increase resistance to drought stress (He and Sheffield 2020). Therefore, manipulation and overexpression of genes related to the synthesis pathway of these metabolites to increase the amount of SMs have been suggested as one of the effective strategies to increase the resistance of plants to various stresses, including drought stress (Yadav et al. 2021b).

2.3 Cold Stress Alters Secondary Metabolism

Plants must grow at suitable temperatures to complete their growth and development. Both high and low temperatures require plants to cope with various challenges. A low temperature is one of the most detrimental stresses for plants living in temperate regions (Janská et al. 2010; Peng et al. 2015). Cold stress is divided into two classes: chilling stress, which is low temperatures between 0 and 15 °C without freezing (Chen L et al. 2020), and freezing stress, which is temperatures below 0 °C (Zhang et al. 2020). Freezing stress is more harmful to plants than chilling stress. It causes many damages such as chilling stress, a decrease in photosynthesis, osmotic damage, desiccation, oxidative stress, inhibition of protein synthesis and enzyme activities, a decrease in membrane permeability, ion leakage, and dehydration in cells and tissues (Ramakrishna and Ravishankar 2011). Low temperatures significantly affect plant growth and development by causing reduced root length, leaf loss, reduced leaf expansion, symptoms such as chlorosis and necrosis, and damage to reproductive organs such as pollen and pollen tube (Lyons 1973). Freezing stress causes the formation of ice crystals in both the intracellular and intercellular spaces. The ice crystal formation in the intercellular space causes dehydration and the withdrawal of water from the cell due to the decreasing water potential in the apoplastic

Table 19.2 Some SMs synthesized in plants exposed to drought stress

Plant	SMs	Function	References
Papaver somniferum	Narcotine (alkaloid)	Responses to oxidative stress	Kundrátová et al. (2021)
Pisum sativum	Phenolic compounds	Antioxidant: neutralizes free radical damage	Sutulienė et al. (2021)
Hypericum perforatum	Pseudohypericin, hyperforin, hypericin	Antioxidant activity	Torun et al. (2021)
Oryza sativa	Spermine (polyamine)	Maintain water balance, stabilize cell membranes, improve water use efficiently	Li Z et al. (2020)
Salvia officinalis	Carnosic acid (diterpenes)	Antioxidative protection	Pavić et al. (2019)
Vitis vinifera	Ferulic acid (hydroxycinnamic acid)	Antioxidant activity	Hodaei (2018)
Cola acuminata, P. somniferum camptothecin	Narcotine, morphine, and codeine (alkaloids)	ROS scavengers, antioxidant activity	Yang et al. (2018)
Chrysanthemum morifolium	Apigenin (phenolic compound)	Antioxidant activity	Hodaei et al. (2018)
Glycyrrhiza glabra	Glycyrrhizin	ROS scavengers Antioxidant activity	Hosseini et al. (2018)
Amaranthus tricolor	Hydroxybenzoic acids, hydroxycinnamic acids (flavonoids)	Antioxidant activity	Sarker and Oba (2018)
Mentha sp.	Cineole (monoterpenes)	Antioxidant activity	Llorens and Vacas (2017)
Thymus vulgaris	Cineole (monoterpene)	Antioxidant activity Electron-donating	Llorens and Vacas (2017)
Salvia officinalis	Monoterpenes	Antioxidant Massively increased in respond to drought stress	Radwan et al. (2017)
Pinus sylvestris	Abietic acid (terpenoids)	Resistance of water deficit	Sancho-Knapik et al. (2017)
Hypericum brasiliense	Quercetin (phenolic)	Antioxidant activity	Selmar et al. (2017)
Catharanthus roseus	Vinblastine (alkaloid)	Enhancing the activities of antioxidant enzymes	Liu et al. (2017)
Camellia sinensis	Catechins (phenolics)	Antioxidant activity	Wang et al. (2016)
Oryza sativa	Polyamines	Antioxidant activity	Berberich et al. (2015)
Zea mays	Zealexins and kauralexins	Osmotic stress tolerance	Vaughan et al. (2015)
Gossypium hirsutum	Ascorbic acid, glutathione and α-tocopherol	Antioxidant activity	Hussien et al. (2015)

(continued)

Table 19.2 (continued)

Plant	SMs	Function	References
Eucomis autumnalis	Iridoids (monoterpenes)	Antioxidant activity	Masondo et al. (2014)
Triticum aestivum	Glutathione, homotaurine	ROS scavengers: against oxidative damage Maintain of cellular redox balance	Zechmann (2014)
Hypericum brasiliense	Rutin (phenolic)	Antioxidant activity	Dal Belo (2013)
Salvia officinalis	Monoterpenes	Promoting reactions which consume NADPH-H^+ Increased activity of enzyme corresponding in this reaction	Selmar and Kleinwachter (2013)
Labisia pumila	Phenolic compound	Induction in activity of PAL Increased in photosynthesis and quantum yields	Jaafar et al. (2012)
Catharanthus roseus	Vinblastine, vincristine, vindoline, catharanthine (alkaloids)	Regulating nitrogen content	Zhang et al. (2012)
Triticum aestivum	Spermine (polyamine)	Increased cell water status Osmoprotectants	Alcázar et al. (2010)
Citrus reticulata	Spermine (polyamine)	Antioxidant: ROS scavengers	Shi et al. (2010)
N. tabacum	Nicotine (alkaloid)	Ripening in leaves	Cakir and Cebi (2010)
Scrophularia ningpoensis	Catalpol, harpagide, aucubin, harpagoside (glycosides)	Antioxidant: ROS scavengers enhancing the activities of antioxidant enzymes	Wang et al. (2010)

space. Intracellular ice formation often leads to cell death, as it causes membrane rupture, changes in membrane permeability, mechanical deterioration in the protoplasm, and deformation of the cell wall (Levitt 1980; Steponkus 1984). The damage to the cell membrane of the cold is largely due to dehydration. A low temperature causes changes in the lipid content of the cell membrane, with an increase in phospholipid content and a decrease in the ratio of cerebrosides in general. Fatty acid saturation of the cell membrane of plant species and its sensitivity to cold are interrelated (Uemura and Steponkus 1999). Since the ratio of saturated fatty acids is higher in the membranes of plants that are sensitive to cold, membrane leaks occur as the membrane tends to pass from the liquid mosaic phase to the solid gel form during cold stress. Cold-tolerant plants has a lower transition temperature (the temperature at which it changes from the liquid mosaic phase to the gel phase) since it has higher unsaturated fatty acids (Wang et al. 2006). The organelle that is firstly and most severely affected by cold stress is chloroplasts (Liu et al. 2018). It causes changes in the structure of thylakoids and swelling (Kratsch and Wise 2000).

Additionally, low temperatures also decrease photosynthesis due to the reduction of stomatal opening and the inhibition of CO_2 exchange. However, since the photosynthetic apparatus captures more photons than necessary, PS II inhibits electron transport and causes photoinhibition, and photodamage occurs with the degradation of the D1 reaction center protein (Szilard et al. 2005; Yang et al. 2017). Under stress conditions, ROS are produced in the chloroplasts, mitochondria, and peroxisome and apoplastic regions of plants (Xie et al. 2019). The main reason for the formation of ROS in chloroplasts is stomatal closure, as well as restrictions in CO_2 fixation due to disruptions in the electron transport chain (ETC) (Mignolet-Spruyt et al. 2016). Similarly, disruptions in the ETC in the mitochondria cause ROS production. ROS induce lipid peroxidation; deterioration of DNA, lipid, and carbohydrate structure; and inactivation of enzymes (Foyer and Noctor 2005). Plants increase the biosynthesis of different SMs to be protected from these damages. In a study conducted on *O. basilicum* L., it was determined that the application of 4 °C cold stress increased the amounts of camphor, bornyl acetate, eugenol, methyl chavicol, and methyl eugenol, as well as the the activity of superoxide dismutase (SOD) and GPX antioxidant enzymes (Rezaie et al. 2020). In the study, it was also determined that the total phenolic and flavonoid amounts were increased compared with the control group. These increases in the activities of antioxidant enzymes and the amounts of total phenolic and flavonoid levels have been associated with protection against ROS toxicity. This high increase in the amount of phenolic compounds was attributed to the increase in phenylalanine ammonia-lyase (PAL) activity. Phenolic compounds are SMs with the potential to scavenge ROS and prevent lipid peroxidation as electron and hydrogen atom donors (Huang et al. 2019). While flavonoids and phenolics serve as scavengers, unsaturated fatty acids also help increase tolerance to cold by improving cell membrane fluidity (Li J et al. 2019; Li Q 2020).

Sun et al. (2021) detected increases in the amount of free fatty acids, lysophosphatidylcholines, and lysophosphatidylethanolamine, which are biomarkers of freezing damage, in cold stress-tolerant and cold stress-sensitive *A. arguta*. These accumulations indicate membrane damage caused by cold stress. It was determined that the amounts of phenolic compounds, such as hydroxytyrosol, tyrosol, and oleuropein, and the enzyme activities of PAL and polyphenol oxidase increased in the leaves of olive trees exposed to −7 °C (Ortega-García and Peragon 2009). The authors associated polyphenol oxidase and oleuropein with the antioxidant defense system. Additionally, it was determined that the accumulation of anthocyanin and flavonoid in *A. thaliana*, *Petunia hybrid*, and *Z. mays* plants exposed to cold stress (Janas et al. 2002; Yang et al. 2018); the total phenol concentrations and particularly the genistein amount in the roots of *Glycine max* plant (Janas et al. 2002); and the chlorogenic acid production in *M. domestica* tree were increased. It has been reported that low-temperature stress also increases the synthesis of phenolic compounds, which participate in the structuring of the cell wall and serve in the biosynthesis of lignin and suberin (Griffith and Yaish 2004). However, Krol et al. (2015) reported that long-term cold stress decreases the amount of phenolic compounds, and this may be related to the slowing down of some elements of the secondary metabolism. More phenolic reduction was found in the cold-sensitive *V. vinifera* cultivar than the cold-tolerant cultivar. However, it was also determined that the total level of phenolic compounds and antioxidant activity in the cold-resistant cultivar were higher than that in the susceptible cultivar. Glycosylated terpenoids are SMs that play a role in increasing tolerance to cold stress (Yeshi et al. 2022). Zhou et al. (2017) found an increase in the amount of nerolidol in frost-damaged tea and suggested that this increase is a response to cold stress. Zhao et al. (2020) reported that increases in the level of glycosylated sesquiterpene and nerolidol glucoside, which have antioxidant and ROS scavenging ability, in the tea under cold stress may be effective in increasing tolerance to cold stress. Additionally, with the effect of cold stress, terpenoids, such as β-phellandrene, (E)-β-ocimene, δ-elemene, α-humulene, β-caryophyllene, withanolide A, withaferin A, and nerolidol glucoside, and increases in the concentration of phenolics, such as pelargonidin, anthocyanins, anthocyanidins, genistein, and daidzein, and alkaloids, such as vindoline, were detected (Janas et al. 2002; Dutta et al. 2007; Copolovici et al. 2012; Mir et al. 2015; Jeon et al. 2018; Zhao et al. 2020).

Data obtained from studies on different plants indicate that polyamines are also effective in increasing tolerance to cold stress. It is stated that the polyamine levels of plants such as *T. aestivum*, *M. sativa*, and *P. antiscorbutica* increase considerably under cold stress, and this increase in the amount of polyamine may be related to cold tolerance (Akula and Ravishankar 2011; Kovacs et al. 2011). In a similar study, it was reported that putrescine and polyamines of spermine and melatonin synthesized in the *D. carota* plant protect against apoptosis caused by cold stress (Lei et al. 2004). In another study, it was stated that the plant *S. tuberosum* produces polyamine to eliminate the harmful effects of ROS formed by the effect of cold stress (Kou et al. 2018). It increases tolerance to cold by preventing cytolysis by binding to phospholipids in the cell membranes of polyamines (Li and He 2012). Some other SMs under cold stress are mentioned in Table 19.3.

Another response used by plants against cold stress is carbohydrate metabolism. Carbohydrates serve to retain water in cells, stabilize cell membranes, and scavenge ROS. While the decrease in temperature decreased the water potential and starch amount, it increased the amount of soluble sugar, sucrose, mannitol, and osmotin (PR-5 protein) (Antognozzi et al. 1993; D'Angeli and Altamura 2007; Eris et al. 2007). Amino acids such as betaine, arginine, and proline also act as osmoprotectants in increasing tolerance to cold stress (Meilong et al. 2020).

With the activation of genes responsible for the synthesis of SMs, the tolerance level and adaptation of plants to various stress conditions can be achieved (Jan et al. 2021). Determining the genetic responses of plants to stress is one of the important research areas for developing cold stress-tolerant plants. *GOLS1*, *GOLS3*, *GR-RBP3*, *HYDROLASE22*, *RHL41*, *CAU1*, *PME41*, *DREB26*, and *CRK45* are necessary genes for increasing the tolerance of *Camellia sinensis* to cold stress (Samarina et al. 2020). In the study of *O. basilicum* L., it was determined that cold stress (4 °C) increased the amounts of methyl eugenol and methyl chavicol and that these metabolites were in a positive correlation with the expression levels of eugenol synthase 1 (*EGS1*) and eugenol O-methyl transferase (*EOMT*) genes. Therefore, *EGS1* and *EOMT* genes have been proposed as candidate genes for genetic manipulation of the

Table 19.3 Different SMs synthesized in plants under cold stress

Plant	SMs	Function	References
Camellia weiningensis, Camellia oleifera	ABA, IAA, prenol lipids, organooxygen compounds, fatty acyls	Stomatal closure and decreasing water loss Signal transduction, energy storage	Xu et al. (2022)
Camellia sinensis	Catechin, dihydroxyphenylacetic acid, procyanidin B2, galactose	ROS scavengers Osmotic regulatory	Yan F et al. (2022)
Zea mays	ABA, raffinose, trehalose-6-phosphate, proline, monosaccharides	ABA: upregulation of *LEA* genes Raffinose: protecting the photosynthetic apparatus from oxidative damage, osmoprotectants	Guo et al. (2021)
Triticum aestivum	Putrescine, spermine, spermidine (polyamines)	Antioxidant: ROS scavengers	Alcázar et al. (2020)
Saccharum spontaneum	Trehalose (sugars), brassinosteroids	Osmotic regulatory, signal transduction	Yang et al. (2020)
Glycine max	Phenolics	Antioxidant: ROS scavengers, redox properties, inhibitors of lipid peroxidation in cell membrane	Ozfidan-Konakcı et al. (2019)
Artemisia annua	Artemisinin (terpenoid)	ROS scavengers Stimulation of SOD activity	Vashisth et al. (2018)
Fagopyrum tartaricum	Anthocyanins, proanthocyanidins	Antioxidant: ROS scavengers	Jeon et al. (2018)
Brassica oleracea L. var. *italica Plenck cv. 'Lord*	Glucosinolates, flavonols, and vitamin C	Antioxidative properties	Mølmann et al. (2015)
Withania somnifera	Withanolide A , withaferin A	Antioxidant: ROS scavengers	Mir et al. (2015)
Centella asiatica L.	Asiaticoside, madecassoside (triterpene glycosides)	Plant cell adaptation	Plengmuankhae and Tantitadapitak (2015)
Vitis vinifera	Caffeic, ferulic acid, *p*-coumaric acid	Antioxidant: ROS scavengers	Krol et al. (2015)
Artemisia annua	Artemisinin (sesquiterpene)	Antioxidant: ROS scavengers	Brown (2010)
Capsicum annuum L.	Total phenolic, proline, total protein	Antioxidant: ROS scavengers	Koç et al. (2010)

phenylpropanoid biosynthesis pathway in increasing the cold tolerance of *O. basilicum* (Rezaie et al. 2020). It was determined that cold stress increased the levels of steroidal alkaloids, glycoalkaloids, phenolic acids, and flavonoids in *S. viarum*, a medicinal plant (Patel et al. 2022). It has been reported that there is a correlation between the transcription levels of genes involved in the biosynthesis of glycoalkaloids and flavonoids and the amounts of these metabolites. Recent research confirmed the expression and posttranslational modifications of genes that control the production of SMs to increase plant tolerance to such stresses.

2.4 Production of Plant Secondary Metabolites Under Heat Stress

In the last five decades, increases in CO_2 and other greenhouse gases because of human activities have caused the world to warm by approximately 0.85 °C (Bein et al. 2020). This degree may seem small, but it is not. Even an increase of 1 °C is the beginning of the road to disaster. When an increase of 2 °C is reached, the temperatures normally seen once every decade will begin to be seen every 2 years. When it reaches 1.5 °C, this temperature increase will be seen almost every 5 years. Similar results will be valid for excessive precipitation and drought. Therefore, heat stress is one of the important factors affecting the growth and development of plants now and in the future. High temperatures cause deterioration of membrane integrity of plants, a decrease in photosynthesis rate, and premature aging of plants. Seed germination inhibition, growth reduction, and excessive ROS production are among their main adverse effects (Hasanuzzaman et al. 2013). Heat stress induces the production of alkaloid and phenolic compounds in various plant species (Ramakrishna and Ravishankar 2011). It has been stated that *F. vesca*, *S. officinarum*, and *L. sativa* plants exposed to heat stress produce high amounts of phenolic acids, antioxidants, flavones, and anthocyanins (Wu et al. 2007). α-Tocopherol and plastoquinone, which are synthesized in high amounts in *L. esculentum* plant under heat stress, facilitate photosynthesis by acting as antioxidants and electron carriers (Havaux 2020). Similarly, the continuous synthesis and emission of terpenes are effective in countering the damage caused by heat stress (Korankye et al. 2017). With the effect of heat stress, increases in the concentrations of terpenoids such as β-phellandrene, 2-carene, α-phellandrene, limonene in *S. lycopersicum* and α-caryophyllene, and β-farnesene in *D. carota* were determined. Additionally, a high amount of flavonoid production has been reported in the *O. basilicum* plant, which is exposed to high-temperature stress (Al-Huqail et al. 2020). Isoprenes synthesized from the mevalonate pathway in plants help to heal the photosynthetic apparatus damaged by the effect of heat shock and to improve thermotolerance (Li and Sharkey 2013). Similarly, increases in the concentration of isoprene terpenoids were detected in *Q. rubra* exposed to heat stress (Hanson and Sharkey 2001). Carotenoids and phenolic compounds such as flavonoid, lignin, and tannin show antioxidant properties under heat stress, scavenge ROS, and protect against oxidative damage (Sehgal et al. 2016). There has been an increase in the amount of anthocyanin, coumaric acid, and caffeic acid phenolics in *D. carota* with the effect of heat stress (Commisso et al. 2016). Alterations in the amount of different SMs under heat stress are mentioned in

Table 19.4 Different SMs synthesized in plants under heat stress

Plant	SMs	Function	References
Arabidopsis thaliana	Carbohydrate modifications, cutin, wax, heat shock proteins	Oxidative stress resistance, cell wall remodelling	Xiang and Rathinasabapathi (2022)
Heracleum sosnowskyi	Furanocoumarin (xanthotoxin, bergapten, isopimpinellin), proline, anthocyanins (osmolytes)	Antioxidant activity	Rysiak et al. (2021)
Solanum lycopersicum	Gibberellins	Thermotolerance and delayed leaf senescence	Jahan et al. (2021)
Medicago sativa	Flavonoid	Powerful antioxidant capacity	Chen S et al. (2020)
Lepidium sativum	Anthocyanin, carotenoid	Antioxidant activity	Al-Sammarraie et al. (2020)
Daucus carota	Terpenoids, phenolics	Antioxidant activity: ROS scavengers	Ahmad et al. (2019)
Artemisia sieberi alba	Flavonoid, tannins, phenols, alkaloid, terpenoids, steroid, proline, mannitol, inositol, and sorbitol (osmolyte)	Antioxidant activity: ROS scavengers, osmoprotectants	Alhaithloul (2019)
Salix spp. hybrid *"Terra Nova"*	Increase in isoprene, decrease in flavonoid	Antioxidant activity, thermotolerance properties	Austen et al. (2019)
Elodea nuttallii, *Potamogeton crispus*, *Vallisneria asiatica*	Carotenoids	Deactivation of H_2O_2	De Silva and Asaeda (2017)
Psychotria brachyceras	Brachycerine (monoterpene-indole alkaloid)	Antioxidant activity against singlet oxygen hydroxyl and superoxide radicals	Da Silva Magedans et al. (2017)
Solanum lycopersicum cv. Mato	α-Phellandrene; β-caryophyllene, 2-carene, limonene (terpenoids)	Antioxidant activity	Copolovici et al. (2012)
Solanum lycopersicum	Volatile isoprenoids	ROS scavengers	Vickers et al. (2009)

Table 19.4. Under heat stress, the synthesis of SMs generally increases, leading to the protection of cellular structures from oxidative damage (Sehgal et al. 2016), but there are also reports emphasizing a decrease in the concentration of SMs in plants under heat stress. Temperature is an important environmental factor affecting anthocyanin metabolism in plants. In some studies, it has been reported that high temperatures inhibit the expression of genes that control anthocyanin synthesis and the accumulation of activators (Wang et al. 2016; Rehman et al. 2017). It has been reported that there is a decrease in the levels of anthocyanins and carotenoids in many species such as *V. vinifera* and Brassicaceae, due to partial pigment degradation and reduced gene transcription in plants under the

high-temperature stress (Yang et al. 2018). Again, in a recent study, Liu et al. (2019) reported that a high temperature decreased the amount of anthocyanin in the *S. tuberosum*. Authors pointed out that the reason for this decrease was the directing of the flow to lignin and chlorogenic acid biosynthesis of isoprene, a more beneficial metabolite with antioxidant and thermotolerance properties (Wahid et al. 2012; Austen et al. 2019).

Plant survival strategies against high temperatures include osmoprotectants such as chaperones, proline, glycine betaine, sugars, and polyamines (Sakamoto and Murata 2002; Gepstein et al. 2005; Chen et al. 2007). In the study conducted on *V. aconitifolia* exposed to 42 °C for 7 days, increases in the amount of proline and total sugar and the activities of antioxidant enzymes were shown as evidence of thermotolerance (Harsh et al. 2016).

2.5 Plant Secondary Metabolites Produced in Response to Heavy Metal Stress

Heavy metal stress is one of the main abiotic stress factors that prevent metabolic processes in plants due to reasons such as contamination of soil, air, and water, high bioaccumulation, toxicity, and lowering the quality of natural products produced by plants (Keunen et al. 2016; Sahay and Gupta 2017). Heavy metal stress causes changes in the conformation of chloroplasts in plants and increases the efficiency of various signaling (ethylene and jasmonic acid) pathways that stimulate aging (Keunen et al. 2016). They produce ROS and damage DNA, RNA, and protein by causing oxidative stress (Kumar and Sharma 2018). They decrease the amount of chlorophyll *a* and *b* due to the inhibition of enzymes involved in the biosynthesis of pigments (Rai et al. 2016). For example, it has been reported that Pb stress decreases the amount of photosynthetic pigments even in *B. juncea*, which is used in heavy metal phytoremediation (Chandra and Kang 2016). Plants protect themselves from the toxicity of metals by various mechanisms. These mechanisms include antioxidant defense, binding to the cell wall or deposition in the vacuole, returning the metal ions in free form or complex form to the rhizosphere, synthesis of low molecular weight organic acids, accumulation of osmoprotectants, chelate formation with sulfur donor phytochelatins and metallothioneins, and production of SMs such as isoprenoids, phenolics, flavonoids, and carotenes (Dalvi and Bhalerao 2013; Umar et al. 2013; Khare et al. 2020). All these studies indicate that SMs can be an effective strategy for reducing the toxicity of heavy metals (Table 19.5). Since the cell wall is the first barrier that metals encounter, cell wall components protect the protoplast by binding to metals. For example, the functional groups of lignin bind more than one metal ion to itself. Phenolic compounds such as lignin, quercetin, coumaric acid, catechin, ferulic acid, and myricetin protect the cell against metal stress by contributing to the increase in cell wall thickness (Guo et al. 2008; Krzesłowska 2011). The

Table 19.5 Biosynthesis of some SMs in plants under heavy metal stress

Plant/metal	SMs	Function	References
Hypericum perforatum/Se	Hypericin, hyperforin (essential oil) phenolic	Antioxidant activity	Nazari et al. (2022)
Salvia sclarea/Cd	Phenolic, anthocyanins, carotenoids	ROS scavengers, carotenoids reduce oxidative stress in chloroplasts	Dobrikova et al. (2021)
Imperata cylindrica/Cu	Hydroxycinnamic acid, cyanidins, flavons	Antioxidant activity, cyanidins protect the photosynthetic complex	Vidal et al. (2020)
Belamcanda chinensis/Cu	Tectorigenin, tectoridin, iristectorigenin A, (flavonoids)	ROS scavengers, antioxidant activity	Zhu et al. (2020)
Radish sativus/Cd, Cr, Pb	Glutathione	ROS detoxification, phytochelatin synthesis, chelation of metals	Gao et al. (2020)
Solanum lycopersicum/Ni	Phenols, anthocyanins, flavonoids	ROS scavengers	Jahan et al. (2020)
Medicago sativa/Cd	Xylogalacturonan	Strengthening cell wall (with pectin methylation)	Gutsch et al. (2019)
Tagetes minuta L./Pb	Sabinene, limonene, b-ocimene, b-citral, verbenone (volatile compounds)	ROS scavengers, activation of defense genes	Pazcel et al. (2018)
Oryza sativa/Cd	Phenylalanine, methionine, histidine, lysine	Mitigating levels of metal ions	Fu et al. (2018)
Oryza sativa/Cr	p-Coumaric, caffeic, and gallic acids, protocatechuic, p-hydroxybenzoic	Antioxidant activity, chelation	Dubey et al. (2018)
Corylus avellana/AgNPs	Taxol, baccatin II (taxanes)	Antioxidant activity	Jamshidi and Ghanati (2017)
Zea mays/Cd, Cu, Pb	Chlorogenic acid, vanillic acid (phenolic)	Antioxidant activity	Kısa et al. (2016)
Vigna radiata/Cd	Alkaloids	Antioxidant activity	Nahar et al. (2016)
Vaccinium corymbosum/Cd	Phenolics	Antioxidant activity	Manquián-Cerda et al. (2016)
Tagetes minuta L./Pb	β-Ocimene, α-thujone (volatile compounds)	Activation of defense genes	Sosa et al. (2016)
Prosopis farcta/Pb	Salicylic acid, ferulic acid, vitexin, daidzein, phenolic acids	Signaling molecules Metal chelation ROS scavengers	Zafari et al. (2016)
Vitis vinifera	Flavonoids	Antioxidant activity	Leng et al. (2015)
Solanum nigrum, Parthenium hysterophorus/Cr	Malic and citric acid	Metal binding	UdDin et al. (2015)

(continued)

Table 19.5 (continued)

Plant/metal	SMs	Function	References
Abelmoschus esculentus/Cd, Pb, Zn	Nonprotein thiols	Antioxidant activity	Kandziora-Ciupa et al. (2013)
Vitis vinifera/Co, Ag, Cd	Resveratrol, sesquiterpenoid, phytoalexin	Antioxidant activity	Cai et al. (2013)
Lepidium sativum/As	Lepidine, proline, ascorbic acid	Chelation antioxidant activity	Umar et al. (2013)
Helianthus annuus/Cu	*p*-Coumaric acid	Metal precipitation	Meier et al. (2012)
Artemisia annua/As	Artemisinin	Antioxidant activity	Rai et al. (2011)
Phaseolus vulgaris	Phenolic	ROS scavengers: against oxidative damage, hydrogen donors, metal-chelating capacity, reducing agents	Hamid et al. (2010)
Matricaria chamomilla/Cd, Cu	Caffeic acid, ferulic acid, *p*-coumaric acid, chlorogenic acid, salicylic acid, vanillic acid, *p*-OH benzoic acid, syringic acid	Antioxidant activity, ROS scavengers, chelation	Kováčik et al. (2009)

peroxidase (POX) oxidizes monolignols to radicals that combine with the lignin polymer. These radicals then combine to form the lignin polymer and thus contribute to the strengthening of the cell wall (Wang et al. 2013). Moreover, phenols, alkaloids, and saponins can prevent the harmful effects of metal toxicity by forming stable complexes with different metals or by chelation with metals (Berni et al. 2019; Nobahar et al. 2021). Plants exposed to metal stress secrete root exudate, which includes metabolites such as phenolics, amino acids and derivatives, sugar and organic acids, and proteins, and mucilage into the soil. These metabolites chelate metals in the rhizosphere and apoplast, preventing them from entering the symplast and reducing the toxicity in the cytoplasm (Nigam et al. 2001). Histidine and nicotinamide are amino acids that play an important role in the chelation of heavy metals. Nicotianamine, a free amino acid, can bind metals such as iron (Fe), copper (Cu), and nickel (Ni) (Higuchi et al. 1999). Histidine, which is chelator-like nicotinamide, also forms a complex with zinc (Zn) and Ni, reducing heavy metal toxicity (Salt et al. 1999; Richau et al. 2009). Proline, another amino acid, acts as an osmoregulator in the regulation of the water balance disorder that occurs during heavy metal stress. It also detoxifies $^{\bullet}OH$ and $^1O_2$ and increases the activities of intracellular antioxidant enzymes (Mourato et al. 2012). Organic acids such as malate, malonate, oxalate, tartrate, citrate, and aconitate reduce toxicity by forming chelates with metals in the cytosol (Anjitha et al. 2021). Metallothioneins, which are rich in cysteine, reduce metal toxicity by binding to metals with the thiol group of cysteine (Zhou and Goldsbrough 1994). They also increase tolerance to oxidative stress by acting in ROS detoxification. Glutathione is an important ROS and methylglyoxal (a cytotoxic compound) scavenger and an antioxidant effective in the chelation of metals (Saito et al. 2011). Additionally, phytochelatins, a cysteine-rich polypeptide family that plays an important role in reducing metal toxicity, are also synthesized from glutathione (Yang et al. 2005). Like metallothioneins, the heavy metal is accumulated in the vacuole by forming a complex with the heavy metal with the thiol groups they have, and its free circulation in the cytosol is limited (Sanit`a Di Toppi and Gabbrielli 1999). Anthocyanins (cyanidin, delphinidin, petunidin, etc.) with adjacent hydroxyl groups have strong metal-chelating effects (Tang and Giusti 2020). Janeeshma et al. (2020) found a high accumulation of anthocyanins in maize under Zn stress. Cyanidin gained electrons and formed a complex with zinc, increasing the tolerance to high Zn stress. The phenolic and flavonoid compounds in *G. pseudochina* plants chelate Zn and Cd metals. It has also been reported that *Cinchona* alkaloids can form complexes with different metals, such as Fe, lead (Pb), Cu, and cobalt (Co), and that phenolic compounds such as catechin and juglone can form complexes with Fe (Chobot and Hadacek 2010). It has been determined that tannins extracted from plant seeds can chelate metals such as Zn, Fe, and Cu (Karamac 2009). Many studies conducted to date show that various SMs synthesized under heavy metal stress play an active role in reducing the damage of heavy metals in the cytoplasm by forming chelates with metals.

Antioxidants such as tocopherol, carotenoids, glutathione, ascorbate, and phenolic compounds, such as coumarin, tannin, lignin, anthocyanin, and flavonoids, act as ROS scavengers in plants exposed to heavy metal stress (Maleki et al. 2017). Phenolic compounds and flavonoids, which act as antioxidant compounds due to their hydrogen atom or electron-donating abilities, can directly scavenge ROS (Okem et al. 2015). Phenolic compounds and flavonoids with redox properties act as antioxidants and ROS scavengers and can chelate metals (Rice-Evans and Paganga 1996). For example, it was determined that increased phenolic compounds in *P. vulgaris* exposed to Pb stress scavenge ROS and reduce lipid peroxidation and oxidative damage (Neelofer et al. 2010). The increase in phenolic, flavonoid, and anthocyanin concentrations in *Salvia sclarea* increased its tolerance to Cd metal (Dobrikova et al. 2021). These metabolites have been reported to act as ROS scavengers. It has been determined that Cu metal increases the production of phenolic and lignin compounds in *P. ginseng* and *W. somnifera* plants (Khatun et al. 2008), and Cu^{2+} and Cd^{2+} metals stimulate the biosynthesis of betalain, shikonin, and digitalin (Trejo et al. 2001). Zn^{2+} metal increased lepidine production in *L. sativa* plant (Saba et al. 2000). Thomas et al. (2011) reported that Cd and Co metals stimulated diosgenin accumulation in *T. foenum-graecum*. $AgNO_3$ and $CdCl_2$ increased the concentration of scopolamine and hyoscyamine, and Pb increased the synthesis of phenolic compounds (Winkel-Shirley 2001). The downregulation of the hyoscyamine 6β-hydroxylase enzyme responsible for the synthesis of scopolamine by silver ions increased the amount of scopolamine (Pitta et al. 2000). Winkel-Shirley (2001) reported that plants grown on aluminum-containing soils have a high flavonoid content, and this may help reduce damage caused by oxidative stress.

2.6 UV Stress Affects the Production of Secondary Metabolites in Plants

Light is an important abiotic factor that can affect plant growth, production, and quality of SMs. The responses of different plant species to UV stress differ depending on the signal transmission mechanism, the amount and intensity of light, and the effect of gene expression (Parikrama and Esyanti 2014). UV-B radiation causes the formation of ROS such as H_2O_2 in plants, damaging DNA and chloroplasts, specifically photosystem II (Del Valle et al. 2020). Plants can adapt to UV changes by accumulating various SMs such as terpenoids, flavonoids (flavonols, anthocyanins, catechins, etc.), hydroxycinnamic acids, phenylpropanoids, tannins, cyanogenic glycosides, α-tocopherol, glucosinolates, carotenoids, and alkaloids (Morales et al. 2010; Jan et al. 2021). Ferulic acid, caffeic acid, and *p*-coumaric acid are the most effective phenolics for reducing the harmful effects of UV. Most phenols, such as hydrocinnamic acids, *p*-coumaric acid, and ferulic acid, help in cell wall formation and represent the beginning of lignification (Antonova et al. 2012). Some other SMs in different plants exposed to UV stress and their defense effects are presented in Table 19.6.

SMs accumulated in the epidermal layers of the cells of plants exposed to UV-B stress protect the underlying sensitive tissues against the harmful effects of stress. However, Zhao et al. (2013) reported that long-term exposure to UV-B stress may decrease the protectiveness of these metabolites due to less photosynthate production. The photosensitive and highly stable cellular components absorb excess UV-B and prevent photodamage. UV-B and UV-C stimulate flavonoid synthesis and synthesis of compounds synthesized from the phenylpropanoid pathway (Warren et al. 2003). Flavonoids and phenylpropanoid derivatives, deposited in the epidermal cells, significantly inhibit the effect of UV stress as a UV-absorbing sunscreen (Mazza et al. 2000). In addition to flavonoids, compounds such as carotenoids and anthocyanins accumulate in the upper epidermis of the leaves and form UV-B blocks as UV absorbers and prevent the formation of ROS (Hideg et al. 2013). Flavonoids alleviate photoinhibition and photooxidative damage by eliminating the harmful effects of ROS, owing to their radiation absorption (UV-absorbing) properties (Jordan 2002). UV-B stress increases the concentration of flavonoid content in *H. vulgare*, *P. incarnata*, *P. quadrangularis*, *P. edulis*, and *K. pinnata*, polyamines in *C. sativus*, and flavonols in *P. abies* (Antognoni et al. 2007). As it is known, the cell wall of plants is the largest carbon source in the biosphere. The cell wall consists of polysaccharides such as cellulose and hemicellulose, as well as pectin, lignin, structural proteins, and other compounds. Some studies have shown that while UV-B increases the level of phenolic compounds in the structure of the cell wall, it causes relaxation in the cell wall with the release of -CH_4 from pectin (Ruhland et al. 2005; Messenger et al. 2009). In another study, Cuzzuol et al. (2020) determined that UV-B increased polyphenols such as flavonoids and lignins and the total antioxidant capacity in sun-tolerant *Paubrasilia echinata*. However, it was found that there was an increase in lignin content despite the decrease in hemicelluloses in

Table 19.6 Different SMs synthesized in plants exposed to UV stress

Plant	SMs	Function	References
Amaranthus tricolor L.	Phenolic compounds, flavonoids, anthocyanin, ascorbic acid, betalain	Antioxidant activity, UV-B-absorbing compounds	Wittayathanarattana et al. (2022)
Fagopyrum esculentum	Phenolics	Antioxidant activity	Hornyák et al. (2022)
Solanum lycopersicum	Diterpenes	Antioxidant activity increased when plant exposed to UV stress	Mannucci et al. (2022)
Arabidopsis thaliana	α-Tocopherol	UV-B photoprotection, ROS scavengers	Badmus et al. (2022)
Hordeum vulgare	Flavonoids	Antioxidant activity	Gromkowska-Kępka et al. (2021)
Artemisia annua	Artemisinin (sesquiterpene)	Antioxidant activity	Wani et al. (2021)
Capsicum annuum	Cynaroside (flavonoid)	ROS scavengers	Ellenberger et al. (2020)
Nymphoides humboldtiana	Flavonoid	Antioxidant activity, ROS scavengers	Nocchi et al. (2020)
Psychotria brachyceras	Brachycerine (alkaloid)	UV-screening, prevention of UV-energy absorption, antioxidant activity, detoxification of hydroxyl and superoxide radicals	Porto et al. (2020)
Cuminum cyminum	Terpenoids, flavonoids, anthocyanins, phenols, alkaloids, β-carotene, lycopene	UV-absorbing compounds, carotenoids: receptors of reactive oxygen species, antioxidant activity	Ghasemi et al. (2019)
Trigonella foenum-graecum L.	Phenolics, flavonoids, anthocyanins, aromatic oil compounds	UV-B-absorbing compounds, antioxidant capacity	Sebastian et al. (2018)
Zingiber officinale	Gingerol, zingiberene	Antioxidant activity, longevity, and stress resistance	Lee et al. (2018)
Alternanthera sessilis, Alternanthera brasiliana	Betacyanin (alkaloid), betaxanthin	Antioxidant capacity	Klein et al. (2018)
Prunella vulgaris	Caffeic acid, rosmarinic acid, flavonoids, hyperoside, salviaflaside	Antioxidant activity, high accumulation in vegetative, flowering, and fruiting stages	Chen et al. (2018)
Fagopyrum esculentum	Rutin catechin (flavonoid)	Antioxidant activity	Zheng et al. (2017)
Bixa orellana	β-Carotene	Antioxidant activity	Sankari et al. (2017)

(continued)

Table 19.6 (continued)

Plant	SMs	Function	References
Brassica oleracea	Glucosinolates, phenolics, carotenoids, chlorophyll	Signaling molecules, antioxidant activity	Moreira-Rodríguez et al. (2017)
Fagopyrum esculentum	Quercetin (flavonoid)	Antioxidant activity	Huang et al. (2016)
Coleus forskohlii	Trimethyl citrate, methyl stearate, cadina-1,4-diene, δ-cadinene, cadinene, α-pinene, d-borneol, camphene, etc.	ROS scavengers	Takshak and Agarwal (2016)
Catharanthus roseus	Alkaloids	ROS scavengers	Zhu et al. (2015)
Psychotria brachyceras	Brachycerine	Antioxidant and antimutagenic activity	Nascimento et al. (2015)
Artemisia annua	Artemisinin	ROS scavengers	Pandey and Panday Rai (2014)
Catharanthus roseus	Vinblastine, vindoline, catharanthine	UV-B-absorbing compounds	Guo et al. (2014)
Vitis vinifera	Terpenes	Antioxidant activity	Marchive et al. (2013)
Fagopyrum tataricum	Catechin, quercetin rutin	Antioxidant activity	Regvar et al. (2012)
Ipomoea batatas	Hydroxybenzoic acids, hydroxycinnamic, flavonols, anthocyanins, catechins	Antioxidant activity	Carvalho et al. (2010)
Mentha x piperita	Menthol, limonene, 1,8-cineole	Signaling molecules	Behn et al. (2010)

sun-resistant ecotypes. The increases in lignin and flavonoid content strengthen the cell wall and increase mechanical resistance, thus reducing the UV-B transfer from the leaf surface to the mesophyll and increasing tolerance to stress (Cuzzuol et al. 2020). Additionally, epidermal cuticle configurations are capable of scattering some of the UV radiation, although small reflectivity may be required for UV scattering.

Antioxidants are compounds that protect against oxidative stress caused by various stress factors. Metabolites such as ascorbic acid, phenolic compounds, carotenoids, glutathione, flavonoids, and α-tocopherol, which are nonenzymatic antioxidants, serve to scavenge ROS species and prevent lipid peroxidation (Miret and Munné-Bosch 2015). Moreover, phenolic acids such as hydrocinnamic acid, anthocyanins, stilbenes, and various other phenylpropanoid pathway compounds also have a high antioxidant activity (Agati and Tattini 2010). For example, the concentration of phenolics, a compound with antioxidant properties, increases with the effect of UV-B stress. However, these antioxidant capacities of SMs vary not only from their concentrations but also from their biochemical structures and the cellular regions (cell walls, vacuoles of epidermal and mesophyll cells, chloroplasts, trichomes) where they are synthesized and accumulated. For example, monohydroxylated B-ringed flavonoids containing a single -OH group absorb more UV-B than dihydroxy B-ringed flavonoids containing two -OH groups (Agati and Tattini 2010). It was found that flavonoids with the catechol group in the B ring showed better antioxidant properties (Agati et al. 2009). It has also been stated that light increases the biosynthesis of terpenoid indole alkaloids in *C. roseus* (Liu et al. 2018). Increases in the amount of carbonic acid, a diterpene, were also determined in *R. officinalis* under UV-B stress (Luis et al. 2007). It has been reported that carbonic acid, an antioxidant, prevents the deterioration of the structure of the cell membrane by preventing lipid peroxidation against UV-B stress (Munne-Bosch and Alegre 2002). Carotenoids, which act as photosynthetic pigments, were also increased in plants exposed to UV stress (Sankari et al. 2017). It protects the thylakoid membrane lipids of carotenoids and some terpenoids against high light damage. Xanthophylls and tetraterpene carotenoids increase photosynthesis by preventing photooxidative damage in the photosynthetic apparatus (Jahns and Holzwarth 2012; Pattanaik and Lindberg 2015).

Carotenoids act as ROS scavengers during stress and protect thylakoid membranes and proteins. They prevent free radical chain reactions by reacting with the products formed because of lipid peroxidation and protect the photosynthetic apparatus (Niyogi et al. 2001; Swapnil et al. 2021). UV stress causes anthocyanin accumulation in *P. avium*, *M. domestica*, *P. frutescens*, *D. carota*, and *F. vesca* (Winkel-Shirley 2001; Ramakrishna and Ravishankar 2011). In a study investigating the effects of anthocyanins accumulated in the mesophyll and epidermis against UV stress, it was determined that the antioxidant activity of anthocyanins accumulated in the mesophile against oxidative damage was more effective than their sunscreen properties (Kytridis and Manetas 2006). In plants exposed to UV-B stress, an increase in alkaloid biosynthesis was determined by the effect of the tryptophan decarboxylase enzyme and WRKY6 factor (Mehrotra et al. 2018). In a similar study with *P. brachyceras* leaves under UV stress, alkaloid increases were detected due to the increase in the expression of genes encoding the enzyme that produces tryptamine, the indole precursor of alkaloid synthesis (Nascimento et al. 2015).

3 Plant Secondary Metabolite Synthesis Under Biotic Stress

Nematodes, fungi, viruses, insects, viroids, and bacteria cause serious damage by affecting the growth and development of plants. Plants have developed various defense mechanisms against pathogens. Phytochemicals with antimicrobial effects, such as phenolics, flavonoids, coumarins, terpenoids, lignins, alkaloids, stilbenes, and glucosinolates, are important metabolites of defense responses in plants. The first barrier against pathogens in plant defense is the cuticle and cell walls (Berto et al. 1999). The accumulation of cutins or waxes increases resistance to the pathogen (Xu et al. 2022). Cuticles, which are rich in cutin, prevent the germination of spores of fungi and mycelial growth due to their hydrophobic properties. Additionally, triterpenoids, the main components of cuticular wax, confer chemical resistance to fungal pathogens. It has been determined that 16-hentriacontanone (palmitone), which is the main component of the cuticular wax of *A. squamosa*, shows resistance and antifungal activity (Shanker et al. 2007). The SMs associated with defense in plants are generally divided into two groups: phytoanticipins and phytoalexins (Mansfield 1999). Phytoalexins and phytoanticipins are SMs with antimicrobial properties against insect, microorganism, and herbivorous attacks (Morant et al. 2008). Phytoanticipins such as saponin, glucosinolates, and cyanogenic glucosides are low molecular weight antimicrobial compounds, which exist in plants before infection or also occur after infection.

Phytoanticipins can accumulate in dead cells or be excreted into the rhizosphere. The inactive forms are stored in the vacuole. When necessary, they are hydrolyzed and become active, that is, toxic. For example, quinone, catechol, and protocatechuic acid have inhibited the germination of the spores of *C. circinans* and *B. cinerea.* Glycosides and glucosinolates are synthesized in healthy tissues before infection but are activated when tissue damage occurs. Although found at higher levels in healthy plants, saponins with surfactant properties are glycosides that impair the integrity and function of the membrane by binding to the sterols in the cell membranes of some pathogens (Tiku 2020). It has been determined that avenacins localized in the roots of the oat plant prevent *G. graminis* var. *tritici* infection (Osbourn 1996). However, it was determined that 26-desglucoavenacosides A and B, which are active forms of avenacosides localized in the leaves and shoots of the oat plant, have antifungal properties (Gus-Mayer et al. 1994a, b; Osbourn et al. 1994). Since some saponins bind to proteins and inhibit proteinases, they impair digestion in the guts of insects (Amtul and Shakoori 2014). Newman (2014) reported that saponins isolated from *B. vulgaris* leaves have a deterrent activity against *P. xylostella*. α-Tomatine, which is the main saponin of tomato and is found at high levels in the flowers, leaves, and fruits of the tomato plant, provided a high resistance against fungi such as *F. oxysporum* f. sp. *lycopersici* and *V. albo-atrum* (Smith and MacHardy 1982; Pegg and Woodward 1986). However, α-tomatine has been reported to be active at a certain pH. For example, since *A. solani* lowers the pH at the infection site, α-tomatine becomes inactive, so the pathogen cell membrane cannot break down, and the antifungal effect disappears (Roddick and Drysdale 1984). Cyanogenic glycosides containing nitrogen are degraded by hydrolytic enzymes such as β-glycosidases and hydroxy nitrile lyases, released by plants after infection to produce hydrogen cyanide, which is highly toxic to pathogens (animals, insects, etc.) (Poulton and Li 1994; Tiku 2020). Hydrogen cyanide binds to and inhibits cytochrome oxidase to stop electron transport, damaging the respiratory system of predators. However, plants protect themselves from the toxic effects of hydrogen cyanide with detoxification enzymes (Miller and Conn 1980). Glucosinolates, which are S-containing glycosides found in members of the Brassicaceae, are converted by myrosinase (a thioglucosidase) into different products such as nitrile, thiocyanate, and isothiocyanate, which are highly toxic to many pathogens. The toxic effects of these degradation products on pathogens such as *Alternaria* sp., *P. parasitica*, *L. maculans*, and *M. brassicicola* have been determined, and it has also been reported that they can be used as fungicides against other plant pests such as grains (Mari et al. 1993; Angus et al. 1994). Benzoxazinoids, another phytoanticipins, are predominantly found in grains such as wheat, rye, and corn and in some dicot plants with antimicrobial properties. In response to tissue damage caused by pathogen attack, they are hydrolyzed by β-glycosidase to produce toxic BX-Glcs aglycones (Korte et al. 2015; Del Cueto et al. 2018). Various compounds synthesized from the phenylpropanoid pathway exhibit antifungal properties by inhibiting spore germination and serve as phytoanticipins. For example, caffeic acid, *p*-coumaric acid, ferulic acid, and methoxycinnamic acid induce resistance to *A. flavus Link* and *A. parasiticus Speare* (Sobolev et al. 2006). The protective effects of hesperidin against *P. digitatum*, kaempferide triglycoside and hydroxyacetophenone against *F. oxysporum*, and sakuranetin against *M. grisea* infection have been determined (Marchesini et al. 1996). Phytoalexins, which include substances synthesized through the terpenoid and phenylalanine pathway, are low molecular weight antimicrobial compounds and get accumulated in plants after infection and inhibit the growth of bacteria and fungi (Jeandet et al. 2013) and inhibit spore growth and growth of hyphae to pathogenic fungi. They are thus considered defense compounds against diseases caused by pathogens. However, the amount and rate of accumulation of phytoalexins affect the development of pathogens (Duke 2018). Stilbenoids are metabolites derived from the amino acid phenylalanine. *p*-Coumaryl-CoA and malonyl-CoA enable the production of resveratrol (3,5,4′-trihydroxy-trans-stilbene) and various flavonoids in plants. However, the activity of the stilbene synthase enzyme is required for the synthesis of these two compounds. Because of this, using a single biosynthetic gene, it is possible to obtain a phytoalexin of the stilbene type, which is an important compound for defense against fungal infection in noninfected plants. Stilbenes, which are also considered phytoalexins, have a strong antifungal activity because they accumulate in the necessary concentrations to prevent fungal infection in plants (Morales et al. 2000). An example of this is the accumulation of pinosylvin and pinosylvin 3-O-methyl ether against *C. versicolor* and *G. trabeum* infection in conifers (Schultz et al. 1992). Resveratrol, a stilbene analog and first isolated from *V. grandiflorum* in 1940, is a compound with many activities such as antibacterial, antiviral, antioxidant, and antitumor (Jeandet et al. 1995; Song et al. 2021). It was determined that resveratrol inhibits the penetration and spore germination of *V. inaequalis* in apples (Schulze et al. 2005). It has also been reported that *B. cinerea* and *P. viticola* also reduce sporangia germination (Pezet et al. 2004). Song et al. (2021) reported that resveratrol derivatives formed due to modifications such as the removal of phenolic hydroxyl groups and ester formation in the structure of resveratrol inhibit tobacco mosaic virus (TMV).

Phenols are the most well-known and common defense compounds against insects, various bacteria, and fungi (Uleberg et al. 2012). Phenol derivatives and tannins prevent the proliferation of bacteria by increasing membrane damage and permeability and inactivating metabolism (Khameneh et al. 2019). Flavonoids, tannins, isoflavonoids, anthocyanins, lignins, phytoalexins, and furanocoumarins are important phenolic compounds that act as defense compounds against pests (Rani and Jyothsna 2010). Phenolics and flavonoids inhibit pathogens by disrupting their structures by causing lipid peroxidation in the cell membrane and mitochondrial membrane in fungi (VanEtten et al. 1994). Phenylpropanoids and flavonoids have phenolic hydroxyl groups that form ionic and hydrogen bonds with peptides and protons, causing the denaturation of proteins and enzymes, thus inhibiting the physiological activities of pathogens, including the reproductive system (Morrissey and Lou 2009). Phenolic compounds also show antibacterial properties by inhibiting enzymes such as NADH reductase and ATP synthase (Rempe et al. 2017). Flavonoids not only inhibit bacterial cell wall proteins and DNA synthesis but also cause inactivation of metabolism (Bouarab-chibane et al. 2019). Additionally, phenolics and flavonoids such as chlorogenic acid synthesized from the phenylpropanoid pathway increase the activities of defense enzymes and activate the SA signaling pathway (Jiao et al. 2018). *p*-Coumaric acid increases the activity of antioxidant enzymes and regulates the PR genes and phenylpropanoid pathway (Yuan et al. 2019). It has been reported that N-hydroxypipecolic acid, a secondary metabolite, can induce systemic acquired resistance (SAR) during pathogen infection (Yildiz et al. 2021). Polyphenols form covalent bonds with SH, OH, or free amino groups of some proteins of phytopathogens, causing the degradation of the 3D structures of proteins and thus inactivation (Zaynab et al. 2018). Polyphenols such as catechins have been reported to be effective in defense by changing plasma membrane permeability and oxygen production in different bacterial species such as *P. aeruginosa*, *S. marcescens*, *B. bronchiseptica*, *B. subtilis*, and *S. aureus* (Wang et al. 2018). It was determined that the increase in resveratrol O-methyltransferase and resveratrol synthase 3 enzymes in soybean exposed to *R. solani* inhibited the growth of the fungus (Zernova et al. 2014). Hydroxycinnamic derivatives, oleuropein derivatives, flavonol monoglucoside, and tyrosol derivatives were found to be effective in the defense against *Fusicladium oleagineum*, which causes leaf spot disease in olive trees (Talhaoui et al. 2015). Significant differences in endogenous phenolic levels were detected in plants exposed to fungal infections by *L. angustifolius* (Verma and Shukla 2015). It was determined that the amount of phenolics such as kaempferol, quercetin, caffeic acid, and chlorogenic acid increased in plants against virus infection (Parr and Bolwell 2000). Other SMs that act as defense compounds against fungi and insects are alkaloids such as caffeine, cocaine, morphine, and nicotine (Ogbanna and Opara 2017). Cyanogenic glycosides, another N-containing compound, are also important SMs with toxic properties, which play a role in the defense against herbivores and insects (Santisree et al. 2020). The nicotine found in tobacco leaves binds to the receptors of nicotinic acetylcholine, blocks endogenous neurotransmitters, and causes paralysis and even death in insects (Dewey and Xie 2013). It has been reported that dhurrin is highly effective in deterring insects in *S. bicolor* by its effective hydrolysis and subsequent release of cyanide (Krothapalli et al. 2013). Since terpenoids have repellent properties against herbivores, they prevent larvae feeding and reduce egg laying (Maffei 2010). It has been determined that latex, which is secreted from the roots of the dandelion plant and is in the terpene group, protects the plant against *M. melolontha* larvae (Huber et al. 2016). Studies on some SMs found to be effective in the development of disease resistance to pathogens in plants are presented in Table 19.7.

Table 19.7 Some SMs synthesized against pathogens and their functions

Plant	SMs	Function	References
Oryza sativa	Hydroxycinnamoyl-tyramine conjugates	Antibacterial, antifungal	Shen et al. (2021)
Avena strigosa	Avenacins (triterpene)	Antipathogenic	Li et al. (2021)
Oryza sativa	Phenolamides	Antifungal	Fang et al. (2022)
Solanum lycopersicum	β-Phellandrene, lycosantalonol (mono-diterpenes)	Antifungal	Zhou and Pichersky (2020)
Citrus sinensis	Hesperidin (flavanones)	Antibacterial	Soares et al. (2020)
Anacardium occidentale	Agathisflavone (flavonoids)	Antimicrobial	Andrade et al. (2019)
Aesculus hippocastanum	Aescin (saponin)	Antifungal	Trdá et al. (2019)
Canavalia gladiata	Gallotannin (tannins)	Natural antioxidant, antibacterial agents	Gan et al. (2018)
L. radiate	Lycorine, colchicine, galanthamine, 3-epimacronine, deoxytazettine, N-allylnorgalanthamine (alkaloid)	Insecticidal	Yan et al. (2018)
Sorghum bicolor L.	Dhurrin (cyanogenic glucoside)	Antiherbivore	Emendack et al. (2018)
Vitis vinifera	d-Viniferin, pterostilbene	Antifungal	Viret et al. (2018)
Cotton	Phenol, gossypol	Antivirus	Mandhania et al. (2018)
Vaccinium myrtillus	Chlorogenic acid	Antiherbivore	Hernandez-Cumplido et al. (2018)
Peganum harmala	β-Carbolines (alkaloid)	Antibacterial	Suzuki et al. (2018)
Solanum nigrum	Myristic acid, veremivirine, oleuropein glucoside (alkaloids)	Antifungal	Tiku (2018)
Solanum nigrum	Glycoalkaloids	Insecticidal	Spochacz et al. (2018)
Arabidopsis thaliana	Menthol (monoterpene)	Antifungal	Lin et al. (2017)
Nicotiana sp.	Pyridine alkaloid (nicotine)	Antibacterial	Stevenson et al. (2017)
Capsicum spp.	Capsidiol	Antifungal	Lee et al. (2017)
Ricinus communis	Ricinine and its derivatives (alkaloid)	Antibacterial, antifungal	El-Naggar et al. (2017)

(continued)

Table 19.7 (continued)

Plant	SMs	Function	References
Zanthoxylum piperitum	Pellitorine (alkaloid)	Insecticidal	Kim and Ahn (2017)
Waltheria indica	Quinoline (alkaloid)	Antifungal	Cretton et al. (2016)
Pisum sativum L. cv. Arkel	Shikimic acid, gallic acid, chlorogenic acid, syringic acid, coumaric acid, cinnamic acid, salicylic acid, myricetin, quercetin, kaempferol	Antipathogenic	Jain et al. (2015)
Olea europaea L.	Quinic acid, cyclic polyols	Antibacterial	Luvisi et al. (2017)
Citrus sinensis	Hesperidin, rutin	Antibacterial	Soares et al. (2015)
Hypericum perforatum	Phenylpropanoid, naphtodianthrone	Antifungal	Gadzovska et al. (2015)
Prunus amygdalus	Cyanogenic glycosides	Antioxidant	Tiedeken et al. (2014)
Psoralea corylifolia L.	Psoralen (furanocoumarin)	Antipathogenic	Ahmed and Baig (2014)
Cucumis sativus	Cucurbitacins	Antifungal, antibacterial, antiherbivore	Shang et al. (2014)
Ricinus communis, Euphorbia peplus, Jatropha curcas	Casbene diterpenoids	Antifungal, antibacterial	King et al. (2014)
Vitis vinifera	Caftaric acid, procyanidin, quinic acid	Antibacterial	Wallis et al. (2013)
Solanum lycopersicum	α-Solanine, α-tomatine (steroidal glycoalkaloids)	Antifungal, antibacterial, insecticidal	Itkin et al. (2013)
Oryza sativa	Diterpenoid (phytoalexin)	Antifungal	Kanno et al. (2012)

In addition to these phytochemicals, SA, jasmonic acid (JA), and ethylene (ET) are critical in regulating defense responses. The JA, SA, ET, and methyl jasmonate are signal molecules that take part in the fight against pathogens and stimulate the antioxidant system and secondary metabolite. Defense against biotrophic pathogens is mediated by an SA-dependent pathway in plants, whereas neurotropic pathogens usually induce a defense system mediated by JA and ET (Fig. 19.2). Insect or pathogen attacks cause the accumulation of endogenic hormones such as SA, JA, and ET, which will activate the defense mechanisms in plants. Specific plant hormones such as SA, JA, and ET, on the other hand, are effective in the formation of hypersensitive response and SAR, by acting as stimulants in the synthesis of antioxidants that are effective in creating resistance to pathogens and harmful insects, with various SMs, phenolics, phytoalexins, and pathogen-related proteins (PR) (Jumali et al. 2011) (Fig. 19.2).

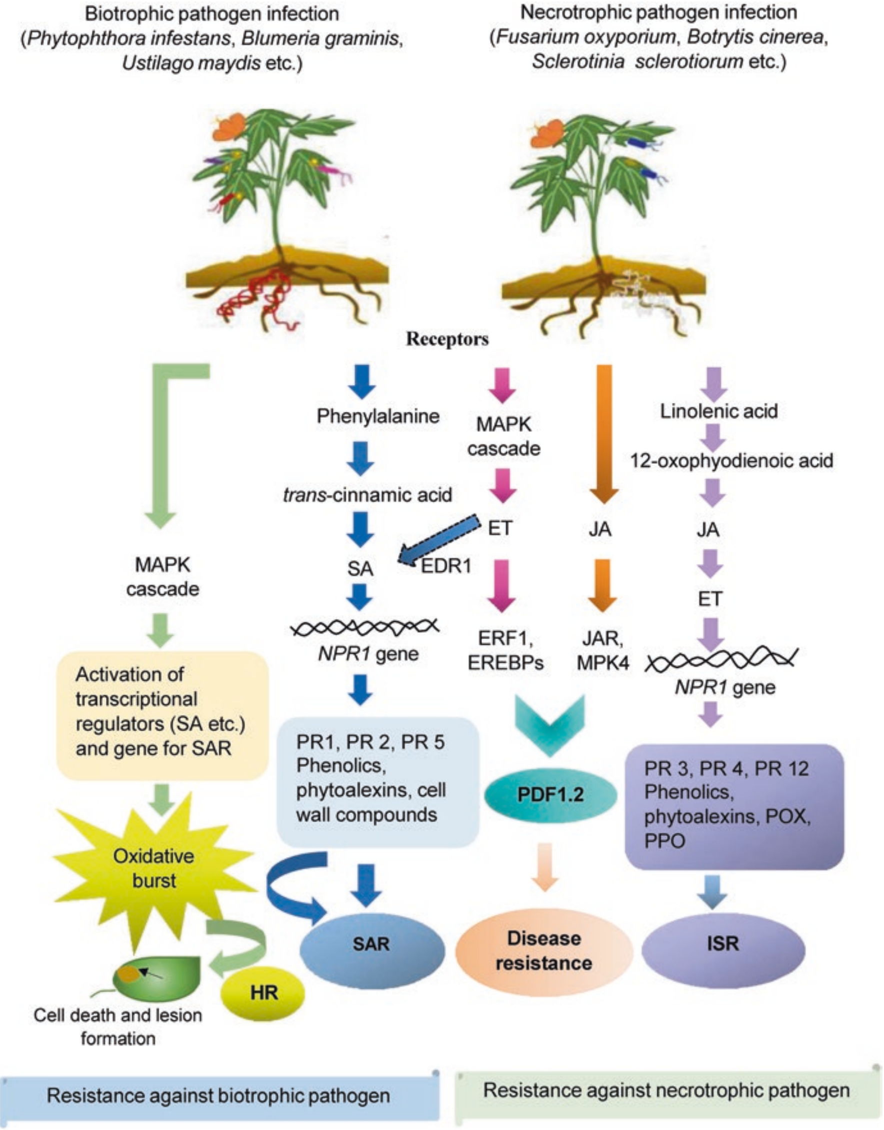

Fig. 19.2 SA, JA, and ET signal transduction pathway and disease resistance (*ET* ethylene, *EREBPS* ethylene-responsive element-binding protein, *EDR1* enhanced disease resistance 1, *ERF1* ethylene response factor, *HR* hypersensitive response, *ISR* induced systemic resistance, *JA* jasmonic acid, *MAPK* mitogen-activated protein kinase, *NPR1* nonexpressor of pathogenesis-related genes 1, *PAL* phenylalanine ammonia-lyase, *PDF1.2* plant defensin 1.2, *PR* pathogen-related proteins, *SA* salicylic acid, *SAR* systemic acquired resistance)

PR proteins, with 17 families identified in different plant species, are considered markers in SAR (Van Loon et al. 2006). Chitinases belong to the PR-3, PR-4, PR-8, and PR-11 classes and catalyze the hydrolysis of chitin, which is a component of the fungal cell wall and helps in the development of resistance to the pathogen. The hydrolysis of glucan, another structural component of the fungal cell wall, is catalyzed by glucanase, a PR-2 class protein (Van Loon et al. 1994). PR proteins show the following different functions: PR1 (antifungal), PR2 (β-1,3-glucanases), PR3 (chitinases), PR4 (class I and II chitinases), PR5 (thaumatin-like proteins), PR9 (peroxidases), PR12 (defensins), and PR13 (thionins) (Van Loon and Van Strien 1999). Studies have shown that genetically modified potato plants expressing tobacco PR-5 osmotin are more resistant to *P. infestans*, *F. solani*, and *R. solani* (Rivero et al. 2012). More resistance to *C. arachidicola* and *A. flavus* is developed in peanuts due to the overexpression of the rice chitinase gene (Prasad et al. 2013). Besides, defensin and thionine serve as effective defense responses against various phytopathogens in antimicrobial proteins rich in small cysteine (Kaur et al. 2011).

Investigation of metabolite pathways specific to a plant species, determination of biosynthetic genes, and transfer of the gene responsible for the synthesis of the metabolite to the plant that does not contain this metabolite have allowed the development of plants resistant to pathogens. The many SMs such as isoflavonoids, hydrocinnamic acid amides, terpenes, camalexin, and alkaloids besides stilbenes or genes encoding the enzymes involved in the synthesis of these metabolites can be transferred to other plants and in this way a resistance against various diseases (Muroi et al. 2012; Rook 2016). The genomic sequence of the beta-amyrin synthase enzyme involved in the biosynthesis of saponins, following the cloning from *A. strigosa*, and expressed transgenically in turf plants has developed resistance to fungal pathogens such as *F. culmorum*, *S. nodorum*, and *G. graminis* (Silva et al. 2018). Tobacco plants overexpressing heterologous phenylalanine ammonia-lyase (PAL) transgenes have been observed to show resistance to *C. nicotianae* and *P. parasitica* fungal pathogens (Way et al. 2002). It has been reported that it acts as a repellent against *M. sexta* in transgenic tobacco plants containing volatile isoprene, thereby preventing the feeding of this herbivore (Laothawornkitkul et al. 2008).

Another strategy is to increase the resistance in transgenic plants formed by transferring genes encoding polyamines such as spermine, spermidine, and putrescine, which serve to increase resistance or tolerance to biotic stresses. Hazarika and Rajam (2011) have reported that when they transferred a gene that is effective in polyamine synthesis to tomato plants, disease resistance developed in tomato plants against wilt disease caused by *F. oxysporum* and early blight caused by *A. solani* together with an increase in polyamine synthesis.

The limitations of the traditional breeding methods such as time loss and high cost have led to the development of plant tissue culture techniques such as in vitro protoplast fusion, secondary metabolite production, and haploid technology. The protoplast fusion is based on the combination of the nuclei and cytoplasm of two separate protoplasts through chemical or electrical means. The plant resulting from this combination is called somatic hybrid (Lakhani et al. 2016; Tiwari 2018). In the control of plant diseases caused by some fungi, *Trichoderma* species, known as biocontrol agents and distributed in many parts of the world, have been used. These fungal species increase antagonistic properties by producing bioactive substances in the fight against plant diseases and stimulate SAR in plants with their hyperparasitism (Shah and Afiya 2019). The studies at a molecular genetic level have also focused on increasing the proteinase or chitinase activities acting on the pathogen cell walls or by increasing the copy number of suitable genes or combining these genes with strong promoters (Pcbh1, ech42) to increase the biocontrol ability of *Trichoderma*. The protoplast fusion is a good tool in the improvement of *Trichoderma* species and the development of hybrid strains in other filamentous fungi. It has been reported that this technique is useful for developing superior hybrid strains and enhancing the antagonistic activity of *Trichoderma* spp. against various fungal pathogens such as *F. oxysporum*, *M. phaseolina*, *R. solani*, and *S. rolfsii* (Lakhani et al. 2016).

Secondary metabolite production is another way to obtain pathogen-resistant plants using various methods in tissue cultures. SMs, such as alkaloids, phenols, flavonoids, lignins, organic acids, peptides, steroids and derivatives, tannins, terpenes, and vitamins, may be produced using cell culture techniques. These substances may be produced in vitro using a cell and tissue culture technique. Another method used in the production of SMs is elicitor application. Elicitors are stimulants that allow the plant to protect itself by producing antimicrobial substances in case of stress conditions (Narayani and Srivastava 2017). The elicitors that act as signals bind to elicitor-specific receptors on the cell membrane of the plant, and the signal is detected, activating the transduction cascade, inducing the expression of the relevant genes and transcription factors and the synthesis of the SMs (Halder et al. 2019). Oligogalacturonic acids in the plant cell wall stimulate the synthesis of phytoalexin, whereas chitin in the fungus stimulates the synthesis of phenolic compounds (Gadzovska et al. 2015). When elicitors such as SA and methyl jasmonate are used as stimulants, they induce defense against pathogens by stimulating stilbene and gymnemic acid biosynthesis (Chodisetti et al. 2015; Xu et al. 2015). It was determined that phytohormone applications such as abscisic acid, gibberellin, and ET increased the amounts of phenolic compounds (Liang et al. 2013). Tashackori et al. (2018) in their study, in which *P. indica* used the cell wall as an elicitor, found that it caused significant increases in the amounts of cinnamic acid, ferulic acid, SA, myricetin, kaempferol, diosmin, and flavonoids lignins and lignans in *Linum album* cell cultures. Significant increases were detected in the amounts of PAL, anthocyanin, carotenoid, flavonoid, phenolic, and antioxidant capacity in pepper seedlings treated with proline. The increase in the PAL activity induced by proline increased the amounts of flavonoids and anthocyanins, thus increasing the tolerance of pepper against *P. capsici* infection (Koç 2017, 2022). Kumar et al. (2008) have reported that an application of toxins created by different plant pathogens to the cultures produced with cell suspensions, somatic embryos, and organogenic and embryogenic calluses may allow the pathogen-resistant plants to be developed. It has been determined that when compounds belonging to *P. megasperma* are applied to a soybean plant in the cell cultures, they produce a secondary metabolite called glycolide, and similarly, when a compound obtained from the pathogen *P. aphanidermatum* is applied, it produces various SMs such as ajmaline, tabersonine, and catharanthine (Razdan 2003).

4 Conclusion

The biosynthetic mechanisms of SMs, one of the most important defense strategies developed by plants for survival, are regulated by various stress factors. Many studies have shown that abiotic and biotic stresses cause changes in the levels of phenolic compounds, terpenes, alkaloids, flavonoids, antioxidants, osmoregulators, carotenoids, anthocyanins, glucosinolates, and phytohormones in plants. Stress tolerance in plants can be increased by manipulating the biosynthesis and accumulation of SMs. For this, it is important to identify the genes encoding the enzymes of the secondary metabolite pathways, such as the mevalonate (MVA) and methylerythritol phosphate and (MEP) pathways for terpenoids and carotenoids, the shikimic acid and tricarboxylic acid pathways for alkaloids, and the malonic acid and the shikimic acid pathways for phenolics. Another effective option for increasing the production of SMs is elicitor application. Additionally, different strategies can be combined to produce a high amount of desired – targeted – compounds.

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Chapter 20
Sustainable Crop Management for Drylands

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Abstract Drylands are areas characterized by low ratios of annual precipitation on an average to potential evapotranspiration. The soil in these regions naturally has insufficient reserves of organic carbon (C) due to less diverse climatic conditions. Instead of this limited availability of organic carbon, they contain sufficient amount of persistent inorganic carbon primarily in the form of soil carbonates. Sustainable crop management in dryland areas is one the most challenging issues across the globe. There are many factors that influenced the sustainable crop production in drylands that are grazing, tillage practices, and vegetative covering. The inappropriate management of such components of dryland agroecosystems leads to degrading processes including environmental resources degradation, soil erosion, and ultimately desertification. The main problems for the farmers in dryland areas are unsustainable agricultural yield production, frequent drought conditions, weather variability, disease and pest infestations, and loss of genetic variety. Many advance agricultural approaches have been discussed in the present review study for sustainable crop management in dryland environments which comprises numerous strategies such as watershed management practices, dry agricultural farming approaches, crop and variety selection, and integrated management strategies for pest control and crop rotations. Ultimately, it is concluded that the soil of dryland is potentially of great importance for long-term environmental services and sustainable agriculture system.

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1 Introduction

The total proportion of dry regions on the earth's surface is around 41%, which are distinguished by low ratios of annual precipitation on an average to potential evapotranspiration (between 0.05 and 0.65) (Osman 2018). Due to restricted climatic conditions, the soil in these regions naturally has a low stock of organic carbon (C). In the form of soil carbonates, instead of this limited availability of C, they contain enough persistent inorganic carbon (Hag Husein et al. 2021). Most dryland agroecosystems have an appropriate chance for extending system of irrigation because many other strategies must be needed for optimized land use (Pankaj et al. 2020). In grasslands and drylands, improper management practices such as heavy soil conservation, removal of vegetative cover, or intense grazing resulted in the loss of 13–24 Pg C (Bhattacharyya et al. 2015). Which become the basis of many major degrading procedures such as loss of ecosystem services, soil erosion, as well as eventually desertification. Threats to global sustainability such as malnutrition, poverty, and significant economic losses particularly in regions with arid climates have been closely correlated with desertification (Hill et al. 2008).

The FAO of the United Nations has reported that 25% of land of the world is seriously degraded (Zaman et al. 2018). This statistic showed that we are not protecting our land enough. The insufficient attempts to overcome this problem imposed various impacts on food security, the climate, and health of the environment (Chigbu et al. 2019). Inaction is frequently caused by the trade-off between meeting urgent individual demands as well as protecting the endless sustainability of ecological services (Zuo et al. 2021). Due to decrease in ecosystem services, the economic concerns become more apparent because of land degradation process (Chasek et al. 2019). "The Economics of Land Degradation Initiative's" the Value of Land reviewed show the ecosystem services data that economic value damages due to degradation of land also evaluates the cost of the ecosystem service's lost values globally range from USD 6.3 to 10.6 trillion. Provisioning services such as food, fresh water, lumber, and fiber are among the ecosystem services that are lost, as are regulating services such as cultural services, pollution control as well as supporting services such as soil formation, nutrient cycling, or water filtration utilizing these services sustainably will aid in reducing poverty in all of its forms (Oguh et al. 2021).

2 Dilemma Related to Dryland Agricultural System

Unsustainable agricultural yields, frequent drought periods, weather variability, high rates of soil erosion, deforestation, and loss of genetic variety are the primary issues for farmers in the drylands (Chimwamurombe and Mataranyika 2021).

2.1 Water

Water is essential to life for all living things. Certain plants have evolved some modifications which help them in their survival in semiarid, dry, and even desert environments (Ayangbenro and Babalola 2021). However, when aridity increases very few species evolved adaptive traits, which help them to thrive in drylands. But the overall production of biomass is reduced (Maestre et al. 2021).

2.2 Heat and Wind

Heat and wind have a significant influence on how quickly water vaporizes from leaf surfaces of plants by raising the temperature. Crops may also experience mechanical harm from wind as well.

2.3 Disease and Pest Infestations

Disease and pest infestations are more prevalent in drier areas as compared to those that are of wetter areas, for example, nematodes become a serious issue in sandy soils (Abd-Elgawad 2019).

3 Dryland Salinity

When accumulated salt concentration in soil becomes increased to a point where they interfere with the growth of plants in the root zone in nonirrigated environments, it results in dryland salinity (Rengasamy et al. 2022). The mobilization of salt from salinized soil frequently caused the downstream consequences on water resources as well as the loss of associated infrastructure, environmental assets, and social values (Ngo et al. 2022). Salinity can have direct negative effects on agricultural systems (Corwin 2021). The issue of dryland salinity arises when internal (leaching) and exterior (runoff) drainages are insufficient to eliminate the excessive concentration of salts (Mainuddin et al. 2021). That can originate from a variety of sources, most frequently from rainfall or dry fall (wind-borne) (Hu et al. 2021). Primary salinity develops due to pedogenesis in the context of geological dynamics while secondary salinity develops from human-induced land-use change such as clearing for agriculture. Arid lands salinity is frequently related to sodic soils and waterlogging (Bogunovic et al. 2019).

3.1 Challenges to Drylands

Dryland areas are presently facing some of the new difficulties that arise due to alterations in climatic pattern which influenced on biogeochemical patterns and net main production as well as increasing the increasing number of individuals in human population (Lian et al. 2021).

3.2 Advance Agricultural Approaches for Dryland Environments

3.2.1 Efficient Water Shed Management Practices

Nowadays, watershed management is a commonly used technology for the advancement of rainfed agricultural system. Numerous components of the watershed approach aided in both mitigation and adaptation (Hewawasam and Matsui 2022). For instance, farm ponds, check dams, other water and soil conservation measures regulate the runoff water and reduced intensity of floods after heavy rainfall (Meaza et al. 2022). The Graph 1 is a description of some of the most significant and high-potential adaptation and mitigation strategies are described with the help of graph (pattern of yield variation in WS (watershed) and NWS (Non-Watershed) areas (Rafiei-Sardooi et al. 2022).

3.2.2 Conserving and Storing Rainwater

All these practices involve both ex situ and in situ rainwater conservation for reusing with rainfed crops (Venkateswarlu 2019). For agriculture, the basic source of irrigation is the increased use of ground water and the pumping of water through the deep tube wells (Sarkar 2020). It is also possible to lessen reliance on ground water. According to one estimation, around 28 million ha of rainfed land in central and eastern states have the capability to bring about 114 billion cubic meters runoff water for supplemental irrigation system to irrigate 25 million ha area of rainfed (Mishra et al. 2018).

3.3 Strategies Adopted for Dryland Agricultural System

3.3.1 Stimulate Water Uptake Process

Creating a rough, cloddy surface by tillage practices to extend the duration for the rain helped to seal the surface and dissolve the clods (Arora et al. 2022). While preparing the seed, as compared with large seeds, small seeds should generally have a mellower, finer bed (Mihretu 2019). Harvesting simultaneously followed by a formation of mulch of stubble on the ground which not only actively stopped droplets of rain from falling immediately over soil but also obstructs the water movement downward the slope and increased the interval for the water to be absorbed (Bhat et al. 2019).

3.3.2 Limit the Runoff of Water

Water logging is not an issue to some extent, but the discharge of water and its associated erosion must be minimized (Qureshi and Perry 2021). This can be achieved by different ways like field slopes should be minimized and agricultural crop lands should be levelled, all plantings and tillage must be parallel to (or across from) the slope of the ground and these ridges will prevent water from flowing downward (Zheng et al. 2021).

3.4 Minimizing the Loss of Soil Moisture Contents

3.4.1 Limiting Soil Evaporation Rate

Each grain is encircled by a continuous watery layer in the soil. The film thins as water drawn up from below replaces surface water as it evaporates (Louge et al. 2022). Wilting happens when it gets too fine for roots of plants to take in.

- Tree or shrub shelter belts decrease speed of wind and create shadows, which alone can minimize wind erosion and also evaporation by 10–30% (Miri and Davidson-Arnott 2021).
- Mulching lowers soil temperatures and speed of the air flow near the earth's crust (Wang et al. 2019).
- A 2- to 3-inch-deep layer of earth mulch can be produced by shallow tilling. This layer is discontinuous from the subsurface water and dries out fast, avoiding further loss. After every rain, more tillage is required to repair the discontinuity. This is most practical when there are only a few significant downpours separated by a great deal of time (Balogh and Watson 2020).

3.4.2 Bunding

Bunding is the first crucial stage in dry farming. Every hundred feet, level contours are determined using a survey of the terrain (Dhopte 2020). For unique slopes, it is advised to build a bund 18–24 inches high for every two feet of fall. 12-inch-high bund every 250 feet is still considered advantageous, even on very flat territory. By building recurring waste weirs with a sill that is half the height of the bund, excess storm water can be discharged. As a result, there will be less loss of topsoil and water (Rao et al. 2022).

3.4.3 Strip Cropping

Crop rotation, which involves cultivating crops that can promote soil erosion and soil vulnerability, is accompanied by various actions aimed at preventing these processes (Ananda and Herath 2003), retained soil fertility on large scale, blockage to flow of runoff water and water precipitation in soil is elevated, and enhanced water intake by plants (Ong and Leakey 1999).

3.5 Dry Agricultural Farming Approaches

Dry agricultural farming approaches are a collection of methods used in anticipation of impending severe droughts to lessen the effects of strains brought on by dry circumstances (Okogbenin et al. 2013). The sets of agricultural practices described are as follows:

3.5.1 Mulches

Although this technology has many advantages and is relatively easy to use, it nevertheless has certain drawbacks. Water permeates easily through porous soil and is absorbed as water films along the soil grains as it moves downward (Elehinafe et al. 2022). A continuous water column is created by these films that rise to the soil's surface. Around all of the soil grains with which it comes into touch, the film has a tendency to maintain the same thickness (Sultan et al. 2021). Capillary water is the name for the thin layer of water in the soil which solely supplies water to plants (Li et al. 2021).

The soil surface must be covered by at least one ton per hectare to be more effective and two tons per hectare yields the highest benefit per unit of residue (Zeng and Hausmann 2022). Even at 8 tons per hectare, benefits can still be attained as shown by Graph 2 (as influenced by mulching, number of leaves per garlic plant).

3.5.2 Soil Compaction and Management Tactics

Tillage and ploughing are fundamentally necessary for the highest crop development and production quality (Bankina et al. 2021). Ploughs are used at the appropriate periods to provide tillage for these objectives. When ploughing, the soil should not be excessively moist or dry. Wet soil becomes compacted or forms puddles when it is ploughed while dry soil turns powdery (McCarthy 2021). When it is, making neither of them suited for producing crops. The use of a steep mold plough for soil preparation is efficient. A healthy crop yield should result from ploughed soil acting as a reservoir for rainwater.

The following are the goals of ploughing: to create a cloddy and rough clumb surface which will boost absorption of moisture, lessen runoff, and prevent wind and water erosion; to control or destroy weeds that compete with crop for nutrients, water, and sunlight; and to eliminate or stop the development of a hard pan (sole), which may form after repeated shallow harrowing or ploughing (Monteiro and Santos 2022). This hard pan can prevent capillary rise of water from the subsoil, restrict water storage, and inhibit root growth, and aerating the soil encourages bacterial activity, which in turn encourages the organic waste's breakdown and the discharge of nutrients of soil. Ghosh and Daigh (2020) also elaborated that many amaranth growth indicators responded differently to various tillage techniques as shown in Graph 3 (effect of tillage method on the growth of leafy Amaranth large green).

3.5.3 Density of Planting

Lower seeding rates (by 50–70%) and wider row spacing than those utilized in places with ample precipitation are required in dry locations because of the limited moisture availability (Babatunde 2022). Because there are fewer plants, each one gets more moisture and nutrients, increasing the likelihood that the crop will mature before the resources run out. That provided one such example, stating that lower and higher grain yields of the bean (*Phaseolus vulgaris* L.) were achieved from rows R1 (50 cm) and R3 (30 cm) with means of 4.10 and 2.34 t ha^{-1}, respectively, at varying row spacings. As a consequence, the grain yield of beans increased by roughly 42.92% when the row spacing was raised from 30 to 50 cm (Coleman et al. 2021).

3.5.4 Crop and Variety Selection

Variety selection is crucial. In general, varieties that have excelled in locations with irrigation or significant rainfall are not suitable for dryland circumstances (Mohtashami et al. 2020). A lot of agricultural practices on dryland farming become collapsed, partly because the criteria for variety selection were not understood (Xu et al. 2022).

3.5.5 Variety Requirements for Dry Farming

Dwarf cultivars will produce less transpiration since their leaves have a smaller surface area and fewer stomata. Deep, numerous, and effective root systems improve moisture absorption. For the crop to develop before the driest and warmest time of the year and mature before the totally depletion of moisture supplies, early and quick-maturing types are crucial (escape mechanisms). Pusa rituraj, pusa dofasli, and Arka meghali are some examples of crop varieties that are resistant also adaptable to rainfed circumstances (Puértolas and Dodd 2022).

4 Sustainable Crop Development

In arid and semiarid environments, pulse crops such as dry pea should be used in sustainable agriculture intensification to boost yields (Liu et al. 2020). Due to its high adaptability and lower water requirement than cereals, pea has replaced fallow land in these areas more and more (Ansari et al. 2021).

4.1 Rotational and Nonrotational Advantages

By enhancing yields and improving soil and environmental quality, pea helps succeeding crops in both rotational and nonrotational ways (Lenssen et al. 2018). Because of the fixation of nitrogen (N) in the atmosphere, pea residue has a higher N concentration and a lower N fertilization rate (Enrico et al. 2020). Rotational benefits also include better availability of soil water for future crops due to pea residue reduces uptake of water (Karyoti et al. 2021). When compared to continuous nonlegume farming, nonrotational benefits include lower weed, insect, and disease infections; enhanced availability of S, K, and P; soil structure improvement; substance of growth produced from pea residue; reduced N leaching; and decreased greenhouse gas emissions. Other advantages include lowered crop failure risk, increased biodiversity, and higher agricultural profitability (Rosa-Schleich et al. 2019).

4.2 Integrated Management Strategies

Weeds are competitors of crops, which can change the water and nutrients availability (MacLaren et al. 2020). Therefore, integrated management strategies can increase crop yields by suppressing weeds (Khan et al. 2019).

4.3 *Nutrient Manipulation and Seedling Characteristics for Dryland*

Strong potential exists for fertilization to change morpho-physiological characteristics of plants (Sohrabi et al. 2022). Changes can sometimes lead to an increase in water absorption and help to maintain the water cycle (Sprenger et al. 2019). In other words, such alterations bring about by increasing nutrient availability weaken seedling resistance to drought (Chaudhry and Sidhu 2022). Dryland seedling production should discriminate between the two types of features and determine the ideal growing environments, such as fertilization schedules to favor the former (Benami et al. 2021). Changes in leaf nutritional content, as well as morphological and physiological features, are stimulated by fertilization application (Abdallah et al. 2020). As water usage efficiency rises as a result of improved nutritional status, an increase in photosynthetic rates could benefit seedling performance (Rai-Kalal and Jajoo 2021). Limitations of phosphorus and nitrogen also have an impact on the fine root architecture and morpho-functional features of plants (Marañón et al. 2020). Additionally, in response to N deficiency, particular root length rises (Gupta et al. 2020). These alterations may not indicate an improvement in the uptake capability of mobile resources such as water, but they have been linked to an increase in plants' ability to capture soil nutrients, especially stationary resources such as phosphorus.

5 Strategies for Pest Control

The pest management techniques are based on either inherent characteristic of cropping systems such as crop rotation, farm plot location, intercropping, or on specific responses to pest attack such as use of plants that act as insecticides or repellents and timing of weeding (Kansiime et al. 2019). Planting and harvesting seasons, crop associations, closed seasons, mechanical control, the use of herbal remedies (Engler and Krarti 2021) and occasionally dealing with pests in a supernatural fashion are only a few examples of cultural control strategies used in traditional pest management techniques (Król et al. 2019).

5.1 *Integrated Pest Management of Insects in Dryland Agricultural System*

There are four main categories into which the most significant management strategies are grouped in IPM (Hutchins 2020). These are pesticides, resistant in host plants, biological control, and cultural practices (Matova et al. 2020).

5.2 Resistant in Host Plants

As an IPM strategy, pest-resistant cultivars have various benefits. Once they are created, they are easy to use and generally safe for the environment (Bonner and Reinders 2018). Host plant resistance has been used to combat arthropods and plant infections, but it has also been used to combat weeds (Aradottir and Crespo-Herrera 2021).

5.3 Crop Rotations

Crop rotation is a crucial strategy for controlling winter annual weeds in wheat that was planted in the autumn (Rosenzweig et al. 2018). Downy brome (*Bromus tectorum* L.), volunteer rye, and jointed goat grass are examples of winter annual weeds whose life cycles are comparable to those of winter wheat (Bough 2021). As a result, these weeds are frequently favored by the same environmental factors that favor wheat (Gandía et al. 2021). Crop rotation can also be used to manage summer annual grasses in the Central Great Plains that are connected to corn (Kumar et al. 2019). These weeds include wild proso millet (*Panicum miliuceum* L.), green foxtail (*Setaria viridis* L.), and longspine sandbur (*Cenchrus longispinus*). All of these species go through their whole life cycle throughout the corn growing season, beginning with germination in May and producing seed by late August (Kumar et al. 2020). Rotating to winter wheat might break up the life cycle synchronization between the weed and the crop (Brankov et al. 2021). Thus, rotations of summer and winter annual crops such as corn and wheat can reduce the weed seed bank of both winter and summer annual weeds (Zohry and Ouda 2018).

5.4 Planting Time

The planting time is a significant element that can be used as an IPM strategy. The population of kochia (*Kochiu scopuriu* L.) Schrader was reduced by 60% when proso millet was planted on June 1 rather than May 15, although grain yields were unaffected. Additionally, weed issues can be controlled by selecting crops with various optimum planting time.

6 Dryland Soil's Capability for Long-Term Environmental Services

Despite the drawbacks and unfavorable future projections, dryland soil has a significant capacity to store carbon if the proper management practices and land-use regulations are implemented within the context of ecological intensification (Figs. 20.1 and 20.2). That conceptualization encourages increasing yields without endangering the ecosystem. In dryland areas, increasing soil organic carbon (SOC) stocks has the capability to reduce the present escalation in atmospheric carbon dioxide (CO_2) concentration as well as enhanced other soil characteristics. These characteristics would help to maintain agricultural productivity and ecosystem services while lowering the vulnerability of soil-to-soil degradation processes such as erosion (Thorsøe et al. 2019). This final aspect is crucial for raising the standard of living for the 38% of people worldwide who reside in drylands.

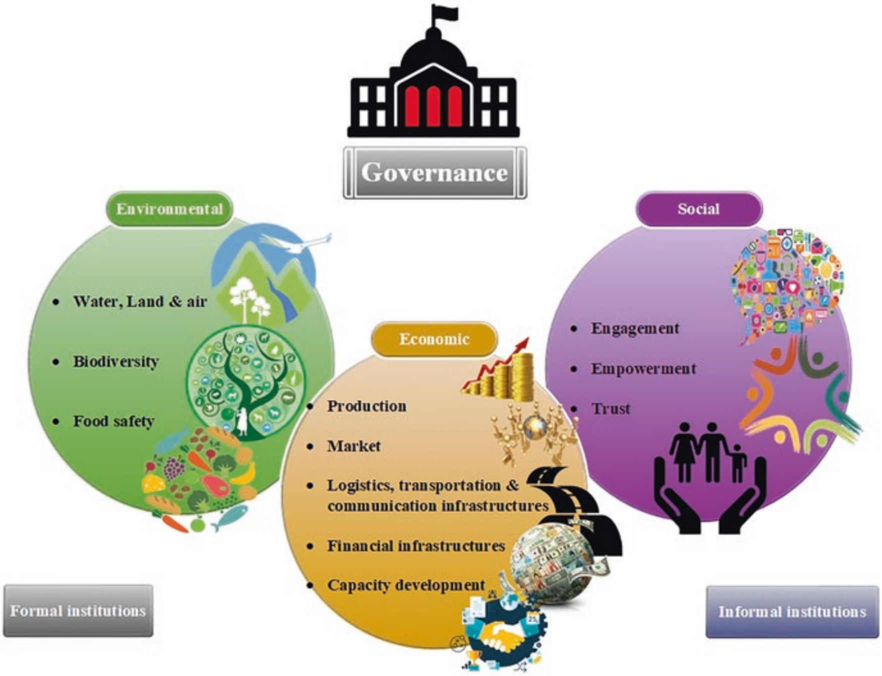

Fig. 20.1 Sustainable agricultural development framework. (Kusnandar et al. 2019)

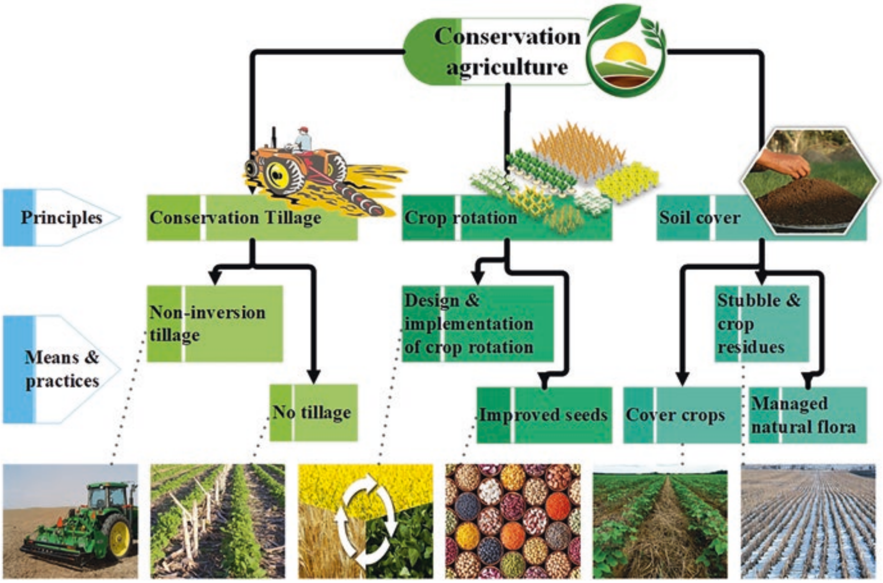

Fig. 20.2 Crop rotations, soil cover, and conservation tillage are three of the main conservation agricultural practices and tools required. (Shambhu Prasad 2023)

6.1 Future Food Needs

It has been questioned whether the agricultural industry would be able to meet future dietary demands or not in a timely manner (Deaton and Deaton 2020). Such worries can be attributed to the fact that agriculture not only satisfies the food needs of about 9.5 billion people but also performs a wide range of additional services such as waste disposal, water purification, the manufacture of fiber, fuel, and chemicals, as well as the preservation of biodiversity and recreation (Kopittke et al. 2019). Additionally, the problem is made worse by the constantly expanding human population because of the increased demand for food (Rohr et al. 2019). It will take an average annual increase in production of 43 million Mg to reach the worldwide goal of 70% more food by 2050. Figure 20.2 illustrates data on global cereal production since 1960 and shows a consistent rise in output. It is important to note that the current rate of growth of 31 million Mg per year will not be sufficient to meet the demand for 43 million Mg (an increase of 39%) in the future (Shah and Wu 2019) as shown in (world cereal production verses global non-CO_2 GHG emissions).

No single solution can completely meet the nutrient needs of the world's population, which is expanding at an exponential rate (Bush et al. 2020). Therefore, coordinated global efforts are required to assure maximum agricultural output with minimal environmental impact. Changes in food distribution, processing, storage, and production that are as revolutionary as those seen in earlier great revolutions such as the green revolution are needed to meet the expanding food requirements of the developing population in an environmentally and socially acceptable manner (Sarkadi 2019) as shown in Fig. 20.2.

7 Environment-Related Issues

Researchers face significant obstacles as they attempt to increase yields because of the exceptional changes that are brought about by global warming and the associated uncertainty (Tramblay et al. 2020). Currently, there are also many other types of needs as well (Zahoor et al. 2022). The current goal calls for an adjustment to a far more comprehensive system of agricultural growth, ecological, and socially acceptable results, making it considerably more complex than simply maximizing crop production (Streed et al. 2021).

7.1 Sustainable Agriculture to Increase Crop Production

Humans depend on agriculture for the necessities such as food, clothes, and shelter. Agriculture has played a crucial part in their existence (Holden 2021). Cereals such as wheat, rice, and maize are the main food ingredients in our diets that provide most of the calories we require (Teferra and Awika 2019). Unfortunately, the majority of agricultural practices for ensuring higher yields such as using more inorganic fertilizers and other chemicals are not sustainable or environmentally friendly. As a result, the gap between the consumption and production of various agricultural products has been growing alarmingly over the past 15 years, and this excessive use of farm inputs poses a danger to our environment. The yield of a crop is significantly influenced by climatic elements because of the nature including temperature, rainfall, and CO_2 (Skendžić et al. 2021).

The rising cost of energy-based inputs, the trend toward declining farm incomes, and the rising need for crop output have all contributed to serious economic issues for conventional agriculture system. Because the ecology, socioeconomic condition, historical and political context of our agricultural systems are so varied, it is essential to develop adaptable and regionally adjustable methods for the resilience and sustainability of agroecosystems in near the future (Fig. 20.1). To control the challenge of ensuring increased crop output with less environmental impact, it has been suggested that raising the yield potential using both modern breeding methods and novel soil/crop management approaches are key strategies.

The current situation demands are not only to rise a crop output but also that it be accomplished in a sustainable manner that ensures greater economic, environmental, and social security. To meet these objectives, researchers must work tirelessly to find novel approaches for sustainable agricultural productivity, improved input efficiency, and the preservation of the agroecosystems and remaining natural resources (Reza 2019).

7.2 Management of Moisture Contents in Dryland Agroecosystems

The most important problem with maintaining sustainable dryland agriculture is effective precipitation management (Li et al. 2020a, b). The main tools available to manage precipitation are soil tillage and crop selection (Bagnall et al. 2022). Maximizing soil precipitation capture, reducing soil water loss, and increasing plant water use efficiency (WUE) are all components of effective precipitation management (Zahoor et al. 2019). Effective precipitation management depends on understanding the relationship between the climate and tillage (Wang et al. 2020). Crop selection, planting season, fertilizer application, and all other factors affect how water is used efficiently (Mbava et al. 2020).

8 Maintenance of Carbon in Agroecosystems on Dry Land

8.1 Soil Carbon Problems

Due to the lack of a substantial soil cover, drylands are typically more susceptible to soil erosion (Duniway et al. 2019). This is typically made worse by intense rainstorms, a reduced stability of soil structure that is typically linked to a small quantity of SOC and intensive human pressure (Saleh 2022). Other elements such as the existence of steep slopes also make drylands more vulnerable to soil erosion (Weeraratna 2022). In turn, the loss of carbon from soil to the atmosphere may be accelerated by factors such as acid deposition and carbonates being exposed to weather elements because of soil erosion (Naorem et al. 2022).

The long-lasting advantages of keeping agricultural remaining on the soil surface in forms of water retention, reducing erosion, carbon sequestration, and nutrient cycling clearly require a trustworthy economic assessment (Guenet et al. 2021). Farmers could greatly benefit from this knowledge in order to decrease the amount of crop leftovers that are now being produced (Shankar et al. 2020).

Residues of crop are remained on the soil after using conservation tillage and more recently no-tillage techniques, which has long been acknowledged as a great way to minimize soil erosion (Hussain et al. 2021). The effectiveness of no-tillage in dryland environments can be improved by recent technical advancements (Yin et al. 2021). The presence of a protective vegetative cover seems to be the most sensible and uncomplicated method for reducing soil C losses through erosion in dryland ecosystems (Jafari et al. 2022). Because of this, farming in those places must follow conservation agriculture principles and leave crop leftovers on the soil's surface.

8.2 Mechanism of Inorganic Carbon Sequestration in Soil

There is a growing acknowledgment that the global C cycle greatly depends on the relationship between agricultural practices and soil inorganic carbon (Raza et al. 2020). Through the development of secondary carbonates, various soil management and land-use strategies have been proposed for the soil inorganic carbon sequestration in dryland ecosystems. In dryland environments, soil inorganic carbon sequestration rates range from 0.1 to 0.2 Mg ha^{-1} year^{-1} (Nachimuthu et al. 2018). In semiarid and arid areas with irrigated soils, carbon storage in inorganic forms has been suggested as a useful alternative.

8.2.1 Biodiversity in the Soil and Ecological Services

In agricultural systems, biodiversity is thought to be essential for the continuity of ecosystem services (Tscharntke et al. 2021). Important ecosystem services can be provided by plant biodiversity (Beillouin et al. 2021). Utilizing that variety in agricultural systems along with other agricultural techniques such as vegetative mulches, fertilizing, irrigation and reducing tillage intensity has an impact on soil C pools enhancing net output (Shah et al. 2022).

Water scarcity is the basic constraint on total yield, crop diversification, SOC dynamics and activities of soil microorganisms in dryland agroecosystems (Lal 2019). There are four key components of dryland agriculture that can boost output, offer ecological services, and raise SOC; legumes and agroforestry are two examples of how to make use of plant diversity (Sauer et al. 2021). Other strategies include managing crop residues properly, learning more about the impact of soil biology on carbon cycling and figuring out the ideal level of ecological crop intensification (Sarkar et al. 2020). Crop rotations that encourage plant diversity typically enhance aerial biomass and support root system diversification with a variety of effects on SOC by root-derived products (Jansson et al. 2021).

8.2.2 Use of More Effective Water Conservation Strategies

Dryland agricultural systems are less productive due to the water deficit conditions caused through the variations in potential evapotranspiration and precipitation (Zhu et al. 2018). The majority of dryland areas experience irregular rainfall, so it is essential to develop regional decision tools to understand the best strategies of agricultural management (e.g., crop selection, timing of sowing, control of soil's cover, rates of N application, and timing) based on the water retained amount in the soil. Making the right judgments would improve the biomass production and the sequestration of SOC (Di Sacco et al. 2021). The water usage efficiency of crops, soil water retention, as well as precipitation capture, all require to be enhanced to achieve this (Vance and Milroy 2022).

8.2.3 Integrating Livestock in Dryland Farming Systems

Grazing and the production of forage crops for limited animal feeding are two ways that livestock activities affect the environment (Sarabia et al. 2020). Currently, livestock farming uses 30% of the Earth's surface area and 70% of all agricultural land worldwide (Hong et al. 2021). Grasslands in dry, semiarid, and tropical climates would be more severely influenced by the rise in demand for animal products in terms of ecological conditions and environmental changes (Zarei et al. 2021). Grasslands have shown lower rates of SOC sequestration than other land uses but given the size of the area covered by this land use, their global impact can still be substantial. Depending on climate factors and management, grasses have different potential for carbon storage.

8.2.4 Prevention and Adaptability to Changing Climate

Prevention to change of climate in the forest and agriculture industries relates to reducing emissions of greenhouse gas from sources related to animal husbandry and agriculture as well as increasing soil carbon sequestration (Panchasara et al. 2021). Adaptability to climate change in these sectors relates to the adoption of activities that lessen the negative impacts of change in climate (Aryal et al. 2020).

8.2.5 Management Improvements Are Seen as an Externality

Dryland soils may have positive social and economic effects on poverty reduction, environmental restoration, and agricultural system sustainability (Tui et al. 2021). At the local, regional, and global levels, increased crop yield, improved agricultural sustainability, and evidence exist for the advantages of increasing dryland C (i.e., mitigation of change in climate) (Rejekiningrum et al. 2022). Therefore, the advantages from farmers' actions may have positive externalities on other stakeholders and may occur now or in the future (Bikomeye et al. 2021).

Externalities suggest that policy measures are required to ensure that better C management is produced at the socially optimal level (Oum and Wang 2020). Through a variety of techniques such as improved carbon trading programs or improved technical farmer knowledge and policy may offer incentives to farmers to generate this social optimum (Del Rossi et al. 2021).

8.2.6 Integrating Carbon Sequestration in Drylands with Global Development Policies

Dryland land degradation involved that the C stored in these ecosystems will be released into the environment in the form of greenhouse gas emissions (de Oliveira et al. 2021). It is also obvious that severe degradation of land in drylands may be a factor in the spread of poverty in many areas (Barbier and Hochard 2018). For drylands, a carbon-market-only strategy is unlikely to be effective because it must also take other factors such as sustainable development and poverty alleviation into account.

9 Sustainable Dryland Agricultural Development

The growing water constraints, land degrading processes, ongoing issues related to malnutrition, and migration because of frequent drought conditions are just a few examples of how the developments in the dryland region reflect how much poverty is prevalent. Future dryland agriculture technology research and developments were seen as being heavily reliant on conservation tillage and crop genetic advancement. Development of agriculture in world's semiarid regions has been typically successful when combined with animal husbandry, full maintenance, and effective application of precipitation resources (Li et al. 2020a, b).

9.1 Applying Fertilizers to Promote Dryland Crops Production

A major element affecting grain weight during the grain-filling period in dryland crops is the transportation and redistribution of dry matter. Under drought conditions, it was examined how different fertilizers and tillage treatments affected the assimilation and remobilization of dry matter during crop grain filling.

9.2 Saving Water Biologically Through Physiological and Molecular Approaches

There are two approaches to enhance the productivity of dryland crops; one is to modify the ecological environment to accommodate crop development and the other is to modify the crop itself to accommodate environmental changes (Chaloner et al. 2021). Drought tolerance and water conservation in biological sense will become a major problem when the inadequate precipitation reserves in semiarid areas that are significantly regulated to the utmost extent (Strauss et al. 2021). As a result, using technology for physiological management and genetic enhancement to boost agricultural productivity in these regions is not only necessary practically but also has significant development potential in the future (Hernández-Castellano et al. 2019).

9.3 Ecological Diversification of Agriculture in Drylands

Dryland's areas present challenging soil and climatic conditions for agriculture due to their poor yearly water balance, short and high soil salinity, low soil organic matter content, and fluctuating rainy season. Due to the rising aridity that estimate for drylands in the late twenty-first century, these conditions are anticipated to worsen resulting in significant desertification processes (Becerril-Piña and Mastachi-Loza 2021). Under this climate change scenario and considering the growing pressure from the human population, the long-lasting sustainability of rainfed agriculture which predominates in drylands is essential for ensuring global food security (Stavi et al. 2022).

9.4 Aims for Maximum Yield Potential in Dryland Agroecosystems

The primary objective of any agricultural system is crop yield. Due to reduced productivity and a wider yield gap in developing nations, it is crucial to boost agricultural production and its stability over time through building resilience to climate change (Mustafa et al. 2019). In fact, improving the crop yield's temporal stability is a top priority for smallholder dryland agriculture in the context of climate change (Wahab 2020). However, drylands see significant fluctuations in rainfall availability over time (Abel et al. 2021), and as a result, the potential for agricultural practices to improve yield stability, particularly in rainfed environments, is retarded by this environmental variability (Gull et al. 2020).

Intercropping depends on the increased yields that come from co-growing various crop species or genotypes on a specific plot of land for a specific amount of time (Griffiths 2019). Accordingly, intercropping encourages the ecological intensification of agriculture by reducing the need for synthetic inputs and increasing resource (e.g., water and N) efficiency and pest management, whose benefits may outweigh the detrimental impacts of plant competition (e.g., fertilizers and pesticides) (Fernández et al. 2022). This is especially true if the intercropping system includes legume species that fix atmospheric nitrogen (Reilly et al. 2022). The stress gradient hypothesis postulates that in stressful situations as opposed to more mesic ones, plant facilitation occurs more frequently than competition which may insights important light on the viability of intercropping in dryland agriculture (Epafras 2019) as shown in (Table 20.1).

Table 20.1 Research gaps and recommended actions to improve the ecological intensification of agriculture in drylands

Research questions	Recommended approaches	References
Can crop productivity and services of ecosystem promoted at the same time by ecological intensification services in dryland areas?	Multifunction structure when evaluating different management task, accessing of trade-off, and ecological services by use of stakeholder-based	García-Palacios et al. (2019)
Is agricultural conservation enough in dryland areas?	By the application of long-term field trials are able to evaluate the effect of reduced tillage, residues of crops, and rotation in crops and its stability. For better results crop residues and crop rotation should be able to give high yield	Riptanti et al. (2021), Fonteyne et al. (2020) and Kumar et al. (2020)
What are the phenomena behind generating beneficial impact on crop yield (intercropping) and related to temporary stability in dryland?	With the help of field trials by using optimal functioning trails distribution crop mixture will be identified	Li et al. (2022)
By the use of soil biodiversity, is it possible to enhance carbon accumulation and nitrogen retention in soil (dryland areas)?	On soil organisms, the impacts of different farming practices can be evaluated by manipulative studies	Laban et al. (2018) and de Graaff et al. (2019)

9.5 Maintenance of Dryland Crops

Crop rotation, residue management systems, and reduced or no tillage are all beneficial dryland crop management techniques. The primary constraining element for sustainable crop output in dryland agriculture is the availability of water during crucial periods of crop growth (Welsh et al. 2022).

However, the availability of water is rarely taken into account when evaluating the efficacy of dryland cropping systems; instead, crop output and profitability are used (Nenciu et al. 2022). Instead of only the cropping system, numerous other elements also have an impact on yield and profit (Abrahão and Costa 2018). Therefore, rather than relying exclusively on crop productivity and profit, a crop rotation system in a dryland is more sustainable if it increases soil water (Rosenzweig et al. 2020).

9.6 Soil Water Profile and Fallow Development

Fallow is the duration between crop harvest and the planting of the next crop. For the years 2000–2006, W-CR-GS-F and W-CR-SB-F had higher profile ASW at corn development and harvest than W-CR-SF-F (Table 20.2). The accumulation of ASW

Table 20.2 Average available soil water at planting and harvest, fallow accumulation, and water use of corn, sorghum, sunflower, soybean, and winter wheat in W–F†, W–GS–F, W–SF–F, W–CR–SB–F, W–CR–SF–F, and W–CR–GS–F rotations grown near Tribune, KS, from 2000–2006

Rotation	Soil water availability									
	At planting					**At harvest**				
	Corn	**Sorghum**	**Sunflower**	**Soybean**	**Wheat**	**Corn**	**Sorghum**	**Soybean**	**Wheat**	**Sunflower**
W-F	–	–	–	–	223a	–	–	–	–	77
W-GS-F	–	175	–	–	187b	–	90	–	–	90
W-SF-F	–	–	147a	–	144c	–	–	71	–	80
W-CR-GS-F	148a	133b	–	–	151c	91a	72	–	–	88
W-CR-SB-F	146a	–	–	130	138 cd	93a	–	–	110	85
W-CR-SF-F	125b	–	116b	–	121d	76b	–	74	–	77
HSD	18	15	15	–	20	11	9	NS		
	Fallow accumulation					**Water use**				
	Corn	**Sorghum**	**Soybean**	**Wheat**	**Sunflower**	**Corn**	**Sorghum**	**Soybean**	**Wheat**	**Sunflower**
W-F	–	–	–	–	150a	–	–	–	–	428a
W-GS-F	–	78a	–	–	98b	–	330	–	–	375b
W-SF-F	–	–	64a	–	72 cd	–	–	300a	–	342c
W-CR-GS-F	58	44b	–	–	83bc	327	306b	–	–	342c

Abbreviations: *ASW* available soil water, *CR* corn, *F* fallow, *GS* grain sorghum, *HSD* Tukey's Honest Significant Difference test, *M* proso millet, *NT* no-till, *RT* reduced tillage, *SB* soybean, *SF* sunflower, *W* winter wheat during the period of fallow (the time in between wheat harvest as well as maize planting) was similar across all corn-based rotations as shown in (Table 20.2).

Profile ASW at sorghum planting and fallow accumulation before sorghum planting were higher for W-GS-F compared to W-CR-GS-F for grain sorghum-based rotations over the 2000–2006 timeframe (Table 20.1; Schlegel et al. 2019). When it came to profile ASW at sorghum harvest, there was no significant variation between the two rotations (Schlegel et al. 2020).

9.7 Dryland Corn Production Efficiency

The main goals of the RFM system are to maximize the effective precipitation concentration into the rooted soil profile of crops, reduce inefficient evaporation of tiny rainfall events, and stimulate crop development (Luo et al. 2021). In the RFM system, cropland is formed into an M-shaped ridge-furrow microtopography, plastic film is used to thoroughly cover the soil surface, and then crops are planted in furrows. The width of the ridges and furrows can be altered in accordance with the crop's requirements and the local environment (Wang et al. 2021).

The main purpose of the RFM system is to collect rainfall that has runoff from the ridges in the furrow bottoms. But without film mulching, precipitation drainage from the ridge surface is only feasible once the topsoil's soil moisture has reached up to saturation. For infiltration, rainfall runoff from the ridge to the furrow is constrained when the intensity and length of the rainfall are low. Without film mulch, a ridge and furrow design can increase the soil's evaporation area, allowing only partial rainwater to seep into the shoulder soil of the ridges and much of it to potentially evaporate quickly. In ridge-furrow design without mulching, the soil water evaporation capacity was greater than in plain cropping. Due to the waterproofness and hydrophobicity of plastic film, film-mulched ridges allow nearly all precipitation to condense at the bottom of furrows before entering the soil through plant-standing holes in the furrows. Additionally, rainwater in film-mulched soils is less likely to evaporate, which significantly improves the water availability in the crop-rooting zone of the soil (Zheng et al. 2020). As a result, precipitation use is more effective.

10 Warming Effects of Film Mulching

Warming effects of film mulching influenced the cultivation of maize on plateau when the air is too cold (Fang et al. 2021). A warm-weather and water-intensive crop is corn. Lower temperatures, low precipitation, and poor cropland are characteristics of the Loess Plateau's arid regions that make them unsuitable for the development of maize. However, the RFM system improves soil heat and moisture conditions which should result in a significant improvement in maize production when fertilizer application is increased. The yield which was three to four times more than the local traditional wheat yield can be raised several times in regions with an average annual rainfall of 320 mm (Shoukat et al. 2022).

11 Conclusion

Considering all this study of literature review about sustainable crop management for drylands, it could be said that well-developed and advanced agricultural practices and water conserving strategies as well as integrated management strategies are the key components for sustainable agricultural production in dryland areas. This can fulfill the future food demands for increasing population. Above all of these socioeconomic and ecological services of dryland agricultural systems, current challenges of dryland systems which developed by changes in climatic pattern influenced on biogeochemical patterns and net main production as well as increasing the increasing number of individuals in human population. That is why they must be addressed properly for sustainable crop management.

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Chapter 21
Crop Improvement in the Desert

Nimra Shehzadi, Filza Ishfaq, Athar Mahmood, Muhammad Mansoor Javaid, Maria Naqve, Abdul Jabbar, and Ahsan Aziz

Abstract The capacity of a plant to maintain optimal cellular homeostasis under biotic and abiotic stressors is essential for plant growth and development. Desert ecosystems occupy almost 35% of the planet's land area. As a result of climate change, more regions are anticipated to experience water scarcity. Owing to its fatal impact on plant growth, development, and reproduction, which foreshadows a food shortage and significant economic losses, water deficiency has emerged as a global hazard. Drought-tolerant plants known as xerophytes may thrive and flourish in these challenging conditions. All xerophytic plants have similar forms, structures, and shapes to survive in such a xerophytic environment, even though they are not closely related to taxa. Xerophytes and the various ways in which they adapt to arid environments are currently a topic of interest on a global scale. The unexpected scarcity of evolutionary transitions between drought-avoiding and halophytic succulence may be explained in this chapter. The morphological, anatomical, and physiological adaptations and survival strategies that allow xerophytes to grow and complete their life cycles in dry and semiarid environments are also covered in this chapter.

Keywords Abiotic stress · Xerophytes · Management strategies

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1 Introduction

Deserts are a part of the land where extreme temperatures occur and it is a highly dry land area with sparse vegetation covering 10–50% of land surface such as lichens, tundra, steppes, and scattered high-altitude vegetation (Voigt et al. 2020). According to some other definitions related to deserts, any environment that is free of plants is considered to be a desert; some deserts have very low temperatures, i.e., frigid deserts (Alsharif et al. 2020). Harsh conditions of deserts are only able to support sparse vegetation but it may be possible to grow shrubs or herbaceous plants in normal environmental conditions as these do not cover enough land area (Liu et al. 2020; Wang et al. 2020). Arid conditions are very common in deserts but this is only the fault of practices carried out by humans such as the heavy grazing of cattle on an already stressed environment (Ajani and van der Geest 2021).

In geologic terms the conditions of deserts appear to be relatively recent in origin (Pepper and Keogh 2021). Deserts also represented extreme temperatures during the Cenozoic Era as a result of aridification and cold temperature (Siesser 2020). This extreme temperature led to the formation of the margins (tropical and temperate) of the growing deserts (Eckardt et al. 2022). The distinct plant families of deserts and tamarisk families (first appeared) in the Miocene and evolved in salty areas (Pfadenhauer and Klötzli 2020). The ancestors of desert plants emerged from moister habitats and the fact that evolution occurred on many continents independently (Eckardt et al. 2022). This is due to the intrinsic characteristics in widespread desert families; as a result the migration of plants occurs with the help of seed dispersal to the surrounding the desert areas by chance (Prach and Walker 2020). Such migration occurs in between the areas of the northern and southern regions of deserts of Africa and also in some regions of the Americas during the dry climatic conditions (Mashwani 2020).

Globally, climatic-change water shortage is a daily issue that is becoming a major problem in many regions of the world (Abedin et al. 2019). In desert regions, the rate of precipitation is low and unpredictable. The dryness of the deserts is increasing day by day owing to the interruption of environmental changes (Pfeiffer et al. 2021). The average annual precipitation in most deserts is less than 400 mm, making hard climatic conditions for the desertic plants due to moisture shortage (Mashwani 2020). Drought is the primary distinguishing factor of a desert and the primary limit to which desert organisms must adapt. The harsh environment of desert regions is due to low moisture levels relative to precipitation (Liu et al. 2022).

Most of the surface of the earth is covered by oceans, which almost make up 71% of the Earth's surface, with the remaining area being land, about 29%. Deserts actually make up 33% according to past studies and research, or one third of the surface area of the land (Kidd et al. 2017). The Kalahari and Namib deserts (South Africa) and the Sahara desert (Northern Africa) are examples of desert areas (Alsharif et al. 2020). The Middle East in the Arab World is one of the world's largest sandy deserts (the Empty Quarter and the Negev Desert) (Al-Dousari et al. 2022). Many of the largest and driest deserts are found in North Mongolia and China; however, the Taklamakan desert borders the Gobi (west). In North India and parts of Pakistan, the Thar desert is suggested to be the most heavily populated desert. Agriculture takes advantage of one of these vast, dry, and isolated climates (Alsharif et al. 2020; Khan et al. 2021a) (Fig. 21.1). Deserts are hot but there are also cold-climate deserts. Related to past studies, the continent of Antarctica has the largest cold desert and northern Africa has the hottest desert (Sahara Desert) covering nine million square kilometers (Williams 2021; Shay 2021; Sawant and Dalavi 2022).

The life that exists in these areas faces harsh conditions, which appear to have a detrimental impact on living organisms such as plants and microbes (Parrilli et al. 2021). Extreme temperatures are common in deserts as during the day time the temperature range goes high (hot) owing to the lack of vegetation, but at night the opposite occurs as the temperature range falls (cold). It has been reported that in hot deserts the temperature ranges from 40 C to 50 C during the day time but falls to 0 C at night. In the desert, another environmental issue is intense solar radiation, which may reach 840 GJ km^2 per year (Mohammed et al. 2021).

In desert habitats, water scarcity is another major abiotic stress factor. Desert areas have water-controlled systems in which life is managed by balancing moisture loss and water supply (Richmond 2019). In addition, the combination of low rainwater and increasing evaporation rates owing to temperature changes causes desert water sources to be depleted (Querejeta et al. 2021). Many factors, such as high wind, soil erosion and temperature fluctuations have caused soil degradation and nutrient depletion, leading to increased cost of agriculture production (Rafik et al. 2022).

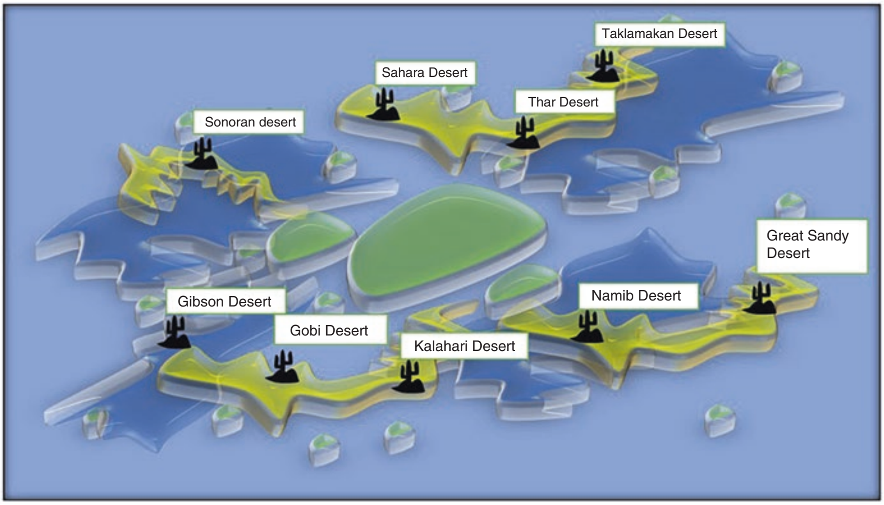

Fig. 21.1 Distribution of deserts across the land surface (Alsharif et al. 2020)

2 Anatomical Features of Desert (Xerophytic) Plants

Desert plants are named xerophytic plants and are classified into ephemerals, succulents, and nonsucculents (Frank 2021). Plants grown in xeric conditions are well adapted physiologically as well as morphologically. In addition to morphological adaptation such as a high level of root system, changes also occur in the stem (cladode and phylloclade) and special leaves are present to prevent water loss (transpiration) such as sclerophyllous, microphyllus, trichophyllus, or sometimes caucus. Water loss is limited as a result of specialized tissues such as rhizodermis with outer cell walls (thickened) (Wang et al. 2021a) and a well-specialized suberized exodermis, which is sometimes accompanied by various layers of thin- or thick-walled suberized cells. Root systems with shallow and deep roots exist in semi-arid conditions. The root systems of mature African rue plants, like many of the world's invasive weeds, have widespread deep tap roots and lateral roots (Heinrichs and Muniappan 2019).

Ephemerals are associated with the drought-escaping kind as they have no capability to tolerate drought conditions (Hemati et al. 2022; Kumar et al. 2022). When the rainfall season comes, ephemerals germinate and quickly move to the maturity stage such as flower and fruit formation (species of Papilionaceous and Composite) (Chinga Chamorro 2019). Succulent plants can store water in their stems and leaves as found in Cactaceae (rounded stem). These also include C_4 perennial woody plants such as *Haloxylon ammodendron* (native of northwest China). Nonsucculent plants can successfully survive in conditions of water scarcity, and these are also associated with true xerophytes or euxerophytes. Plants that survive in drought conditions are weak and small in growth and development (D'Arco 2018; Grigore 2021).

3 Desert Plants as Food Crops

Many of the crops such as rice, wheat, and soyabean (C_3 plants) show low efficiency of water use and photosynthetic rate (Yadav and Mishra 2019). Some other crops are also used as desert crops, suggested to be C_4 plants, such as maize, sorghum, and sugarcane, which are heat-tolerant crops, but they may require water consistently in dry and semi-arid environments (Serba et al. 2020). When the temperature rises, evapotranspiration occurs rapidly as a result of this high amount of water required for maintaining the agriculture. Food plants of different deserts include not only plants but also some other food sources such as palms, lilies, and cattails, which provide a source of nutrition to desertic people (Elias and Dykeman 1990; Wrangham et al. 2009).

4 Extreme Environmental Conditions (Abiotic Stresses)

Globally, life exists in these areas facing harsh conditions, which badly affect the living organisms by abiotic factors such as drought, salinity, extreme temperature (high or low), and other environmental stresses (Haggag et al. 2015). Solar radiation is a fundamental driver of desert conditions, leading to extreme heat and aridity (Alsharif et al. 2020; Deshmukh et al. 2019; Coleine and Delgado-Baquerizo 2022).

The highest radiation range globally is found in the Arabian Peninsula to the Sahara deserts (areas receiving the most radiation) (Alharbi and Csala 2021). The main reason behind these high levels of radiation is the presence of these areas on the Equator and because of less cloud coverage.

Related to abiotic stresses, water scarcity is also another issue for plants that causes difficulties for those plants that grow under harsh desert conditions (Wahab et al. 2022). Deserts are also associated with water-controlled systems as survival can be maintained to balance the loss of water and water availability. In the desert, the main sources of water for life are precipitation (rainfall), ground water, atmospheric vapor, and fog (cold deserts). Additionally, when temperature rises and rainfall rates fall (annually) then the rate of evapotranspiration (water loss) increases, and water reserves in deserts rapidly decrease (Riedl et al. 2022). The shortage of rainfall in the deserts depends on four factors:

- The global atmosphere maintains twin belts of dry, rising air over the tropics known as Hadley cells (Riedl et al. 2022).
- Aridity is mainly due to the pattern of marine circulation that cools the air along the western coast of South and Central America, Africa, and Australia, lowering its moisture-carrying capacity.
- Mountain ranges make rain shadow effects (Riedl et al. 2022).
- Water is limited if there are long distances between the center of the continents (such as China's Gobi and Taklamakan deserts) (Papelitzky 2021; Zhang et al. 2019b).
- Arid soil is found in desert areas for many reasons such as strong wind erosion, fluctuation in temperature, sedimentation, and most importantly, water deficiency. In most parts of the deserts, on the basis of this, the soil is considered "aridisols". Some features of "aridisols" (Rasooli et al. 2021) are shown in Fig. 21.2.

Furthermore, the soils of deserts are arid owing to sparse vegetation cover in the biological soil crust (BSCs). The soil crust consists of soil particles mixed with other lichens, mosses, filamentous cyanobacteria, and fungi, which show bonding between soil particles, making the soil surface and cohesive bonding show how fertile the soil is and stable in the harsh environment of the desert (Kheirfam and Roohi 2020). The cohesive nature of BSCs protects the fertility of soil from high wind and water erosion. The soil particles aggregate to enhance the soil structure of soil. These are helpful in improving the nutrient availability present in the soil and improving the water-holding capacity of the soil. These cohesive forces are formed

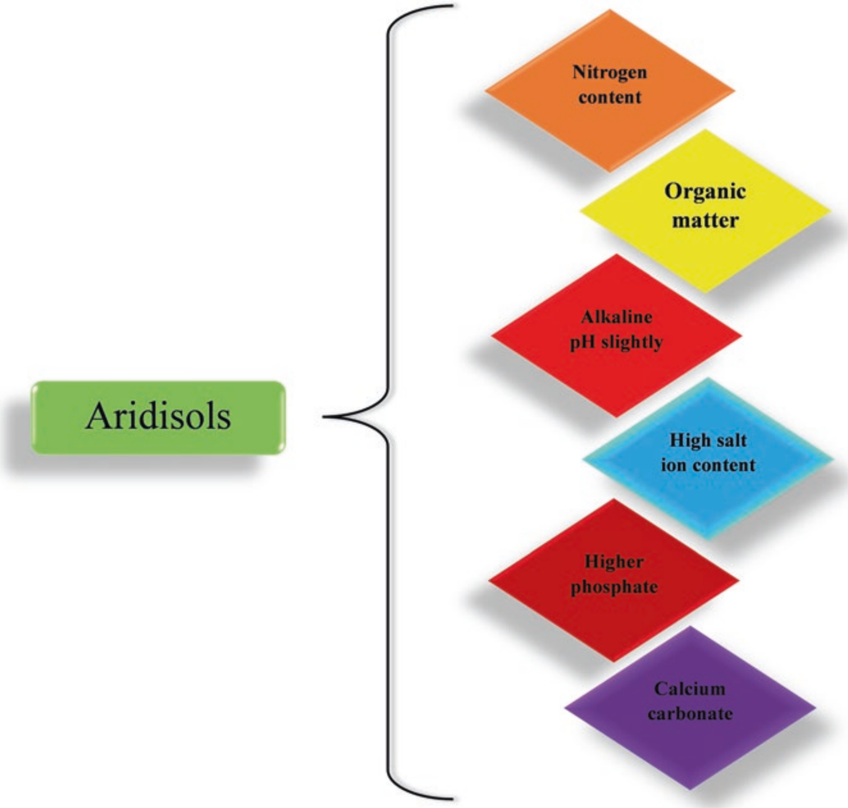

Fig. 21.2 Characteristics of desert soils (Brooks et al. 2018)

owing to the polysaccharide layer present on the soil surface, which is produced by some of the BSC microbial community members (filamentous cyanobacteria) (Costa et al. 2018; Usharani et al. 2019).

Another characteristic of desert soil is soil salinity, as saline soil is a major issue of deserts. It is reported that 20–30% of irrigated soils are affected by salt and about 50% of the arable land area are estimated to be salinized by 2050. Large amounts of sand present in the soil owing to a high rate of evaporation but low precipitation rate. Saline soils have severe effects on plants and ecosystem due to ion toxicity, osmotic stress, and ion imbalance (Or and Lehmann 2019). Sodium and chloride ions have negative impacts on the membrane of cells as well as protein metabolism and energy balance disturbed by enzymes (Gałęska et al. 2022; Mukarram et al. 2021).

4.1 Adaptation of Desert Plants Against Extreme Environmental Stresses

The desertic plants are allowed to grow, develop, and reproduce as a result of adaptation due to extreme fluctuations in the environment (Ramakrishnan et al. 2021). Deserts were considered as old civilizations such as Atacama, Sonoran, Mojave, and Chihuahua. In deserts, early people got food, shelter, fuel, and medical remedies from plants. But now plants prove beneficial for human life in medical, economic, and industrial form. Harsh conditions of deserts have a negative impact on plant growth and development and cause the decline of scarce grass and shrub growth (vegetation). In deserts, the flora is of two types: one is annual or perennial succulent plants (stem or leaf succulents) and the second is nonsucculent plants (shrubs, herbs, trees, and grasses).

In deserts, the temperature and radiation levels are high, which has harmful effects on plants. As a result of this some changes occur such as high production of reactive oxygen species (ROS) (Wang et al. 2022). These ROS can destroy the cell structure such as damaging DNA, cell membrane, lipids, and proteins. Because of these stresses, plants in deserts change the angle or size of leaves; for example, the vertical and steep angle of leaves reduces the absorbance of light and less heat will be absorbed (leaves are thick in order to store water) (Tserej and Feeley 2021). Flavonoids (phenolic compounds) are produced in desertic plants, which is considered to be another mechanism for reducing water loss or by forming a layer of cuticle over the leaf (Tredenick and Farquhar 2021).

Desertic plants use another mechanism to overcome the harmful impacts of high temperature and high solar radiation, by changing the rate of photosynthesis, as these replace photosynthesis with photorespiration and absorb less energy (Tredenick and Farquhar 2021). The photosynthesis process used by the desertic plants is different from basic definition of photosynthesis such as crassulacean acid metabolism (CAM) found in Agavaceae (agave) and Cactaceae (cacti). The cell membrane is saved from high temperature with the help of heat shock proteins (HSPs), which allow protein folding and maintain the stability of the plasma membrane (Nover 2022). The desertic plants are well able to survive under high temperatures owing to the presence of HSPs such as *Agave tequilana* (a succulent plant that is resistant to high temperature) (Niethammer 2020).

The water scarcity issue is mostly found in desertic plants because the temperature is high and the transpiration rate directly proportional to the temperature. But plants adopt some changes to overcome drought condition such as the seeds of annual plants remaining dormant by using this strategy and these will germinate whenever suitable conditions are available (Liu et al. 2021; Peguero-Pina et al. 2020). The perennial plants of deserts close their stomata, follow CAM photosynthesis phenomena, and adopt some morphological changes, for example, roots of desertic plants grow their roots up to 70 m long such as *Acacia erioloba* trees in South Africa (Pfadenhauer and Klötzli 2020). Desertic plants closure their stomatal pore at low potential in order to lower the level of gaseous exchange. The leaf area, leaf angle, and hydraulic conductance are the adaptations made in desertic plants to survive in such harsh conditions (Peguero-Pina et al. 2020).

Another strategy is that desert plants form soil particles, which helps the grass species to adhere to soil very strongly. This trait is known as the rhizosphere, which was first found in semi-arid regions of deserts. It has been reported that the rhizosphere is found mainly in wheat, maize, and barley. The main function of the rhizosphere is to increase root hairs and the production of mucilage (Marasco et al. 2018).

Plants are of two types with regard to salinity: one is halophytes, which are able to tolerate salinity, and the second is glycophytes, which are unable to tolerate salinity (Karakas et al. 2020). Halophytes make some changes in the morphology of roots (longer tap roots). Tap roots can access humidity in soil at greater depth. Other mechanisms are also present, such as vacuoles and granular compartments, which have the ability to store solutes (sequester ions) in order to maintain the turgor pressure of the cell. Desert plants also follow another mechanism to stay longer in harsh environments by stopping the uptake of salt (transport to leaves) with the help of transporters (Na^+ and K^+), closure of stomata, and antioxidant enzymes introduced owing to ROS scavenging. It also includes the production of plant hormones in the plants (Bueno and Cordovilla 2020).

Some changes occur structurally and functionally in desert plants owing to the harsh environment. Desert plants come in contact with the communities of microbial colonies and these microorganisms will help to inhibit the surrounding soil particles such as nitrogen-fixing bacteria and plant growth-promoting bacteria (PGPB) (Loera-Muro et al. 2021). These microorganisms are found in the phyllosphere (aerial parts of the plants), endosphere (inside the plant), rhizoplane (on the root surface), in the form of liquid released from roots (root exudates), which is able to attack the microbes as a result of this nutrients being richly produced in this region compared with other areas of soil. There are different factors that show the selection, addition, and enrichment, and some changes occur dynamically (plant microbes) (Dastogeer et al. 2020; Gupta et al. 2021) (Fig. 21.3).

4.2 *Role of Bacterial Community in Desertic Plants*

The host plant genotypes and the bacterial populations interaction in their rhizosphere is a complex process influenced by various factors, including geographical location and soil conditions. Previous studies reported that the rhizosphere includes more acyl homoserine lactone -producing microbes than the top layer of the soil (Parray et al. 2019). Plant diseases such as *Pseudomonas* and *Sinorhizobium* can influence plant gene regulation, promote plant growth, and promote systemic resistance to diseases. Such plant growth-promoting rhizobacteria (PGPR) have been in abundance in the root nodules of desert plants such as agave and cactus (Dwibedi et al. 2022). Desert PGPR are adapted to extreme conditions such as heat and high salt, and they use genetic traits to enhance plant development and soil quality (non-arid soil bacteria). The PGPR can enhance plant growth and productivity in different environments (arid, semi-arid, semi-arid, and hyper-arid) (Ayangbenro and Babalola 2021). It also helps to produce more fertile soil, greater crop yields, and increased agronomic sustainability, also contributing to the development of desert habitats.

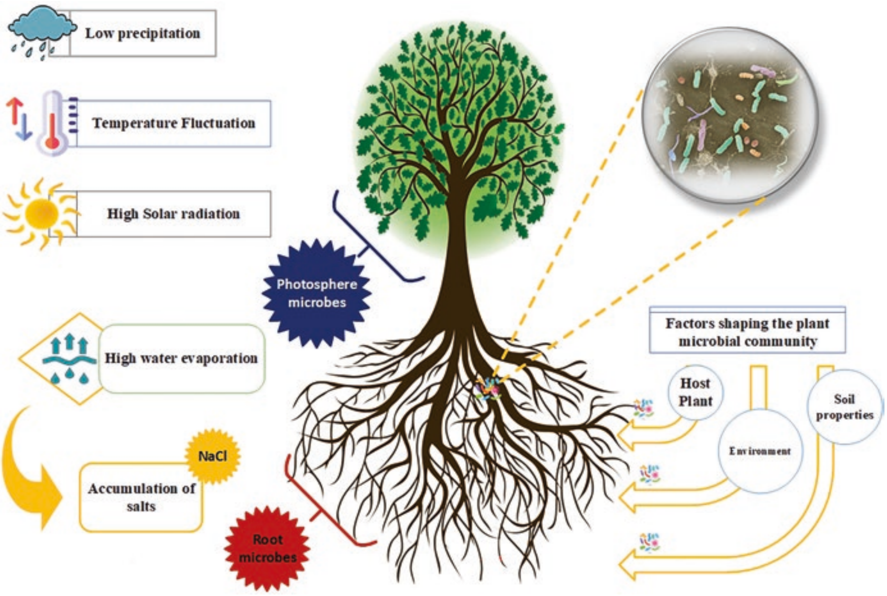

Fig. 21.3 Life in the desert. The illustration highlights the abiotic factors affecting life in the deserts, such as the low precipitation and high temperature fluctuations, and high solar radiation, which results in high water evaporation resulting in the accumulation of salt ions in the soil causing soil salinity and affecting the soil composition. Plants in the deserts live in close association with the microorganisms that inhabit the plant aerial parts, inside the plant root and in the zone around the root (root microbiota) where the root exudates are secreted to attract the bulk soil microorganisms. A number of factors, including soil properties and composition, the water availability, the soil electrical conductivity, and pH, are responsible for shaping the plant microbial communities and filtering the selected microorganisms to improve the fitness of plant and microorganisms. A second factor is the location and the associated climatic conditions, and finally, the host plant, for the selection of the most beneficial associations, through means of plant defense mechanisms and immunity, root exudate secretions (this includes different quorum sensing-mimicking compounds), and the host plant genotype

Watering the plants would not be able to improve deteriorated soil by using standard methods (Guo 2020). As a result, researchers have focused more on isolating native PGPR and found that this improves soil fertility and plant development in impacted areas. Furthermore, PGPR was diseased with plant cowpea and gives an example of the good adaptation of plant development and nutrient uptake in semi-arid plants (Ojuederie et al. 2019). Furthermore, coating seeds with the Bacterium isolate significantly increased germinating seeds, fresh and dry weight, shoot and root length, as well as leaf area (Cardarelli et al. 2022). For example, In China's Gurbantünggüt Desert *Salicornia europaea* L. is considered one of the most common pioneer halophytes (salt accumulating). Additionally, the PGPB were successfully injected into drought-stressed wheat plant growth, increased soluble sugar content, chlorophyll content in the leaves, and decreased proline levels, indicating drought stress tolerance in wheat plants.

5 Locust Attacks on Desert Plants (Biotic Stress)

The desertic locust, named *Schistocerca gregaria*, considered the oldest locust, created a devastating effect on the crops and range land of deserts, acting as a pest attack in larger parts of the world such as Africa and Asia (Jhiknaria 2021; Showler et al. 2022). The population of locusts increases when the water amount becomes lower and the vegetation remains less. As a result of this, these contain pheromone-modulated changes (morphologically and behaviorally) and aggregation occurs, which produces nymphal bands and adult swarms. Within 2019 and 2020, the population of locusts increased periodically in deserts, which are known as breeding areas where such production of progeny occurs (Kietzka et al. 2021). Recently, many episodes of locust attack were reported from early research and literature, i.e., from the plague of 1986 to 1989, the upsurge of 1992 to 1994, the 1998 outbreak, 2003 to 2005, and the most recent event started in 2018 (Showler and Lecoq 2021). Owing to locust attacks related to the last 80 years devastation and destruction of crops were caused (desert), such as one million grape vines in Libya, and 167,000 tons of grains wasted in Ethiopia, which is sufficient to feed one million people for a year. In Pakistan, it is considered that desert locust attacks declined in number but there is not enough information in the past literature (Singh et al. 2022).

5.1 Locust Attack (South Asia)

South Asia contains different areas such as Afghanistan, Bangladesh, India, Iran, Bhutan, Maldives, Nepal, Sri Lanka, and Pakistan (Jatoi et al. 2021). These are all the most agriculturally important parts of this continent where there is a high rate of locust attacks. The southern parts of the borders of Indo-Pak contains the Thar desert, where most breeding of the locust occurs (Chouhan 2018; Dandabathula et al. 2020). A long time passed (1947–2021), but the desert attacks could not be controlled as the swarm of locust increased time to time. About five noticeable attacks occurred in South Asia in the past few years (2018 to 2021). From Iran, swarms spread into Pakistan largely because of the suitable environmental conditions (Diamond 2021). The worst episode of locust attacks for 26 years has been reported in literature in India. Rajasthan (state government), for example, provided US $80 million to assist farmers to control the attack of locusts on deserts (Jhiknaria 2021; Showler et al. 2022). For a large-scale control operation (locust attack), India's government announced on 24 August 2020 that the spreading of locust swarms was controlled (Pervaz 2021; Yamano et al. 2021) (Table 21.1).

Table 21.1 Desert locust episodes in South Asian countries 1961–30 January 2021

Country	Desert locust-affected area (km^2)	Years of major desert locust activity	Infested crops	Control tactics	References
Afghanistan	123,200	2002–2003	Apple, pomegranate wheat	Conventional insecticides	Showler et al. (2022)
Bangladesh	6000	2019–2020	Bean, peanut sweet	Smoke, conventional	Cock and Van Vuuren (2020)
Bhutan	2400	2019–2020	Black tea, vegetables	Conventional insecticides	Kimathi et al. (2020)
India	1795.84	1978,1993, 2020	Pulses, soya bean, sugarcane	Biopesticides, conventional insecticides	Ghosh (2020)
Nepal	1100	2019–2020	Maize, rice, soy	Conventional insecticides	(Joshi et al. (2020)
Pakistan	260,785	1961, 1993, 2019–2020	Cotton, wheat, chickpea	Conventional insecticides	Topaz et al. (2012)

5.2 *Locust Attack (Pakistan)*

In the last 100 years, Pakistan is considered to have had the most attacks of locust such as 1926, 1952, 1962, and 1992 (Usman et al. 2022). In reaction to the current incident, Pakistan's Space and Upper Atmosphere Research Commission established desert locust-prone zones based on many factors such as plant distribution, soil type, desert locust history, and meteorological circumstances (Giribabu et al. 2022). At least 161,720 km^2, or 36.9% of Pakistan, has been identified as being vulnerable to desert locust invasion. Swarms that formed in Saudi Arabia (Rub al Khali) began spreading west (Red Sea to the Horn of Africa, south into Yemen, and east to Iran) by late 2018. Then, swarms increased in Pakistan and then spread to different parts of the world (Kenya and Uganda in East Africa). By June, swarms had infested crops in the Dasht, Kund Mesori, Mastung, and Quetta districts of Pakistan's Baluchistan Province, and had damaged cotton, *Gossypium hirsutum* L., in the Khairpur, Ghotki, and Sukkur districts of Sindh Province.

5.3 *Impacts of Locust Attack on Desert Plants*

The locust attacks the agriculture and about 20% of Pakistan's total agricultural yield and the agricultural economy of Pakistan was disturbed in 2020 (Khan et al. 2021b). Adverse effects of a locust attack on crops that is caused by drought conditions (2–3 years) and the lower availability of water. The economic inflation rate becomes high; the cost of sugar becomes almost double, and flour prices increased about 15%. Baluchistan is the largest province of Pakistan geographically, which covers the large land area (42%) including Punjab 25.8%, Sindh 69.9%, and Khyber Pakhtunkhwa 12.2% (Yamano et al. 2021). Finally, some (locust) attacks on desert crops – Punjab's Pakpattan district (23.4%), Bahawalnagar district (16.2%), and Lodhran district (10.6) – were spread by swarms. The districts of Baluchistan Province (Karachi and Kharan) were infested between 7.1% and 7.6% and the districts of Khyber Pakhtunkhwa province (Laki Marwat and Tank) were infected between 3.3% and 7.1%. Sindh Province (Kashmoor and Benazir Abad) was considered to have the most infested districts.

5.4 Integrated Pest Management Against Locusts (Asian Countries)

The state government started a program named National Integrated Pest Management (NIPM), with the major aim of controlling the productivity of desert crops, which is disturbed by attacks of locusts (Pandey et al. 2021a). It has been reported that no resistance develops against the locust attack naturally by any other insecticides. Therefore, NIPM played a major role focusing on interventions (early), economics with regard to how much it will cost to control the locust attack, the adoption of increasingly benign tactics, and insecticide handler and applicator safety (Dohbia 2022). No insecticides used for desert locust control in Pakistan are Class A (extremely hazardous) or Class B (highly hazardous) as designated by the World Health Organization. Use of relatively low toxicity tactics might also reduce the incidence of human intoxication from consuming sprayed desert locusts. The risk of human intoxication (occurs when live bacterial cells are ingested, which then produce toxins in the body) by consuming sprayed desert locusts may be mitigated (Oguh et al. 2019). Additionally, this might lessen the accumulation of pesticide containers that are occasionally used to keep food, water, and animal feed without first decontaminating them.

The NIPM needs some factors such as the biology of the desert locust, outbreaks, and their controls which are considered flexible in overcoming desert locust attacks (Pandey et al. 2021b). Other than insecticides, biopesticides are also present to control the spreading of locust attacks on crops in Pakistan and Somalia but these are not adequate for the wide spreading of locusts. Conventional synthetic insecticides are more effective and faster at controlling locust swarms compared with others (disadvantage). Biopesticides are very useful for sustainable pest management practices, but like any pest control method, they come with specific challenges and considerations related to safety for both people and the environment (Zhang et al. 2019a). It has been reported that some nations have shown concern that the variety of different isolates found in one country that has a desert locust problem will pose an exotic risk to other nations, including those that are relatively close.

In India, semi-chemicals are not effective. Many other strategies, such as digging trenches to catch nymphal bands, burning tires to get smoke from them and repellents are also used, as well as manually killing locusts with tree branches and other implements, and applying flour particles to block locust mouthparts. In addition , desert locusts destroy all crops and pasture vegetation (Wang et al. 2021b). Development of crop varieties that are completely resistant to locusts is a big challenging endeavor however, some crop varieties that show partial resistance or tolerance to locusts has been developed. The most suitable approach at the present time depends on the time of the treatment, focusing mainly on the initial stages of gregarization. Since the 1980s, long-lasting, expansive organochlorinated pesticides have not been used to manage pests; therefore, it is no longer feasible to expect breeding regions to be protected from a single application of an insecticide to plants (Engelbrecht et al. 2020).

To achieve early treatment, insecticide treatments must be planned before time, which requires observation that is effective enough to notice the beginning of the phase change. In order to effectively check desert locust attack (between outbreaks), surveillance technologies must be reliable. To understand the concept of breeding inside Pakistan and assaults from other nations, it is essential to use global information system (GIS) imaging, meteorological data, and to evaluate the geohistorical desert locust activity and management (Usman et al. 2022). In Pakistan, for initial treatments, many of the quantitative parameters are required in order to stop the attack of locusts on desert crops (Ahmad et al. 2022). Owing to localized environmental and climatic changes, early interventions cannot be achieved by Pakistan alone. In order to overcome this threshold, Pakistan needs help from India to sort out the locust attack against desert crops.

6 Planning of Earlier Treatments Against Locust Attacks

Many countries are affected such as African and Asian countries by recent locust attack episodes. About US $ 7.3 billion have been lost (agriculture) in South Asia (Iran), US $ 2.5 billion have been lost by India, and Pakistan lost about US $ 1.3 billion. Locust swarms can cause significant localized damage and pose a serious threat to agriculture (Hewitt 2019). Swarms have the ability to migrate (political boundaries) through water bodies such as the Red Sea, Persian Gulf, Atlantic Ocean, etc. Impacts related to economic and society provide suggestions that cooperation is good enough to overcome the serious attacks of locusts on desert crops compared with individual countries focusing on protecting the agricultural economy (Sah et al. 2020).

Two techniques have been developed to decrease the rate of locust attacks. The first one is the default response to locust attacks that have reached advanced outbreaks and showing the immediate risk related to agricultural production. The second one is the preferred strategy (proactiveness and involves treatments). This is applied when the initial stages of locust attack present and can kill them before upsurges and plagues develop on desert crops. Coordination matters in both cases but proactiveness shows relatively better results and reduces the episodes of locust attacks (Showler 2019).

7 Exceptional Adaptive Strategies Attained by Desert Plants

7.1 Succulence

Many desert plants can collect and store water in specialized cells in their stems, leaves, or roots (during even light rainfalls) (Luo et al. 2021). These water-retaining tissues defend the plants from long periods of dryness. This is an adaptation that the plants of deserts store water in the specialized parts of their plant body (arid regions). Saguaro can survive for up to 200 years, but it grows slowly. The trunk's surface is folded like a concertina, allowing it to rise, and it is well known that the moisture content of the surface layer promotes root dispersion greater than that of the deeper layers. Under low water availability, root diameters (not so wide) are thought to constitute a strategy for increasing absorptive surfaces and nutrient absorption (Takahashi et al. 2022).

7.2 Sclerophylly

This is also an adaptation to resolve the stress against drought conditions. The leaves cannot experience permanent damage (wilting) and the process of sclerophylly helps to recover the leaves of the desertic plants (Alonso-Forn et al. 2020). The rate of transpiration is much reduced owing to the presence of a thick layer of cells, a waxy cuticle, and sunken stomata. Seasonally, when combined with dimorphic species of plants, sclerophylls are present mostly in special habitats (arid and semi-arid). It is associated with other activities such as pathogen defense or a reaction to nutrient scarcity (sclerophylly). It is reported that stiff leathery leaves are much more common in those plants that are resistant to drought in all regions across the world. Because of the thick cuticle and thick-walled epidermal cells a sclerophyllous leaf shrinks (dry environments). Whereas thin-walled mesophyll cells severely shrink and intercellular gaps increased. One of the key features of sclerophyllous leaves is the presence of specialized cells known as sclereids, which contribute to the strengthening of leaf tissues. When water availability is limited, closure of the whole structure is reduced, which lowers the risk of mechanical injury. Sometimes, in dry conditions, a sclerophyllous leaf shrinks because of the thick cuticle and thick-walled epidermal cells, whereas intercellular gaps are increased owing to severe shrinkage of thin-walled mesophyll cells. The photosynthetic rate remains constant, even when other leaves wilt owing to the danger of water stress (Iqbal et al. 2020).

7.3 Seasonal Dimorphism

When the moisture is present in the leaves, then the structure and quality are influenced. It is reported that seasonal dimorphism is another strategy for overcoming the dryness in desert plants. Those species have the ability of seasonal dimorphism and then transpiration will occur slowly. On long twigs (dolichoblasts), large leaves lost at the start of the dry season are replaced by the young developing leaves on short twigs (branchyblasts) (Iqbal et al. 2020).

7.4 Reflectivity of Leaves

Desertic plants show reflectance as the leaves remain cool, such as brittlebush (*Encelia farinose*) and white bursage (*Ambrosia dumosa*) because of its color. The sunlight is reflected by the desertic plants owing to their color, and waxes and hairs are present, which help to minimize the rate of transpiration. Stomata also play an important role owing to their property of closure, which provides plants with permission to maintain the level of the water, when the high amount of water inside soil carbon absorption will be minimized. Owing to a sharp increase in temperature, diffusion provides resistance for water vapors to be reduced. Environmental changes stomata density and exhibits a more adaptable response; even under drought conditions, stomatal size is also reduced (Crawford 2019).

8 PGPR Application for Maintaining Agriculture

Plant growth-promoting rhizobacteria can increase the availability of nutrient concentration in the rhizosphere by fixing nutrients, thus preventing them from leaching out. As an example, nitrogen, which is needed for the synthesis of amino acids and proteins, is the most limiting nutrient for plants (Daniel et al. 2022).

9 Conclusion

About 33% of the total area of land is occupied by desert. Life existing in the desert faces harsh environmental conditions such as abiotic and biotic stresses. Abiotic stresses include high temperature, high radiation, and water scarcity. Owing to the harsh environment of deserts, the growth and development of shrubs and grasses becomes limited. For the survival of crops in desertic areas, the selection of genes is the most important factor. In this way plants are able to survive under drought conditions, salinity, and high temperatures. For sustainable agriculture in deserts (biotic stress), crops may get help from communities of bacteria that have specific features such as higher gene expression during dormancy and showing lower gene expression during nutrient cycling. Both these adaptations show the presence of bacterial communities and help to face the harsh environmental conditions (deserts). Those bacteria found in deserts are due to the presence of the rhizosphere, phyllosphere, and rhizosheath, as all these are influenced by a suitable environment, vegetation cover, and soil aridity. In plants, a mutual relationship is formed between the host plant and microbial communities to perform better in the harsh environment of the desert, which improves the morphology and physiology, and develops resistance against diseases.

In conclusion, PGPR performed well in plants to overcome the different stressors such as salt, heat, drought, and high UV radiation. These play a key role in improving the fertility of the soil and increasing the yield of crops in deserts. In future, genomics will change the world for the better, causing adaptation and the evolution of new techniques and life in a desertic environment. The second green revolution, which is looming from the ground below desertic plants, will bring changes.

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Chapter 22
Importance of Soil Management in Sustainable Agriculture

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Abstract With changing climate and declining fertile soil, the pressure on land to sustain the huge global population is intense. Soil management with respect to organic matter, nutrient turn over, and conventional agricultural practices thus becomes vital pillars of crop yield and sustainable agriculture. The bottlenecks in maintaining the sustainable practices include pest infestations and bioaccumulation of toxic metals through its entry into the food chain. The knowledge and understanding coupled with schematic implementation of low external input sustainable agriculture (LEISA) and high external input agriculture (HEIA) may be an effective strategy to counter the declining status of fertile soil profile. Further, soil acts as an important carbon sink which accounts for 50–66% of global carbon loss, which indicate the necessity of soil management in the context of carbon sequestration.

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Climate change can trigger intensive soil erosion, reduced soil fertility, and drastic reduction in agricultural productivity lead into soil de-stability. Therefore, this chapter intends to decipher the different prospects of sustainable agricultural practices through regulation of strategies associated with soil management, organic carbon and matter, nutrient management, pest reduction, and pesticide application, etc. This chapter is expected to aid the literature by providing a wider scope of view for sustainable agricultural practices.

Keywords Climate change · HEIA · LEISA · Pesticide effect · Soil management · Soil organic matter

1 Introduction

Global food security with expanding population is heavily dependent on climate-resilient agriculture and agricultural sustainability. With ever-changing agricultural practices from early agricultural society to till date, the need for climate-change adaptability and soil management is inevitable. Practices concerning the type of agriculture, regulation of crops, management of soil, cycling of nutrients, regulation of organic matter, and use of advanced devices have attracted worldwide attentions. Focus has now been shifted from a market-driven agriculture (that solely focuses on productivity and profits) to sustainable agriculture (that largely focuses on sustainable integration of physicochemical, biological, socioeconomic, and eco-centric approaches).

Sustainability of any ecosystem requires sustainable input and output of energy flow (Odum and Barrett 1971). Thus, to achieve sustainable agroecosystem nutrient management plays a pivotal role to maintain regular flow of energy. Efficient nutrient management can support self-sustained nutrient cycling with least interference from outside. In addition to the maintenance of agroecosystem, its protection from disease can ensure sustainability of agriculture (Jindo et al. 2021). To achieve this target, integrated pest management practices hold the beacon among various strategies.

Soil is the storehouse of nutrients and microorganisms and therefore balanced regulation of the nutrients, and soil biota is a challenge in sustainable agriculture. With growing pressure of productivity, pollution, and chemical supplements, soil management thus becomes a bare necessity at all stages of agriculture (De Corato 2020). The projected rise in population warrants soil sustainability for continued productivity. Thus, research concerning the importance of soil management in sustainable agriculture is a necessity now and in the future.

Soil management in general explores various prospects of total soil biodiversity management while supporting long-term agriculture (Thiele-Bruhn et al. 2012). Thus, regular and schematic soil management becomes the backbone of sustainable agriculture. The recent practices have also integrated urban waste management by utilizing waste as agricultural inputs (Pasquini 2006). Hence, soil management in connection to sustainable agriculture is not just restricted to agricultural practices but extends beyond conventional waste management too. This aspect has been a part of growing research topics exploring new dimensions in sustainable agriculture (Ducasse et al. 2022). Therefore, many of the recent developments, principles, and practices concerning sustainable agriculture have utilized the waste regulation and management to benefit the economics of agriculture.

The influence of tillage, the importance of crop rotation, the decomposition of organic matter, management of soil biota, regulation of pests, importance of mineral and nutrient cycling, and mulching play an important role in soil management. These features are integrated with various principles that are exclusively discussed in this chapter. The current study therefore explores the principles and practices that can pave the way for sustainable agriculture. It specifically focuses on sustainable nutrient management, nonconventional agricultural practices, pest management techniques, and soil management. Underlying objective of the work is judicious utilization of natural resources with least disturbance to ecosystem for fulfilling the food demand of exponentially growing population.

2 Nutrient Flow and Transformation

Total stock of the nutrients is crucial for sustainability of agriculture. Albeit, available, or easily convertible to available form of nutrients plays significant role in crop productivity. Various biochemical reactions modulate the availability of nutrients. Linkage between nutrient pools can be explained through nutrient flow, which can elucidate the performance of any agroecosystem. Various managed nutrient flow such as external input to agroecosystem (i.e., application of fertilizers and crop harvesting) or unmanaged nutrient flow such as leaching and runoff of nutrients can alter the total stock of nutrient. Figure 22.1 explains some of the major processes that determine the availability of nutrient in soil. Natural ecosystem preserves the efficient nutrient flow (Crossley Jr et al. 1984), on the contrary in managed ecosystem such as agriculture; nutrient cycling gets disturbed, nutrient storage capacity get reduced and develop unsynchronized nutrient flow in and out of the ecosystem (Hendrix et al. 1992). Spatial and temporal impact on nutrient flow is well documented in many literatures (DeLuca et al. 1992). Low temperature reduces the rate of mineralization from organic matter, whereas mineralization enhances in wetted condition.

Nutrient loss due to runoff and leaching is experienced when precipitation exceeds recharge capacity and evapotranspiration. Nutrient flow within ecosystem (agroecosystem) or between two different ecosystems holds primary key to achieve sustainable agricultural system. Magdoff et al. (1997) explained the short-term requirement of nutrient for agroecosystem to achieve sustainable output though a comprehensive schematic diagram, which is shown in Fig. 22.2. Input-based high

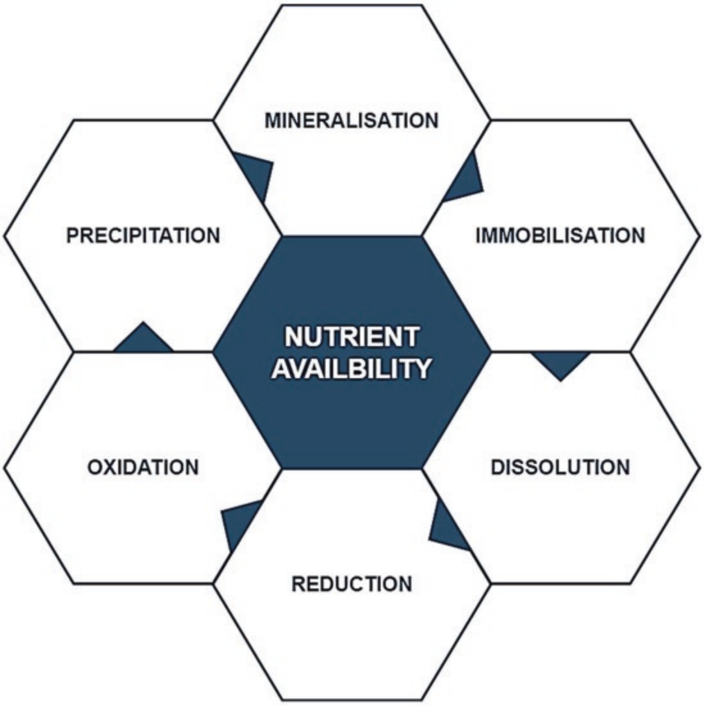

Fig. 22.1 Major processes that controls nutrient availability

productivity agriculture can damage natural nutrient cycling and soil properties; as a result, crop loses its capacity to withstand extreme climatic condition or unstable agro economic scenario such as the recent impact of COVID-19 (Westhoff et al. 2020). Bender et al. (2016) advocated that enhanced soil biodiversity through soil ecological engineering can magnify the ecological services and fortify sustainable agriculture. Spatial and temporal ecological intensification in agro-management system can reduce external nutrient input and maintain healthy ecological services (Krupek et al. 2022). Agroecosystem can maintain long-term fertility with high productivity when nutrient addition to the ecosystem exceeds loss of nutrient (Magdoff et al. 1997), whereas nutrient losses through mineral dissolutions, desorption, and mineralization can lead to the reduction of fertility in long term (Bray and Watkins 1964).

Soil microorganism modulates transformation of nutrient into various forms and its cycling. Soil microorganism can effect soil edaphic factor such as soil pH, which influences nutrient balance (Mulder et al. 2011). Bertini and Azevedo (2022) highlighted the role of soil microbes in regulating carbon cycle. Phosphorous availability in soil was significantly affected by soil trophic structure (Mulder and Elser 2009). Magdoff et al. (1997) simplified the roles of soil organism in various natural nutrient flow processes, which is shown in Table 22.1.

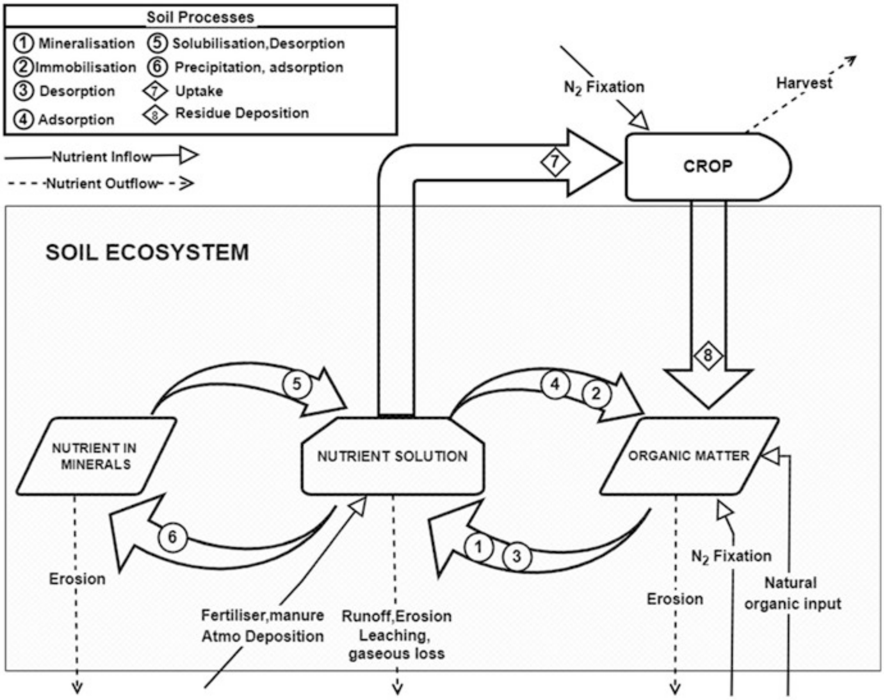

Fig. 22.2 Nutrient flow and physicochemical processes in soil in nutrient cycling

Table 22.1 Involvement of soil organisms in various natural nutrient flow processes

Nutrient flow processes	Soil organisms involved
Transformation processes	
Immobilization	Bacteria, fungi
Mineralization	Earthworms, nematodes, protozoa, bacteria, fungi
Precipitation, adsorption, redox reaction	Bacteria
Nutrient inflow	
Nitrogen fixation	Bacteria
Nutrient outflow	
Erosion	Ants, termites, earthworms, fungi
Gaseous loss/leaching	Ants, termites, earthworms, fungi, bacteria
Soil-plant flow	
Uptake by plants	Bacteria, mycorrhizal fungi
Organic residue incorporation	Earthworms, beetles

3 Nutrient Management for Abiotic Stress

Balanced nutrient management is a key element to achieve sustainable agriculture, in the event of abiotic stresses (Hossain et al. 2020). Plant resistance to abiotic stress can be achieved through modification in the morphological, biochemical, and physiological processes, which is influenced by microelements such as iron (Fe), zinc (Zn), and manganese (Mn) and macroelements such as sodium (Na), potassium (K), and phosphorous (P) (Fageria et al. 2002). Calcium (Ca^{2+}) concentration in cytosol can be considered as primary osmotic stress signal for plants (Gong et al. 2020). Various protein kinase enzymes such as rapamycin regulates signaling pathways for realignment of metabolic and transcriptional activities during abiotic stress such as heat, cold, salt, osmotic stress, and nutrient deprivation (Haq et al. 2022). Singhal et al. (2022) observed various plant growth regulators influence network signaling perception to regulate plant growth in case of multiple abiotic stress.

Water stress condition reduces the nutrient uptake capacity of the plant (Shone and Flood 1983). Enhancing water use efficiency, which is associated with the rate of stomatal conductance and transpiration, can reduce water stress (Mak et al. 2014). Agronomic strategies such as fertilizer management, timing adjustments for sowing, irrigation schedule, and planting geometry can be useful to develop water stress tolerance in crops (Jaffar Basha et al. 2017). No tillage (Guzzetti et al. 2019), deep plowing (Sekhon et al. 2010), and mulching (Li et al. 2018) helps to improve water stress resistance capacity in plants. Bader et al. (2021) observed that phosphorous fertilizer application in draught condition can enhance photosynthesis rate, leaf water content, and root biomass. Pierre et al. (2008) recommended N fertilizer to combat water and heat stress. Wang et al. (2013) conducted extensive review to understand the role of potassium to mitigate various abiotic stresses and contended potassium fertilizer can play significant role in mitigating water stress condition including stress induced by salinity, temperature, and pests. Potassium (K) application modulates the activities of the associated enzymes for carbohydrate metabolism, photoassimilation, and translocation process in plants (Zahoor et al. 2017).

Injudicious utilization of irrigation and improper management of fertilizer can lead to the deposition salt content in soil which results in salinization (Doula and Sarris 2016). Salinity of soil can be interpreted when electrical conductivity of saturated extract of root zone exceeds than 4 dSm^{-1}, which is equivalent to 40 mM NaCl at 25 °C and the exchangeable sodium content is 15% (Shrivastava and Kumar 2015). Saline soil affects the growing crop through enhanced osmotic stress, degraded soil physical properties, and disruption in nutrient uptake capability. Various traditional methods such as tillage practices, land leveling, drainage management for excess water, surface flushing, leaching of salts from top layers of soil, and reinforcement of nutrient in plant roots through application of fertilizers can alleviate salinity issues in agroecosystem (Sahab et al. 2021). Modern agriculture practices intensified the severity of salinization of soil, which threatened global agricultural productivity. Researcher developed various integrated approaches such as seed priming, salt tolerant crop, microbial alleviation, composting, and electro-remediation technology to combat stress induced by soil salinity. Essential nutrient requirement for crop can be maintained through proper nutrient management strategies. Under stress condition induced by salinity, availability of essential nutrient in optimum amount can reduce pressure on the permeability of plasma membrane (Singh et al. 2014). Siddiqui et al. (2010) found ameliorative effect of N application on various growth attributes and physio-biochemical parameters during salt stress. Potassium (K) plays a significant role in the opening and closing of stomata and is necessary for preserving the osmotic balance during salt stress. Antagonistic relationship between Na and K can be utilized to reduce Na toxicity and increase K concentration in root zone through judicious application of Kin saline soil (Wakeel 2013). For membrane-binding sites of enzymes, Na may face competition from Ca ions. Thus, high Ca levels from external input can shield cell membranes from the negative effects of salt (Ismail et al. 2006). Alam et al. (2002) studied the impact of calcium on the growth of different varieties of rice in saline soil. Authors observed that constant ratio of Na and Ca can be maintained by application of calcium sulfate and calcium phosphate to relief plant from salinity-induced stress. Ameliorative effect of $CaCl_2$ in the case salt stress was also reported by (Latef 2011).

Mineral absorption, nutrient uptake capacity of crop, total protein, and protein assimilation in root get affected by stress induced by heat, which reduces the plant growth (Giri et al. 2017). Nitrogen is essential for the metabolism of photosynthetic carbon and the utilization of absorbed light energy, hence N acts as a vital component for maintaining physiological activity under heat stress (Ordóñez et al. 2015). Similarly, K as a macronutrient involves in various physic-biochemical processes and minimizes the excessive formation reactive oxygen species (ROS) in plant (Waraich et al. 2012). Calcium treatment causes plants to develop heat stress resistance by bolstering their antioxidant defense (Kolupaev et al. 2005). Researchers discovered that manganese (Mn) as a trace element has a significant impact in reducing the formation of ROS by raising enzymatic and nonenzymatic antioxidants to combat heat stress (Waraich et al. 2012).

Heavy metal-induced stress can restrict various physiological processes in plants. Rizvi et al. (2020) summarized the impact of heavy metal on plant processes as inhibition of physiologically active enzyme, photosystem inactivation, alteration in mineral metabolism, damage of membrane permeability, and reduced yield with considerable amount of heavy metal accumulation (Moulick et al. 2016a, b, 2017, 2018a, b, c, d). Apart from these, authors also mentioned excessive generation of ROS due to heavy metal toxicity that can damage various cell structures (Choudhury et al. 2021, 2022a, b; Mazumder et al. 2021, 2022). Nutrient management strategies can be useful in alleviating heavy metal stress. Various literatures reported application of N (Garcı́a-Mata and Lamattina 2001; Zhang et al. 2014) and Zn (Yang et al. 2004) can reduce the impact of Cd toxicity. Competitive interactions of secondary metabolites and metal ions (Al^{3+}, Mn^{2+}) for the same active sites of the enzymes result in the reduced heavy metal stress in plants (Choudhury et al. 2021, 2022b, c). Similarly, competitive nature of Fe^{3+} for the same active site of various antioxidant enzyme can ameliorate cadmium (Cd^{2+}) toxicity (Mazumder et al. 2022). Beside pronounced adverse impact of heavy metals from germination to maturity though well documented from time to time (Chowardhara et al. 2019a, b; Saha et al. 2019; Moulick et al. 2019a, b, 2021), the consequences of heavy metal contamination in post-harvest phase as well as on health impacts need to be focused (Moulick et al. 2018d, 2020; Moulick et al. 2022).

4 Agriculture Management Practices

Different agricultural management practices have profound impact on nutrient loss and nutrient addition into the agroecosystem. Various studies indicated that management practices such as crop rotation (Kussul et al. 2022), cover crop (Singh et al. 2015; Perrone et al. 2022)), tillage system practice (Roger-Estrade et al. 2010), and type of crop cultivation can significantly influence various processes of nutrient cycling to achieve sustainable agriculture. Hobbs et al. (2008) advocated conservation agriculture as primary key for sustainable agriculture, which includes no tillage practice with least disturbance to soil, mulching for permanent soil cover, and rotation of crops.

Rooting depth is a pivotal parameter of soil in terms of crop health. Tillage provides suitable seedbed for the seed to grow at optimum soil depth. This method assures reduced competition with weeds while early growing phase of seeds. Tillage practices can influence soil structure and soil erosion; thus, it can affect crop production and land management (Magdoff et al. 1997). Conservation tillage practice can improve the protection of residue mulch on the surface soil; in addition to that, it can reduce the water and soil loss, in comparison with the conventional tillage practice (Lai 1989). It has a significant role in enhancing organic matter content, cation exchange capacity, and soil aggregate stability in the top soil (Cannell and Hawes 1994). Roldán et al. (2003) observed that conservation tillage practices like no tillage management enhanced the soil quality significantly in Mexican soil. Hassan et al. (2022) reviewed the role of zero-tillage system to achieve sustainable agriculture in subtropical and temperate region and contended that zero tillage can improve soil biological diversity, water use efficiency, aggregate stability, and soil structure. Lai (1989) also observed that combined approach of the crop's residue with shallow tillage without inversion can be suitable for the soil, which is vulnerable to hard setting and crusting.

Continuous monoculture practice can reduce the nutrient content and degrade the soil quality. Crop rotation enhances soil organic matter and soil physical properties, which results in increased crop yield (Bullock 1992). It can provide diversified exudates and substrates on the surface and below the surface, which promotes nutrient cycling (Ashworth et al. 2020). Crop rotation method supports enhanced crop growth by increasing water availability in soil, as it influences water infiltration and evaporation rate (Pikul Jr. and Aase 1995). Huang et al. (2003) confirmed an increase from 53% crop precipitation interception index (CPII) to a maximum of 73% through rotation of different crops grown in soil having poor water storage capacity.

Crop rotation in flooded paddy field can initiate preferential pathway for water and solutes through the desiccated cracks. Fuhrmann et al. (2019) highlighted these cracks, as a host for large amount of plant nutrients, amino sugars, and organic C; thus, these pathways merit as hot spot for C cycling in soil. Judicious selection of crop variety with respect to the native soil and its frequency of repetition is utmost vital for sustainable growth, otherwise it can have adverse impact on nutrient content (Kussul et al. 2022).

Cover crop practice can improve organic matter content, replenish N uptake, and reduce nutrient loss (Thapa et al. 2018). It can reduce soil compaction and water saturation through improved soil aggregation. Experiment conducted by McDaniel et al. (2014) shows that crop rotation combined with the crop cover significantly improves the total C, total N, soil microbial biomass N, and microbial biomass C by 8.5%, 12.8%, 20.7%, and 26.1%, respectively. Leguminous plant cover crop (Peoples et al. 2001) and poultry litter (Ashworth et al. 2017) can enhance the availability of N in soil. Cover crop significantly enhances the soil organic matter, which ultimately improves soil chemical and physical fertility (Ramos et al. 2018). Low available nutrients can be absorbed into the soil profile in presence crop residue. Hallama et al. (2019) found that cover crop biomass can accumulate soil phosphorous and later become available to plants through mineralization process. Authors also observed the enhanced activities of extracellular phosphatase enzyme and soil microbial community abundance due to cover cropping.

5 Integrated Pest Management (IPM)

Intensive cultivation system has enhanced the productivity, but at the cost of vulnerability to pests and diseases. Integrated pest management (IPM) can reduce the excessive dependency on chemical plant protection products (Tiktak et al. 2019; Ghosh et al. 2020a, b, 2021, 2022a). IPM balances the environmental threat and economical loss for farmer by prevention of pest infestation. Thus, IPM utilizes all suitable strategies to keep pest population under control thereby avoiding economic damages (Antignus 2000). Principles of IPM based on four major steps, which includes (1) monitoring, and identification of the pest, (2) set action thresholds, (3) prevention of pest infestation, and then (4) control implementation to reduce pest infestations (Fig. 22.3).

Symbiotic interaction of various organism is very crucial for sustenance of any ecosystem. Therefore, it is utmost important to identify the pest, which is a potential threat to the cultivation. Prevention of the pest impact can be achieved by cultural agro-practices such as crop rotation, growing pest free rootstock, and cultivating pest resistant varieties of crops. Control of pest is followed, by proper identification of pest, its monitoring, and determination of action threshold. Initially, less risk control measurement such as application of pheromones to disturb pest mating, trapping, and weeding is used. If IPM methods, which include identification, monitoring, and action threshold, indicate failure of less risk control measure, then

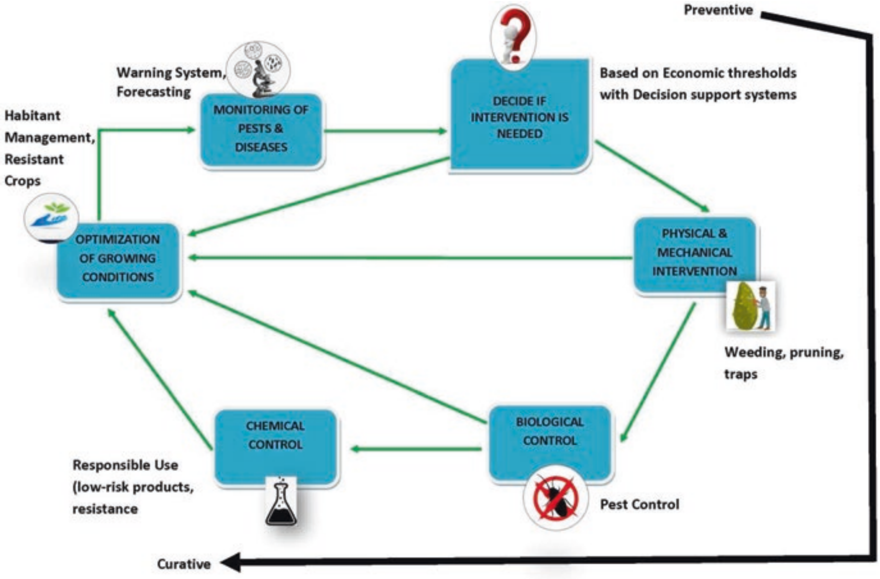

Fig. 22.3 Steps of integrated pest management

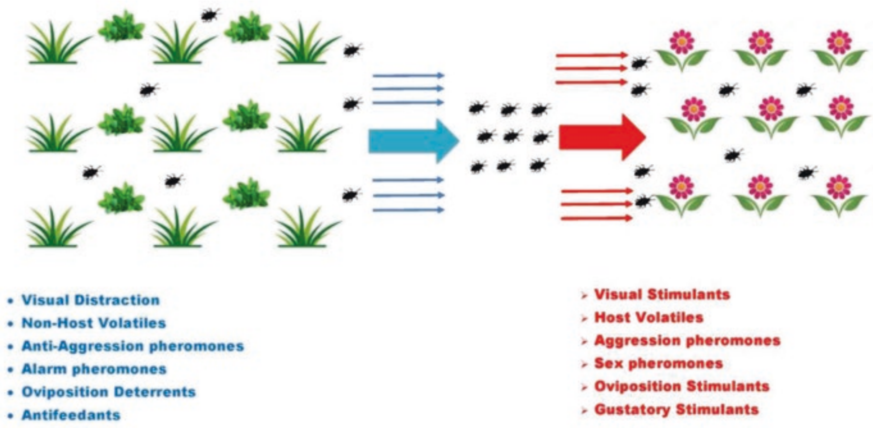

Fig. 22.4 Push-pull strategy of IPM

additional pest control is suggested that involves targeted spraying. High-risk broadcast spraying is the possible course of action in case of failure of targeted spraying.

Cook et al. (2006) suggested the push-pull strategies (Fig. 22.4) that invoke behavioral modification of the pest through introduction of stimuli which divert them from protected resource (crops), making it unsuitable for the pest. In pull strategies, various stimuli such as host volatiles, pheromones, gustatory, and ovipositional stimulants are being used to lure them toward trap crops, which later on can be removed. Transmission of diseases from vector (pest) can be prevented through disruption of vision and manipulation of behavior of vector (pest), so that the contact of the vector with its target crop can be reduced. Spectral sensitivity of insect can be disrupted through colored soil mulches, vertical colored traps, reflective coarse nets, spraying with reflective materials, introduction of photo-selective (UV-absorbing) plastic covers and screens, and UV-absorbing plastic films (Antignus 2000). Banks and Ekbom (1999) conducted stochastic simulation model of agroecosystem to evaluate different IPM methods for reduction of pest colonization. Authors criticized intercropping system for IPM and advocated trap cropping schemes for better control of pest colonization.

Continuous monitoring pest population dynamics, frequency of pest incidence, and crop damage is vital for efficacious pest management system (Karuppuchamy and Venugopal 2016). Sterile insect technique of IPM focuses on the birth control of specific pest species so that targeted area can be protected from pest infestation (Klassen 2005). Unsuccessful mating of sterile insects gradually reduces the ratio of fertile to sterile pest population, thus results in eco-friendly elimination of pest species (Kapranas et al. 2022). Crop-specific pest population dynamics is influenced by various biotic and abiotic factors; therefore, time and space-specific pest incidence prediction with reasonable accuracy can be achieved.

Efficient pest management can be implemented by cropping methods such as mixed cropping, strip cropping, alley cropping, and intercropping. These methods protect the crops through various approaches such as crop camouflage, acting as barrier to particular pest, and facilitating pest enemy growth. Intercropping increases, the diversity of agroecosystem, this introduces more predators, parasitism, and adverse chemical stimuli. Wider plant spacing allows more sunlight penetration and air flow, which can reduce the pest incidence (Asghar et al. 2021).

6 Soil Organic Matter (SOM)

Soil organic matter (SOM) sourced from diverse lithogenic input including litters from vegetation, domestic waste, agricultural waste, biogenic additions, etc., forms the center for nutrient mineralization and soil conditioning. It is the base for all biological activities in soil that eventually defines the soil health and fertility (Rossi and Beni 2018). The diverse the composition of SOM, the better is the health of the soil. Good-quality SOM promotes high biological activity, which is influential in maintaining soil health and quality. Besides this, large SOM pools have been identified as potential reservoirs of plant available nitrogen (King et al. 2020).

Protection of SOM is an important criterion that determines the feasibility of sustainable agriculture (Johnston et al. 2009). Soil rich with protected SOM may yield less crop output since the organic matter breakdown and nutrient mineralization are significantly reduced. SOM experiences three distinct stabilization processes that restrict its mineralization. These are (i) biochemical stabilization (Wei et al. 2021), (ii) chemical stabilization (Blanco-Moure et al. 2016), and (iii) physical stabilization (Jacobs et al. 2010). Based on the biochemical composition, the SOM may be selectively degradable and a large portion of it (e.g., chitin and lignin) can withstand bacterial decomposition. This fraction is fairly stable, very often categorized under recalcitrant fraction and is grouped under the biochemically protected SOM. The recalcitrant fraction may be the initial SOM structure or may be formed due to series of chemically complex condensation and/ or synthesis reactions. Such organic matter that is occluded within soil aggregates constitutes the physically protected fraction. The physically protected SOM fraction is delinked from the soil biology and is inaccessible to the soil microorganisms and enzymatic activities for degradation. Similarly, the sorption of SOM on to mineral surface and complex association between heavy metals and SOM make a part of the organic matter inaccessible for chemical degradation. This part is therefore covered under the chemically protected fraction. Over the years, it has been widely accepted that the physically protected fraction of SOM is the most inaccessible fraction than the other two protections and may lead to accumulation of SOM without any significant biological activity. The sustainable agriculture therefore aims at regulating and managing the composition, diversity, and practices to enhance the bacterial activity and biological process in connection to the SOM.

Based on degradability and ease of mineralization, soil organic matter is divided into two pools, namely, the active pool and the passive pool. While the active pool comprises of the relatively high degradable fraction of organic matter, the passive component comprises of the fairly stable fraction. The very labile and labile fractions make the active pool, and the less labile and recalcitrant form makes up the passive pool (Nath et al. 2018). The active pool is responsible for nutrient mineralization in to the soil leading to crop production, soil fertility, and maintenance of soil health (Wander et al. 1994). The passive pool on the other hand is chiefly responsible for the long-term mineral and carbon build-up leading to nutrient and carbon sequestration. Studies suggest that proper regulation and management of various fractions of organic matter may aid in maintaining the soil fertility while increasing the crop productivity. Since organic matter concentration decreases with soil depth owing to soil compaction, several agricultural practices involving mulching, tillage, gully formation, etc., help regulate soil organic matter and facilitate mineralization. Sustainable agriculture focuses in maintaining a balance between the SOM input and SOM degradation to stretch the fertility period of the soil while maintaining decent crop yield.

7 Sustainable Agriculture: Approaches and Agronomics

As per the definition proposed by FAO (1988), sustainable agriculture is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. FAO further elaborated that sustainable agricultural practices should ensure conservation of water and land with optimization of genetic resource and animal use in an ecologically sound, economically viable, technologically feasible, and socially acceptable manner.

7.1 Principles and Approaches

Sustainable agriculture works under the following five principles:

(i) Optimization of resource use with enhanced efficiency
(ii) Protection, conservation, and enhancement of natural ecosystems
(iii) Protection and improvement of rural livelihood and social well being
(iv) Enhancement of people, community, and ecosystem resilience
(v) Promotion and governance of natural and man-made systems

The International Union for conservation of Nature (IUCN) has outlined different approaches to achieve the goals of sustainable agriculture (Oberc and Schnell 2020) that is represented in Fig. 22.5.

Agroecology is a set of holistic practice that seeks to enhance the enviro and socioeconomic status of the region through implementation of proper planning (involving balance between production and surrounding), resource use (involving

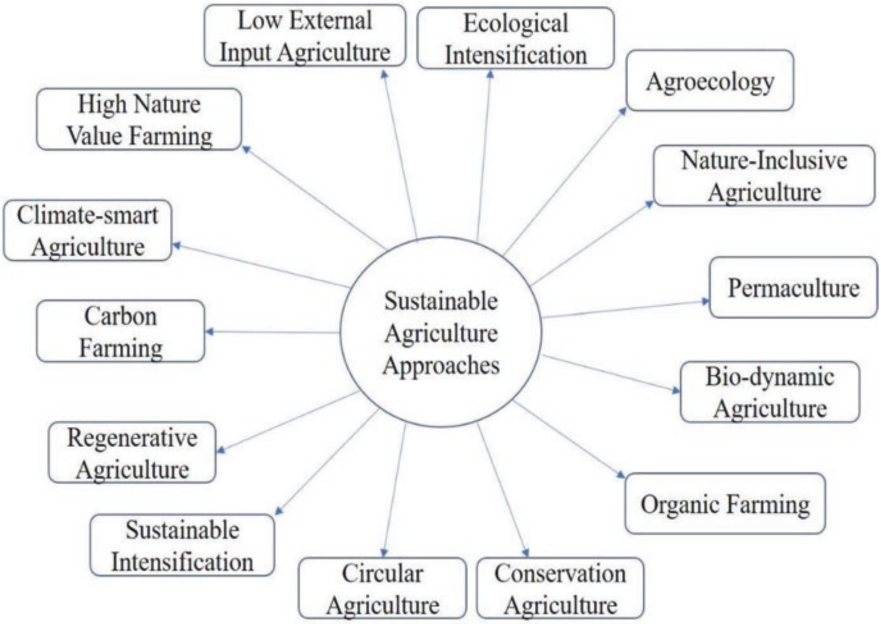

Fig. 22.5 Diagrammatic representation of various sustainable agriculture approaches

nutrient and energy recycling and its optimization), and landscape management (involving management and enhancement of functional diversity, biological interactions, and synergistic interactions among various key ecological processes).

Nature-based agriculture basically targets the minimization of the adverse agricultural impacts on nature and simultaneously maximizes the positive impacts of agriculture on nature. Major practices that are included under the nature-based agriculture are reduction in use of synthetic pesticides and fertilizers, reduced tillage activity, introduction of flowering and herb edges, reduced cattle activities, etc.

Permaculture or permanent agriculture is a set of practices that are constructed taking the system as a whole by replicating the natural processes, patterns, and relationships. It is a long-term approach through the need-based resource utilization, storage of energy, reduction in waste generation, feedback and self-regulation of processes, maximization of the use of diversity, and prompt response to change.

Biodynamic agriculture considers farming as a self-sustained system by using living organisms for control and regulation of pest infestation, avoidance of chemical application, and identifying space for conservation of biodiversity. The use of compost and compositing is encouraged in biodynamic agriculture while preparing grounds for enhancement of living activities.

Organic farming chiefly involves the natural and degradable materials as a supplement for agricultural activities. It strictly restricts the use of genetically modified organisms (GMOs), radiations, chemicals, hormones, and antibiotics in agriculture. Organic farming stresses adoption of crop rotation, cultivating plants for nitrogen fixation, encouraging natural defense, reduce weed and pest impact, and maintenance of soil health and quality.

Conservation agriculture primarily targets the maintenance of soil cover, reduction in soil erosion or soil disturbance and management of crop rotation. This is achieved by the adopting the zero-tillage policy, growing crops and leaving post-harvest residues and using wide range of plants in agricultural activities.

Regenerative agriculture works in close nexus with the conservation agriculture by emphasizing on the restoration of soil organic matter, enhancement of soil fertility, and improvement in the overall health of the soil. The regenerative agriculture also focuses on the improvement in water percolation, and the water retention capacity of soil besides enhancing the biodiversity and resilience of soil. This approach also works on techniques to improve the carbon sequestration potential of soil by converting the soil into a major sink of carbon dioxide.

Carbon farming chiefly concentrates on the reduction of greenhouse gases and long-term storage of soil carbon. This is achieved through increase in forage and biomass by plantation, nutrient management, composting, silvo-pastoral practice, development of vegetative and filter barriers, tillage management, contour stripping, alley cropping, wetland restoration, etc. Carbon farming has economic benefits and therefore is gaining popularity in recent times. It is a long-term strategy to not only combat the GHG emission but also to ascertain social, economic, and community benefits as a whole.

Climate-smart agriculture was designed in view of the food security in changing climatic scenario. Farm and livestock management, growing of crops, aquaculture practice, landscape management, climate-change mitigation, and climate induced risk reduction are few practices followed to reach the goals of climate-smart agriculture. This approach may include the integration of traditional (e.g., livestock management and urban and peri urban agriculture) and high-tech modern agricultural practices (e.g., use of nuclear and isotope techniques) to achieve its goal.

High-nature value farming works on the principle of maintaining the traditional low-intensity and production agriculture that is practiced to preserve nature and biodiversity. The use of machinery and chemicals to achieve productivity goals is at its minimum in this type of approach. However, the high-nature value farming has a low self-sustainability and may face risks of high market demands.

Low external input agriculture or low external input sustainable agriculture (LEISA) is a rapidly growing concept accepted by a large farming community. Mostly involving the natural resources and less dependence on chemicals, LEISA has a high self-sustaining ability. This concept has been discussed in an elaborated manner in subsequent section of this chapter.

Circular agriculture depends on minimization of new food inputs and maximizing the regenerative inputs making it a circular food system. The approach takes careful measures against the leakages of the unavoidable resources such as phosphorus, carbon, and nitrogen. The concept integrates the livestock and animals with the agricultural practice to exploit the bioresource cycling. The concept chiefly discusses on resource efficiency rather than the production efficiency.

Ecological intensification works on the principle of biodiversity conservation, soil fertility management, reduction of pest infestation and diseases, balanced nutrient flows, and diverse plant breeding. The modern practices concerning this approach have added further strategies to enhance this approach. This includes reduction in meat consumption, reduction in dependence on energy, reduced food wastage, meeting consumer's expectation, reduction of environmental externalities, and inclusion of stake holder in decision-making

Sustainable intensification may be defined as the increased yield in minimum land area with minimal environmental damage. Integrated practices involving agroecology, intercropping, organic farming, urban farming, precision farming, etc., are usually followed to achieve the goals of sustainable intensification. Since this approach involves all major practices discussed in other approaches, the sustainability of the system is expected to be high in this case.

7.1.1 Strategies

The conventional pattern of agriculture involves largely the economics of profit, high yield with a little effort in protecting the natural ecosystem, and soil fertility. On the contrary, the sustainable agriculture focuses on the integration of the biophysicochemical, socioeconomical, and techno-ecological sciences, which provides reasonable agricultural output with overall environmental protection. However, the economics related to agriculture have to cope with climate change through reduction in its adverse impacts and maintaining its productivity. This constraint is answered by the implementation of sustainable agricultural practices.

The strategies that the modern agriculture prefers to cope with changing climate include the following:

- Organic farming
- Pest and nutrient management
- Development of genetically modified organisms (GMOs)
- Innovative farming by using modern methods (e.g., drip irrigation)
- Mitigation of soil pollution through bioremediation or phytoremediation methods

Considering the prospects of global sustenance, sustainable agriculture involves two methods, i.e., (i) sustenance of productivity while conserving resources and (ii) contribution of sustainability of large geography and society. These methods consider both the rural and urban areas under the same platform while recycling and managing the wastes generated from these areas through utilization in agricultural activities. The sustainable practices in agriculture are achieved through the ESR (efficiency-substitution-redesign) strategy popularized by MacRae et al. (1989).

The agricultural sustainability involves three levels of strategies, namely, the substitution strategy, the agroecological strategy, and the global strategy (Fig. 22.6).

The level of substitution strategy means the replacement of chemical pesticides and fertilizers with less persistent and less pollutant substances such as biopesticide and biofertilizers. Use of genetically modified species can be more tolerant to pollutants and less toxic to organisms. Similarly, growing symbiotic nitrogenous legumes can tackle the N-related fertilizer issues. The development of substitution strategy is worked out at the local (plot) level by the scientists and researchers. The agroecological strategy as its name suggests uses ecological methods for the development and management of sustainable agricultural practices. Promotion of biodiversity, intercropping mechanisms, crop rotation, composting, application of green manures, and agroforestry systems are few such tactics that characterizes the agroecological strategy. Agroecological strategy therefore is an expanded application of substitution strategy by applying the scale to larger geographical territories. The global strategy, on the other hand, aims to solve global agricultural and societal issues by developing an integrated scheme involving social problems and

Fig. 22.6 Agricultural sustainability

agriculture. The strategy believes that sustainability is achieved not only through farming but also through food systems. It means that the food production should be integrated with food consumption and market demands involving the concepts of alternate food system and local production.

8 HEIA and LEISA

8.1 HEIA

Agricultural practices and shifting of attention toward high yield were found to be a bottleneck for long-term soil fertility. The use of synthetic and lab-based chemical fertilizers and insecticides for agriculture not only deteriorated the soil quality but also impacted the soil biodiversity without helping the long-term economy. The high external inputs through chemical fertilizers and pesticides therefore focused primarily on short-term yield and economy. High external input agriculture (HEIA) assisted in overcoming the rising food demands to sustain a huge population, elimination of diseases due to malnutrition, reduction in pest infestation, increasing productivity of lands, development of new varieties of crops, increasing economic and yield value of lands, etc. The HEIA approach however is not guided by the market economy and is very often found to produce excessive crop yields. HEIA has several other associated disadvantages such as destabilization of soil aggregates due to continuous machinery use; altering the pH, cation exchange capacity, and soil texture; and exposing the land to rapid soil erosion.

8.2 LEISA

Sustainable agriculture received a landmark attention with the development of LEISA. Low external input sustainable agriculture assisted the farmers and especially from the low economic background to ensure the fertility of the crop lands by attaining sustainability (Firth et al. 2020). This is achieved basically be two-step implementations:

(i) Optimization of the use of locally available resources
(ii) Reduction of the use of external inputs (e.g., synthetic fertilizers)

Low external input sustainable agriculture ensures sustainable and long-term fertility of soil with comparatively low crop yield than the artificial fertilizer-based outputs (Mendoza 2005). It is, however, an efficient alternative for external inputs in maintaining the Green Revolution strategies. Since LEISA ensures the use of natural resources as a substitute for synthetic materials (e.g., fertilizers), it is considered to be an eco-friendly method. It is defined by the social, economic, and technical dimensions including the regulatory use of external inputs such as chemical fertilizers and pesticides (if required). Therefore, LEISA is a series of practices followed to restore natural ecosystem involving the local ecological process and minimal use of artificial resources.

8.3 Various Principles of the LEISA Include

- Recycling of nutrients and regulation of organic matter.
- Optimal and efficient use of water resources.
- Ensuring the genetic diversity.
- Sensible use and preservation of genetic resources.
- Judicious use of energy resources and minimization of use of nonrenewable resources.
- Minimization of adverse environmental effects.
- Minimization of use of external inputs.
- Maximization of use of local and natural resources.

Although there are certain advantages and disadvantages of HEIA and LEISA, the appraisal and implementation of each of these are dependent upon the need of the particular situation. Table 22.2 illustrates the basic comparison between HEIA and LEISA.

Table 22.2 Comparative analysis between HEIA and LEISA

HEIA	LEISA
High agricultural productivity in short time duration	Comparatively smaller yield for longer stretch of time
Requires high external inputs in form of chemical fertilizers and pesticides	Dependent on locally available natural inputs. External inputs if required are in very small quantity
Has serious negative impacts on long-term soil fertility and health	Considered as an eco-friendly approach due to the use of natural inputs
Enhances short-term economy	Targets long-term economy
Dependent on imported machinery and lacks indigenous technology	Based on manual labor assisting farmers from low economic status
Has negative impacts on soil biodiversity	Assists in restoring soil biodiversity
Focuses in maximizing yield and profit	Focuses on agricultural sustainability
HEIA is not driven by market demands and needs	LEISA is in accordance with the needs and requirements of the farmers
Chances of pest insurgency is high	LEISA is based on nutrient recycling and uses integrated pest management

9 Conclusion

Nutrient management is the key aspect to maintain nutrient cycling in agroecosystem. It can support the sustainable agriculture production. Conservation agriculture practices are suitable alternative to conventional agriculture. Integrated pest management (IPM) can reduce the dependency on the agrochemicals for the protection of crop without compromising the sustainable output. It is also evident from the discussion that the future strategies concerning the sustainability in agriculture should be an integrated approach of maximizing the natural resource base with minimal dependence on chemicals. Further, agricultural practices should strategize the enhancement of soil carbon sequestration to combat the effects of climate change on agriculture.

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Chapter 23
Sustainable Plant Production from the Soils Degraded with Microplastics

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Abstract The contamination of soil with microplastics (MP_S) has been recognized as the most emerging threat to the soil environment and is a worldwide concern. Yet, the interaction of MP_S at soil plant interface, their phytotoxic impacts, and mechanisms associated with their accumulation remain unclear. This chapter provides knowledge about the different sources, occurrence in the soil, global distribution, and negative impacts on soil and terrestrial plants, as well as possible mitigation measures to control MP_S contamination of the ecosystem based on the existing literature on this topic. Furthermore, we have thoroughly explored the MP_S phytotoxicity, i.e., accumulation and transfer in aerial parts, delaying seed germination and hindering plant growth, photosynthesis inhibition, interference with biochemical compounds, nutrients, and metabolites, triggering oxidative damage, and synthesis of genotoxicity. Furthermore, MP_S effects on different soil features, changes in soil structure, self and load toxicity, and possible mechanisms threatening plants have been explored. In conclusion, this chapter also provides numerous preventive and management options for mitigating MP_S pollution of the soil and opens new ways to fill loopholes in understanding MP_S fate in soil and at the soil-plant interface.

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Abbreviations

=O	Carbonyl
$^{\bullet}OH$	Hydroxyl radical
AtReBt	Antibiotic-resistant bacteria
AtReGn	Antibiotic resistance genes
BY-2	Tobacco bright yellow-2
C	Carbon
FDAse	Fluorescein diacetate hydrolase
H_2O_2	Hydrogen peroxide
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
MDA	Malondialdehyde
MP_S	Microplastics
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
NP_S	Nanoplastics
$O_2^{\bullet -}$	Superoxide radicals
−OH	Hydroxyl
PA	Polyamide
PAEs	Phthalates
PBDEs	Polybrominated diphenyl ethers
PE	Polyethylene
PES	Polyethersulfone
PET	Polyethylene terephthalate
PETase	Polyethylene terephthalate hydrolase
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PMF	Polyester microfiber
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
ROS	Reactive oxygen species
WWTP	Wastewater treatment plants

1 Introduction

Since the first modern plastic was invented in 1907, plastic has been extensively used in different consumer products worldwide, extent of 335 million tons in 2016 (PlasticsEurope 2018) because of it is cost-effective and versatile characteristics (Cole et al. 2011). Overall, the need for plastic is promptly increasing, and it is predictable to be four times by 2050 (Suaria et al. 2016). Therefore, plastics are used in most work in different sectors (i.e., packaging, electrical/electronics, building/construction, medical/pharmaceutical, and households) (Geyer et al. 2017). Such a high level of plastic usage leads to the generation of massive amounts of plastic waste. These huge plastic wastes raise a critical risk to the ecosystem (Su et al. 2022). The slowest degradation rate of this discarded plastic waste is causing serious ecological issues (Mo et al. 2023).

Once introduced into the soil environment, plastic debris gradually decomposes to particle sizes (millimeter and micrometer) as MP_S (<5 mm diameter) and nanoplastics (NP_S) (1–1000 nm diameter) (Lian et al. 2020). Nowadays, MP_S pollution broadly exists in different compartments (air, aquatic, and terrestrial) of the environment, such as rivers, oceans, seas, coastal, lakes, ponds, sediments, soil, and air (Kallenbach et al. 2022; Bank and Hansson 2022). Therefore, this MP_S pollution is grasping the attraction of researchers who recently performed studies related to their adverse effects on microbiota, soil, and plants (Zhang et al. 2019a).

2 Types of Microplastics

Based on chemical composition, different MP_S polymers types prevail in the soil environment as follows: high-density polyethylene (HDPE); polyethylene (PE); polypropylene (PP); polystyrene (PS); polyamide (PA); polyvinylchloride (PVC); polyethylene terephthalate (PET); polyethersulfone (PES); synthetic rubber; and rayon and acrylic (Tian et al. 2022).

2.1 Physical Identification (Shapes/Sizes/Color)

Microplastics are unevenly distributed in the soil, having distinct surface texture, color, shape, hardness, and luster (Wang et al. 2017). Moreover, the shapes of MP_S can resemble natural particles or are dissimilar to natural objects (Lehmann et al. 2020). Possible geometrical shapes can be fragments, films, pellets, microbeads, fibers, foams, strings, and beads (Marrone et al. 2021). Based on the particle sizes, these MP_S can be categorized into five groups based on size, i.e., from 0.02 to 0.2, 0.2–0.5, 0.5–1, 1–3, and 3–5 mm. Most suspected MP_S particles in the soil environment have sharp colors (e.g. black, green, red, blue, and yellow) as well as transparent because these colors are commonly used in manufacturing plastic-based consumer products (Chen et al. 2020a).

3 Classification of Microplastics

The existence of MP_S in the ecosystem can be classified as primary MP_S and secondary MP_S.

3.1 *Primary Microplastics*

Primary MP_S originated from the industries using raw plastic materials of micrometer size (such as microbeads/resin pellets) for manufacturing their products related to cosmetic/personal care, i.e., abrasive, scrubbers, toothpaste, and shower gels, household cleansers and medicine as vectors for drugs (Karbalaei et al. 2018). These primary MP_S can be accidentally discharged into the environment.

3.2 *Secondary Microplastics*

Secondary MP_S are generated by consistent mechanism of abrasion and degradation (braking and weathering) of the larger plastic fragments based on mechanical wear (e.g., winds, hydrodynamic conditions, and complex topography) associated with physical, chemical, and biological processes. Alongside this, the rapid degradation (via a high temperature and UV radiation) of the large plastic material used in different activities of agriculture/industries also produces secondary MP_S (Rose et al. 2023).

4 Anthropogenic Microplastic Soil Pollution

Several anthropogenic sources are held responsible for MP_S pollution in the soil. For instance, a reasonable quantity of MP_S particles is introduced into the agriculture fields where sewage sludge and biosolids are used as fertilizers (Harley-Nyang et al. 2022). To achieve optimum productivity/yield of crops while regulating environmental conditions, plastic film mulching is extensively used in agriculture. A high temperature, heat, and precipitation caused rapid degradation of plastic/vinyl coverings, producing plastic residues (MP_S/NP_S) in soil (Hu et al. 2020; Qi et al. 2018). Microplastics may also enter the soil through plastic littering/waste originating from different activities (cosmetics, paints/coatings, textiles/clothing, and rubber abrasion) (Galafassi et al. 2019), as well as by other dynamic routes such as street runoff, flooding, and atmospheric fallout (Bläsing and Amelung 2018). After the entrance of MP_S into the soil matrix, they have the potential to alter vital processes.

5 Global Abundance and Occurrence of Microplastics in Soil

Globally, the generation of plastics has risen from 230 to 348 million tons per annum for a long period (2005–2017). However, a sharp increment of 13 million tons was observed during 2016–2017 (Geyer et al. 2017). During the usage of plastic for manufacturing, a huge quantity (6300 million tons) of plastic waste is produced. A large proportion (4900 million tons) of that is usually transferred into the soil environment via landfills (Geyer et al. 2017), up to 4–32 times higher than the oceans (Gionfra 2018). It has been reported that total annual input ranged from 63,000 to 430,000 and 44,000–300,000 tons of MP_S in Europe and North America farmlands, respectively. This is an alarmingly high level of MP_S contamination in farmland (Himu et al. 2022). Mohajerani and Karabatak (2020) reported that the treated wastewater sludge (as biosolids) is commonly put in agriculture fields, which results in the accumulation of MP_S, $NP_{S,}$ and other pollutants (such as heavy metals) in arid soils. Comprehensive data analysis revealed that this biosolids application caused annual MP_S accumulation of up to 26,042, 21,249, 13,660, 1518, and 1241 tons of MP_S in arid European soils, the USA, China, Canada, and Australia, respectively.

5.1 Agriculture/Farmland Soil

A prolonged addition of sewage sludge (MP_S ranging from 18 to 41 particles g^{-1}) in agricultural soils in Chile resulted in the accumulation of 97% of fiber MP_S in soil (Corradini et al. 2019). In Spain, sewage sludge application in agricultural soils contributes to average heavy-density plastic loads (3060 ± 1680 MP_S kg^{-1}) and light density (2130 ± 950 MP_S kg^{-1}). Heavy incorporation of sewage sludge resulted in average plastic loads in the soils enhanced by 430 heavy-density MP_S kg^{-1} and 280 light-density MP_S kg^{-1} (van den Berg et al. 2020). Farmlands in China contained a maximum MP_S content (0.28 particles g^{-1} soil) having mean (0.078 ± 0.013 particles g^{-1}) in upper layer of soil (Corradini et al. 2019). Most MP_S particles were composed of PE (43.43%) and PP (50.51%) and were present in the forms (fragments, fibers, and films) as well as in black color/transparent (Liu et al. 2018). Likewise, Zhang and Liu et al. (2018) reported the average concentration of plastic units (18,760 kg^{-1} soil) in wastewater-irrigated cropped areas in southwestern China. In soil aggregates, these plastic particles (up to 95%) were estimated in the size range (1–0.05 mm) of MP_S. Plastic fibers, films, and fragments were the most dominant plant types in these soil aggregates. The research revealed that 72% of plastic particles adhered to the soil aggregates while 28% of particles were dispersed. In southeast Mexico, waste mismanagement resulted in a high concentration of MP_S (0.87 ± 1.9 particles g^{-1}) in home garden soil (Lwanga et al. 2017).

While recognizing the benefits of using plastic mulching, plastic film is extensively used in a vast area (up to 20 million hectares) of farmlands (Liu et al. 2014), especially in northern China. This usage of plastic films expanded four folds (from

0.32 to 1.25 million tons) from 1991 to 2011 (Liu et al. 2014; Wang et al. 2013; Yearbook 2012), which resulted in the accumulation of plastic residues, especially MP_S in farmlands (Ng et al. 2018; Steinmetz et al. 2016). Zhang et al. (2016) estimated average film residue content (121.5 kg ha^{-1}) in Chinese soils under mulching. Likewise, near Hangzhou Bay in China, Zhou et al. (2020) determined the mean quantities of MP_S in arid soil covered with plastic (571 units kg^{-1} soil) and naked portion (263 units kg^{-1} soil). Stereomicroscopy and μ-FTIR analysis revealed that the mulching soil contained MP_S of fibers, fragments, and films shapes.

An investigation was performed to quantify the MP_S contents in three different soils of central China, where they achieved a significantly higher abundance of MP_S in forest soil (4.1×10^5 particles kg^{-1}) than in vegetable (1.6×10^5 particles kg^{-1}) and vacant (1.2×10^5 particles kg^{-1}) soils. In all soil samples, most MP_S prevailed in the shapes of fragments (53%) and fibers (15.2%). The prevailing sorts of polymers were PE, PP, PS, PA, and PVC, especially PE was the most prominent (Zhou et al. 2019).

5.2 Industrial Soil

Most MP_S contents had particle sizes (<1 mm) composed of PS, PE, and PVC. Similarly, Deng et al. (2020) performed a monitoring study to estimate the MP_S contents in sediments of industrial areas located in China. The abundance of MP_S was estimated from 16.7 to 1323.3 items kg^{-1} DW sediment. Polyester (up to 79%) as a polymer type having primarily colored fibers (<1 mm particle size) was detected in sediment samples.

5.3 Coastal Wetland and Floodplain Soil

Helcoski et al. (2020) have estimated the MP_S contents (81–93%) in the coastal wetland. The detected polymers were PE and synthetic rubber (8%) and PS (29%). Based on habitat types (mudflat channel edge or drift line), the mean MP_S numbers in depth (5 cm) were estimated within 23200 ± 2500 m^{-2}. These habitats contain a large number of MP_S because of not having barriers, as in the case of dense vegetation. Non-vegetation mudflats were enriched with microfibers, while vegetated channel edges were with micro fragments. A study was performed to assess the conversion of macroplastics into MP_S through slow breakdown within an intertidal salt marsh habitat (Weinstein et al. 2016). Similarly, the spatial distribution of MP_S in Swiss floodplain soils was assessed. A major proportion of MP_S consisted of mesoplastics (5 mm–2.5 cm diameter). Microplastic particles were transferred into soils through diffuse aeolian transport (Scheurer and Bigalke 2018). Nor and Obbard (2014) found MP_S in various intertidal mangrove habitats in Singapore. The ATR-FTIR spectroscopy suggested that most MP_S were fibrous and had less than 20 μm.

Four polymers were identified, i.e., PE, PP, nylon, and PVC. Likewise, Lourenço et al. (2017) quantified MP_S concentrations in sediments of intertidal wetlands (estuaries) in Africa and South Europe. These authors found 91% of microfibers in sediment samples. These microfibers originated from synthetic polymers, as confirmed by μ-FTIR analysis. The MP_S contents were estimated as 413.8 ± 76.7 and 221.0 ± 25.6 particles m^{-2} in two estuaries (Charleston Harbor and Winyah Bay, respectively) in South Carolina, USA. Mean concentrations of MP_S in the sea surface microlayer of Winyah Bay and Charleston Harbor were 30.8 ± 12.1 and 6.6 ± 1.3 particles L^{-1}, respectively. Higher MP_S contents were found in Winyah Bay (Gray et al. 2018). Li et al. (2020a) analyzed diverse rates of MP_S contents in different mangrove sediments in China, and its interlinked ecological risk was assessed. The highest MP_S contents (2249 ± 747 items kg^{-1}) were found in the Futian mangrove connected with the third largest river (i.e., Pearl) in China. Most of the MP_S contents were a fibrous shape, white transparent in color and size (500–5000 μm). These MP_S were composed of PP, PE, and PS.

5.4 Urban Soil

Du et al. (2020) found four different types (PP, PVC, PET, and PA6) of MP_S in southeastern suburbs soils in China. The largest proportion of MP_S consisted of PET and PA6 (up to 30.2%), and the MP_S particle size ranged from 0 to 35 μm. Over 26.3% of these particle sizes were less than 10 μm MP_S. In contrast, the particle sizes of 20–25 μm and 25–35 μm were in smaller proportions (17.8% and 9.3%, respectively).

6 Detection/Monitoring of Microplastics in Wastewater/Sludge

Recently, scientists have assessed the levels of MP_S transferred into aquatic systems by discharging untreated/treated effluents from wastewater treatment plants (WWTP). Akarsu et al. (2020) reported the discharge rate of MP_S at 1.8×10^8 particles day^{-1} in Mersin Bay, Turkey. Likewise, the immediate release of effluents into the seawater gulf in Finland resulted in a reasonable quantity of MP_S composed of plastic and fiber particulates (Talvitie et al. 2015). Similarly, a high concentration of MP_S (9×10^1 to 1×10^3 m^3) was detected in the effluent from WWTP in Germany (Mintenig et al. 2017). Uncontrolled discharge of microbeads into the WWTP effluent resulted in higher contents of MP_S in Laurentian Great Lake, USA. Microplastics were spherical shapes and multicolored (Eriksen et al. 2013). Olmos et al. (2019) characterized wastewater of domestic WWTP in Cartagena, Spain. They detected primary plastic polymers (PP, HDPE, and fibers made of nylon) having different shapes, i.e., films, fragments, fibers, beads, and foam. After removing MP_S, the final effluent of WWTP containing plastic fragments and low-density polyethylene (LDPE) (as dominant constituents) was applied to the soil. Likewise, MP_S existence was quantified of 4196–15,385 particles kg^{-1} DW from sludge of WWTP in Ireland (Mahon et al. 2017).

7 Effects of Microplastics on Soil Quality and Fertility

7.1 Soil Physical Attributes

A meta-analysis by Lehmann et al. (2020) explored the effects of MP_S shapes (films, fibers, fragments, and foams) and polymer types on the aggregation of soil and decomposition of organic matter. They have demonstrated the adverse influences of fibers on the formation of aggregates. Furthermore, the fragments and foams were essential for co-modulating the soil response. Overall, the MP_S films adversely impacted the formation of aggregates while positively impacting aggregate stability. Lehmann et al. (2020) found a negative relationship between different microfibers (linear shape) and aggregate formation. After applying MP_S-based fibers into newly created aggregates, the microfibers introduce fracture points in the soil, possibly supporting breakdown in case of physical destruction of soil aggregates (Rillig et al. 2019; Zhang and Liu 2018).

Both pot and field experiments were conducted by Zhang et al. (2019b) to investigate the effects of diverse rates (0, 0.1, and 0.3%) of polyester microfiber (PMF) on porosity, bulk density, hydraulic conductivity, and aggregation in the clayey type of soil. Compared to untreated soil, the PMF application enhanced the pore dimension (greater than 30 μm) while diminishing pore dimension (<30 μm). Applied treatments revealed no variation in saturated hydraulic conductivity and soil bulk density. In the pot study, the PMF incorporation remarkably promoted the water-stable large macro-aggregates (>2 mm) up to 39% and 44% in 0.1% PMF and 0.3% PMF, respectively. The constituents of soil solids (e.g. humus and minerals) potentially affect soil bulk density (Zhang et al. 2019b). Depending on different soil types, the amounts of MP_S can alter the porosity and bulk density of the soil (de Souza Machado et al. 2018a), reducing water mobility through the contraction of soil pores (Yang et al. 2020). The prevalence of plastic residues via degradation of plastic film mulching increases temperature (Heißner et al. 2005; Wang et al. 2003) and vapor pressure, which as a result, enhances soil aggregate stability and porosity while reducing bulk density (Wang et al. 2017; Yang et al. 2020).

Likewise, Wan et al. (2019) evaluated the effects of plastic films of different sizes (2, 5, and 10 mm) on the evaporation of water and cracking in clay-type soils. Outcomes of this research showed that plastic residues (all sizes) in soil enhanced water loss from the soil via forming pathways for water mobility. Among all treatments, the most pronounced data was achieved in MP_S treatments having 2 mm particle sizes. Desiccation cracking was found on the soil surfaces of treatments containing (5 and 10-mm particle sizes) because of soil structure disintegration. Whereas treatments containing 2 mm MP_S exhibited a high desiccation shrinkage rate of the soil. This research concluded that plastic contamination could change water mobility in soils while affecting pollutants' vertical mobility.

7.2 *Microbial Community and Enzymatic Activities*

As living biomass, the microbiota is a primary constituent of the soil ecosystem because it plays multiple roles in nutrient cycling in soil (Ma et al. 2016). In addition, soil arrangements into different pore space configurations, functional aggregates, and hydrological characteristics could affect metabolic rates of microbiota and decomposition of organic matter (de Souza Machado et al. 2018a). The occurrence of soil MP_S alters microbial communities and causes variation in nutrient biogeochemical cycling, which as a result, might affect the services and functions of the soil ecosystem. However, the precise mechanism of how these MP_S can influence microbiota, and soil properties are still unclear (de Souza Machado et al. 2018a; Machado et al. 2017). Miao et al. (2019) found that MP_S alter microbial community composition through MP_S-induced niche differentiation. In a study, the existence of PP-derived MP_S stimulates the activities of microbes in soil. Relative to control, treatments containing other polymers, i.e., fibers, polyester, and PA, significantly reduced soil microbial activity (de Souza Machado et al. 2018a). Plastic waste particles in soil stimulated microbial respiration, initiated the activity of fluorescein diacetate hydrolase (FDAse), phosphatase, and β-glucosidase, and enhanced nutrient content in the soil (Yang et al. 2018).

7.3 *Elemental Chemistry*

Once MP_S is introduced into the soil, it can directly/indirectly influence soil functions (de Souza Machado et al. 2018b). It has been suggested that MP_S could be a component of soil carbon (C) sequestration, which reacts with organic matter and forms high-molecular-weight aromatic compounds in the soil (Liu et al. 2017; Rillig 2018). However, Chen et al. (2020b) have reported that polylactic acid (PLA)-based MP_S had no remarkable influence on soil functionality (via enzymatic activities) and the contents of C and nitrogen (N) in soil because of limited weight loss of PLA via slow degradation. The addition of PP-based MP_S in the soil statistically promoted the concentration of inorganic P and dissolved organic C (Liu et al. 2017). Whereas Chen et al. (2020b) reported that PLA-based MP_S reduced the concentration of ammonium (NH_4^+) − N in soil via the sequestration of NH_4^+ −N by containing hydroxyl (−OH) and carbonyl (=O) groups on the surface. Contrarily, the elevated levels of nitrite (NO_2^-)−N and nitrate (NO_3^-)−N in the soil could be due to the enhancement of the nitrification process over time, which facilitated the lower level of NH_4^+−N. Previous literature also reported that the presence of MP_S increases porosity, which, as a result, enhances the airflow in the soil and activates ammonia (NH_3) oxidization to supply adequate dissolved oxygen Chen et al. (2020b).

8 Effects of Microplastics on Different Traits of Plants

Plants are a crucial part of terrestrial ecosystems, play a vital role in edible supply, and serve as the source of diet for humans. The presence of MP_S in the soil is a potential route to get accumulated in the crop, posing an adverse impact on the crop and human health (Wang et al. 2019). Therefore, there is a necessity to understand the primary mechanism of MP_S-induced toxicity in plants. This section provides information about MP_S-induced phytotoxicity and connected mechanisms.

8.1 Overall Health and Physiology

Soil harboring MPs affects plant growth by indirect mechanisms via distorting soil traits or their direct uptake from the soil. In recent years, MPs have affected the numerous traits of several plant species (Li et al. 2022). The accumulation of MP_S in plants results in delayed germination (Bosker et al. 2019), influences the reproductive as well as vegetative growth of crops (Qi et al. 2018), and exerts genotoxicity and ecotoxicity in plants (Jiang et al. 2019). For instance, the higher levels of MP_S in the soil caused poor seed germination, thus leading to poor plant stand and establishment of crops. A recent study revealed a remarkable reduction in seed germination of *Lepidium sativum* (*L. sativum*) with three plastic sizing (50, 500, and 4800 nm) at five concentrations. The confocal microscopy images of fluorescent MP_S revealed that they caused the physical blockage of pores in the seed capsule, consequently inhibiting water uptake and delaying seed germination. The roots of plants act as the first point interacting with pollutants and are studied widely to examine the negative impacts on plants (Bosker et al. 2019). For instance, the adherence of MP_S to the root hairs is known to damage the overall root traits (root tip, diameter, length, surface area, and tissue density) and root elongation, which disturbs juvenile roots and their development. After the absorption of MP_S by the roots, MP_S may translocate to the aerial parts and accumulate in numerous above-ground structures, including stems, leaves, and fruits (Zhang et al. 2022a). Previously, the MP_S uptake by tobacco was investigated in vitro, and it was observed that fluorescent PS nanoparticles accumulated in tobacco Bright Yellow-2 (BY-2) cells through endocytosis (Wang et al. 2022). Interestingly, higher transpiration rates also enhanced the uptake and translocation of MP_S due to the transpiration force as the key controlling power of their transport (Li et al. 2020b).

8.2 *Antioxidant Enzymes and Oxidative Damage*

Soil occurrence of MP_S resulted in the development of reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), superoxide radicals ($O_2^{\bullet-}$), hydroxyl radicals ($^{\bullet}OH$), and electron transport chain damage (Kumar et al. 2022; Yu et al. 2021). Reactive oxygen species are mostly found in plant peroxisomes, the endoplasmic reticulum, and mitochondria (Zhang et al. 2022b). Previously, a low concentration of MP_S improved the activities of numerous antioxidant enzymes via activating the expression of ROS-stimulating enzyme-coding genes. This caused a significant decrease in malondialdehyde (MDA) contents (Gao et al. 2017). The MP_S-induced ROS overproduction is primarily linked to polymer type, surface charge, and size of MP_S (Zhang et al. 2022b). The accumulation of PVC in *L. sativum* (garden cress) showed the most toxic impacts and caused more oxidative damage than PE and PP types of MP_S (Pignattelli et al. 2020). Fava plant subjected to 100 nm PS–MP_S exhibited much more oxidative stress and genotoxicity compared to 5 μm PS–MP_S (Jiang et al. 2019). Therefore, MDA estimation may be used to portray lipid peroxidation due to MPs (Jiang et al. 2019). The aging or degradation of MP_S via physical, chemical, and biodegradable results in the dissolution of several potentially toxic substances [bisphenol-A, phthalates (PAEs), polybrominated diphenyl ethers (PBDEs)], and heavy metals utilized in dying (Luo et al. 2022). Previously, the release of adsorbed toxic compounds by MP_S back into the surrounding environment caused phytotoxicity due to their adhesion to the root surface (Gao et al. 2019). For instance, plasticizers uptake in wheat adversely influences activities of antioxidant enzymes and triggers death of cells via changing expression of genes (Yang et al. 2023).

8.3 *Biochemical Compounds and Nutrient Assimilation*

The accumulation of MP_S of various types and sizes in the soil affects plant growth via disturbing plant hormones, nutrient uptake, and metabolisms (Wu et al. 2020). Barley, when exposed to 2 mL^{-1} PS, altered the carbohydrate metabolism, phytohormone, and redox homeostasis governing system (Li et al. 2021). Similarly, another study revealed that PS-MP_S (<50 μm) accumulation prominently affected different metabolic systems in the leaves of *Oryza sativa*, thereby reducing biomass and growth at higher concentrations (500 mg L^{-1}) compared to lower concentrations (Wu et al. 2020). Furthermore, this alteration in the metabolic pathways delayed the production of essential plant metabolites and controlled the expression of root-related genes, hindering nutrient uptake and eventually reducing plant vigor (Zhou et al. 2021).

Primarily, MP_S contain a significant portion of C, which is ultimately released into the soil. Microbial populations consume this additional C and other essential nutrients to improve their growth (Rillig 2018). The abundance of C in the soil negatively affects plant growth due to nutrient immobilization. Moreover, the fluctuations in soil C:N ratio could also affect plant growth via microbial N immobilization, influencing nutrient availability (Boots et al. 2019; Qi et al. 2020a). Previously, the restricted uptake of essential nutrients in *Arabidopsis thaliana* (*A. thaliana*) (Sun et al. 2020), *L. sativum* (Pignattelli et al. 2020), and *Lactuca sativa (L. sativa)* (Gao et al. 2021) are recorded after the uptake of various MP_S. The accumulation of MP_S obstructed pores of cell walls associated with the aerial mobility of water and nutrients, thereby reducing the growth of plants (Jiang et al. 2019).

9 Possible Remediation Strategies for the Mitigation of Microplastic Pollution and Sustainable Plant Production

The contamination of arable lands with MP_S has recently been recognized worldwide (Khalid et al. 2020). The plants cannot uptake MP_S owing to their large size and high molecular weight (Teuten et al. 2009). However, the weathering of MP_S converts them into NPs, which can pass through the membrane and enter plant cells, possibly providing pathways in the food chain. For instance, PS nanoplastic (0.2 μm) is assimilated via plant roots, which is further transported to the aerial parts and severely disturbs plant growth through changes in intracellular metabolites and alterations in the cell membrane (Li et al. 2020b). Nanoplastics find their way to plant bodies that can be hazardous for living things after their utilization (Shi et al. 2019). Therefore, there is a need to remediate MP_S soils for better plant growth and food production.

9.1 Soil Remediation Contaminated with Microplastics

Remediation of soil contaminated with MP_S casts problems via high variability of MP_S and different properties of soils, especially different amounts of organic matter and clay minerals. In the case of water and wastewater treatment techniques, the number of available solutions is relatively large, e.g., ozonation, coagulation/flocculation, rapid sand filtration, and dissolved air floatation, with high efficiency to the larger size and density MP_S. Also, other techniques such as electrocoagulation, photocatalytic degradation, or membrane bioreactor were successfully tested (Pico et al. 2019; Silva 2021). The strategies for soil remediation are mainly focused on bioremediation with bacteria. However, some studies showed that plants could accumulate MP_S. For this reason, phytoremediation is potentially a green solution for the areas polluted by MP_S.

9.2 Bioremediation

Several microbes have been discovered capable of plastic polymer degradation through enzymatic depolymerization (Qi et al. 2020b). Interestingly, MP_S hydrophobic nature and specific surface area can promote the formulation of new ecological niches in soil for bacteria (Xu et al. 2020). During colonization, microorganisms be able to release enzymes, e.g., PET hydrolase (PETase), from *Ideonella sakaiensis* (Yoshida et al. 2016), which disintegrates polymers into oligomers, dimers, and monomers (Arpia et al. 2021). Recent studies showed that even PE, PET, and PS, which were generally considered nonbiodegradable, were decomposed under the presence of bacteria strains (Wu et al. 2017). Some species and strains of *Actinobacteria*, *Bacteroidetes*, and *Proteobacteria* (Zhang et al. 2019c), *Rhodococcus* spp., and *Bacillus* spp. (Sarker et al. 2020) can biodegrade PE and PS through the synthesis of hydrolytic enzymes. The fungal genera *Aspergillus* and *Penicillium* are capable of degrading > ten sorts of plastics, including PE, PS, and PET (Silva 2021).

However, MP_S may affect absorption and accumulation of chemical toxicants and be a medium for those pollutants. The slow breakdown practice of MP_S may release these adsorbed toxic contaminants back into the adjacent environment, especially organic compounds and pesticides (Andrady 2017; Zhang et al. 2019c). Moreover, heavy metals and antibiotics could be absorbed by the plastic debris, favoring the transmission of antibiotic-resistant bacteria (AtReBt) and/or Antibiotic Resistance Genes (AtReGn) and making water bodies its natural reservoirs (Caruso 2019). The plastic surface can also be colonized by pathogens such as *Pseudomonas*, *Escherichia*, *Acinetobacter*, and fungi such as *Candida*, *Cryptococcus*, and *Rhodotorula*, which play roles in spreading microbial diseases (Parthasarathy et al. 2019).

9.3 Phytoremediation

Some plants have the ability to uptake MP_S. The MP_S traveled in the *L. sativa* via apoplastic transport mechanism and later were aerially transported through vascular system under the influence of transpiration (Li et al. 2019). Microplastics were found to be accumulated by *A. thaliana* (Sun et al. 2020), pepperwort (Bosker et al. 2019), or surface absorption by duckweed (*Lemna minor*) (Mateos-Cárdenas et al. 2019). Further, oxidation stress and adverse effects on photosynthetic pigments were observed in *A. thaliana* (Sun et al. 2020) and *L. sativa* (Li et al. 2020c). Additionally, it was observed that the MP_S altered the germination and growth of *Lolium perenne* (Boots et al. 2019). These limitations may affect the effectiveness of phytoremediation. Therefore, further investigations are needed, and the use of plants for the remediation of soils contaminated with MP_S seems to be a distant prospect.

9.4 Immobilization

As an emerging technology, the immobilization of MP_S has been suggested. However, these methods are used mainly in water and WWTP. Wang et al. (2020) showed promising results of biochar used for filtration and immobilization of MP_S in WWTP, while Tong et al. (2020) indicated that magnetic biochar can be used for immobilization of MP_S also in soils.

10 Management Solutions

It was estimated that upto 42% of whole worldwide plastics are deposited on land and have low pace of degradation, and 10% can be observed in water bodies, which is threat to life in water (Sarker et al. 2020). Plastic contamination is a threat across the globe with great concern about health risks. Besides larger objects identified in water systems, up to 83% can be classified as MP_S (Cózar et al. 2015). However, some calculations revealed that approximately 32% of all plastic synthesized is accessible in terrestrial ecosystems. Others estimated that MP_S contamination on land might be 4- to 23-fold larger compared to the ocean (de Souza Machado et al. 2018b). Therefore, the strategies for MP_S limitation in the environment and remediation strategies preparation are urgently needed. For this purpose, it is necessary to act on many levels, implementing the integrated management system for the life cycle of plastics, which suggests reduction, reuse, recycling, and recovery options (Prata et al. 2019; Arpia et al. 2021).

10.1 Reduction of Plastic Production and Consumption

Reducing plastic litter, as a main source of MP_S in the environment, is one of the most important actions. Packaging, building and construction, and automotive industry are the largest end-use markets in Europe, which give almost 70% of the total European plastic demand (PlasticsEurope 2018). For health and food safety purposes, finding an alternative solution for separate packaging and using single-use plastic products is hard. Nonetheless, avoiding unnecessary packaging (e.g., double-packaging) or choosing eco-friendlier alternatives is required (Prata et al. 2019). Many countries in Asia, Europe, and Africa have introduced restrictions on plastic products (Kibria et al. 2023). Moreover, education seems to be an extremely important tool. Building ecological awareness of societies can be a powerful means of putting pressure on producers who will be forced to look for other, more ecological solutions.

10.2 Reuse, Recycling, and Recovery of Plastics

Well-developed solid waste infrastructure and management connected with highly capable recycling are effective tools for decreasing plastics and later in ecosystem (Prata et al. 2019). As plastics recycling can be considered primary recycling, called closed-loop recycling, which produces superior plastics, secondary recycling is referred to as downgrading, which after mechanical reprocessing, provides lower quality plastic. Other types of plastics classified in recycling and recovery terminology are tertiary recycling, called feedstock recycling, based on the recovery of chemical constituents, and quaternary, as energy recovery. Although recycling has a high priority in waste management, it is still problematic mainly due to the high cost of the recycling process (Prata et al. 2019). Some plastic types are not suitable to recycle, or their low quality does not allow for recycling. It is possible to incinerate with energy recovery as a quaternary recycle type. Although it is a better solution than landfill storage, it is burdened with several atmospheric problems (Prata et al. 2019).

10.3 Other Possibilities for the Mitigation of Microplastic Pollution

Biodegradable polymers such as PLA, polyhydroxyalkanoates (PHA), and others are commercially available and can replace traditional plastics for many applications and can be a solution for environmentally friendly plastic (La Fuente et al. 2023). Microorganisms can degrade it. Microplastics can be used as C sources to provide energy for microbial degradation of polymer plastics (Zurier and Goddard 2021). Also, plastic-degrading enzymes used to catalyze MP_S degradation are promising solutions (Zurier and Goddard 2021). However, the knowledge of secondary metabolite behavior in soils and their toxicity is still very limited. For this reason, the environmental risk assessment of biodegradable polymers needs further investigation (Silva 2021).

11 Conclusions and the Way Forward

Microplastics are widely spreading in different ecosystems, and their plentitude will rise in the coming times because of their usage, inert characteristics, and delayed breakdown. The MP_S accumulation not only impact soil health but also adversely damages plant by direct toxicity from additives or adsorbed pollutants or the ability to change fundamental soil properties. Nevertheless, the extent of MP_S impacts depends on size, shape, type, and concentration. Therefore, it is necessary to understand ways how soil properties alter after MP_S entry in the soil because it will affect soil microbes and plant health. Moreover, there is also a need to understand the interactional role of MP_S on different species of microbes, playing a pivotal role in the decomposition of organic matter and nutrient cycling.

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Chapter 24
Biostimulants in Sustainable Agriculture

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Abstract Agrochemicals are of great importance to enhance growth and productivity for sustainable agriculture. In the past, different techniques have been developed to reduce the usage of synthetic fertilizers and insecticides to protect the environment from hazardous chemicals and to increase plant yield. Among such environment-friendly approaches, one is the use of biostimulants, which is very crucial in the development of plants. Biostimulants increase the water use efficiency and improve soil chemistry, which is suitable for the proper functioning of roots and many other physiological processes in plants that ultimately result in higher yield. Different compounds such as seaweeds, humic and fulvic acids, different plant growth-promoting bacteria, and extracts from algae are used as plant biostimulants. They can be applied to the plants either by mixing in the soil or by foliar applications to enhance the growth and yield of plants. Biostimulants help in nutrient uptake and respond to various biotic and abiotic stresses through hormonal control. They are helpful in nitrogen fixation and making the crop plants resistant to abiotic stresses. Biostimulants are eco-environment friendly and impart a major role in sustainable agriculture to meet the increasing food demands of population. The use of biostimulants for sustainable agriculture is depicted from the literature in controlling the damages by insects and pathogen attack by transcripting the genes through

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signal transduction under various stress conditions. Apart from this, biostimulants are used in management practices of agriculture with the basic aim of minimizing the use of chemical fertilizers to increase nutritional quality and crop production.

Keywords Abiotic stresses · Biostimulants · Soil chemistry · Humic acid · Beneficial microbes

1 Introduction

The term "biostimulant" was used for the compounds that stimulate plant growth but are not nutrients. According to (Rouphael and Colla 2020), biostimulants are defined to be "materials, which in negligible quantities enhance plant development." The authors sought to separate fertilizers and biostimulants, which similarly encourage plant development but used in larger quantities using the phrasal verb "minute quantities" to describe biostimulants (Calvo et al. 2014).

Scientific literature describes the biostimulants to be the compounds, but not fertilizers, which enhance plant development when applied in modest quantities (Du Jardin 2015). Biostimulants include a variety of formulations and include a group of chemicals; however, they are divided into three groups depending on the source as well as composition. Auxins, cytokinins, or their derivatives, which are active plant growth chemicals can be found in detectable concentrations in HCPs like seaweed extracts. Over the ensuing years, the scientific literature used the name "biostimulant" more frequently, extending the range of chemicals and action mechanisms (Genc and ATICI 2019). The term "biostimulant" is used to describe any agent that is helpful to plants but is neither a nutrient nor a pesticide, or a soil enhancer (Savy et al. 2020).

Distinguishing between biostimulants and commonly used compounds applied to plants to enhance the productivity, it is possible to define biostimulants in part by what they are not pesticides and fertilizers (Calvo et al. 2014). Later it was discovered that bacteria and fungi can likewise provide the beneficial effects attributed to chemically synthesized biostimulants, including growth promotion and increased tolerance to environmental stress. For instance, PGPRs, also known as "plant growth-promoting rhizobacteria," can be defined to have favorable impacts on crops rather than by their status as nutrients, insecticides, or soil-improving agents (De Pascale et al. 2017).

2 Main Categories of Plant Biostimulants

Major categories of plants biostimulants include microbial and nonmicrobial species. Among microbial species are arbuscular mycorrhizal fungi, plant growth-promoting rhizobacteria, and *Trichoderma* spp. (López-Bucio et al. 2015).

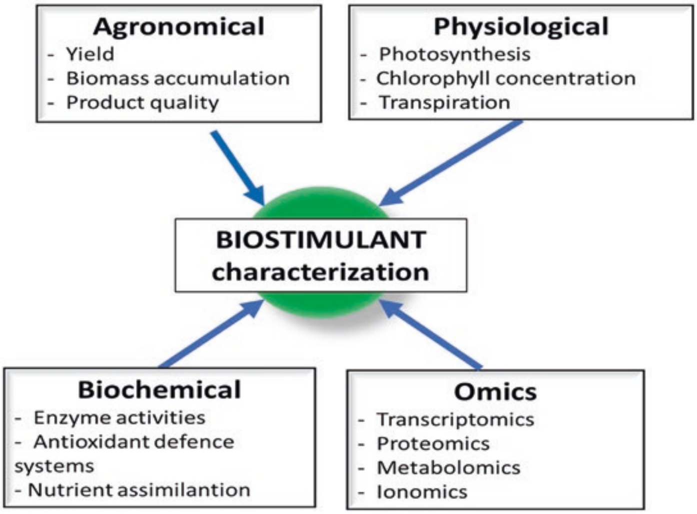

Fig. 24.1 Multidisciplinary approach for the characterization of biostimulants based on crop response (Franzoni et al. 2022)

Nonmicrobial biostimulants include seaweed extracts, chitosan, humic and fulvic acid, proteins hydrolytes, and other inorganic compounds. All these biostimulants have different roles (Fig. 24.1; Franzoni et al. 2022) in plant physiology and developmental process by stimulating the activity of microbes in soil and activating the soil enzymes or plant growth hormones (Tejada et al. 2008). All of the above-mentioned plant biostimulants have physiological effects on both biotic and abiotic stress responses in plants (Gu et al. 2016).

2.1 *Humic and Fulvic Acids*

Natural compounds found in the organic matter of soil are humic substances (HS) come from the decomposition of organisms, microbial remains, and from the metabolism of soil living bacteria utilizing such compounds as substrates (du Jardin 2012). Humic substances are heterogeneous molecules that were primarily classified on the basis of solubility and molecular weight as humic acids and fulvic acids. The humic compounds and their derivatives in soil are formed by interaction of the organic matter and microorganisms. To get the desired products and to enhance the plant growth and agricultural output encourage the interaction between microorganisms and must be optimized (Canellas et al. 2015).

Factors contributing to the heterogeneity in HS effects include the source of humic substances, methods of application, and the quantity applied (Toscano et al. 2018). Sources of HS include naturally humified organic materials (such as peat), composts, and vermicomposts. Additionally, agricultural residues can indeed be carefully broken and oxidized using chemical processes. Rather than decomposing in soil or through composting, producing “humic-like compounds” that are advocated as a replacement for natural HS (Eyheraguibel et al. 2008).

When plasma membrane H^+-ATPase is stimulated, free energy from ATP hydrolysis is converted into a transmembrane electrochemical potential that is utilized to import nutrients is other important role of humic substances played for increasing enhance nutrition in the root (Javaid et al. 2022).

By providing carbon substrates, HS appears to improve invertase and respiration activities. Additionally, hormonal effects are recorded; however, it is frequently unclear whether HS contain functional groups or signaling complexes, release hormonal substances, or activate the microbes which produce hormones (Traon et al. 2014). Stress tolerance is also one of the major roles played by biostimulants. The formation of phenolic chemicals depends on metabolic process of phenylpropanoid, which is important for secondary metabolism and different stress reactions (Ertani et al. 2013).

2.2 Protein Hydrolytes and Other N-Containing Compounds

As a result of proteins hydrolysis from agricultural products, including waste from both plants (such as crop residues) and animals, amino acids and peptide combinations are produced (Kocira 2019). Single or combined molecules can also be made through chemical synthesis. Betaines and “non-protein amino acids,” which cover a diverse range in most of the plants but little is known regarding their physiological and ecological functions, are other nitrogenous compounds (Vranova et al. 2011).

These substances have been demonstrated to serve a variety of functions as plant growth biostimulants in individual cases (Calvo et al. 2014). Modulating N absorption and assimilation has direct consequences on plants, and these effects include controlling the structural genes and enzymes involved in nitrogen assimilation as well as the signaling route for N acquisition in roots. They also provide a linkage between carbon and nitrogen metabolisms via controlling TCA cycle enzymes. Complex protein and tissue hydrolysates have been reported to have hormonal actions as well (Colla et al. 2014). Some amino acids, such as proline, have been found to have chelating properties, which help to eliminate plants from heavy metal stress while also facilitating the mobility and uptake of micronutrients. Some nitrogenous chemicals, such as glycine betaine and proline, confer antioxidant activity by scavenging free radicals, which helps to lessen the effects of environmental stress (Le Mire et al. 2016).

Administration of protein hydrolysates to agricultural soil has positive impacts on growth and nutrition of plants indirectly. Protein hydrolysates have been shown to improve soil fertility by increasing soil respiration, microbial biomass, and activity (Le Mire et al. 2016). The nutrients uptake by roots is thought to be influenced by the chelating mechanism of particular amino acids. Agricultural crops have been found to be increasing in quality, yields, and productivity by proteins hydrolytes demonstrated varying, but frequently significant, gains in yield and quality features (Brown and Saa 2015).

2.3 Seaweed Extracts and Botanicals

Agriculture has traditionally used fresh seaweed as a source of organic fertilizers, but now their effects as biostimulant have been documented (Dalal et al. 2019). This forms the basis for the commercial usage of extracts form seaweed and refined chemicals, including laminarin and carrageenan, and the by-products of their breakdown as well. Most of the algal species come from brown algae, which includes the principal genera *Ascophyllum*, *Fucus*, and *Laminaria* (Khan et al. 2009).

Seaweeds influence the plants as well as soil in different ways (Norrie et al. 2021). They can be applied exogenously as foliar treatments, or in soils. The fixation of cations, which is important for fixing of heavy metals, is facilitated by polyanionic compounds, and the soil microflora encourage the disease antagonists (Craigie 2011). Bioassays and immunological methods have been used to identify cytokinins, ABA, auxins, gibberellins, and other groups of hormone-like substances in seaweed extracts, including sterols and polyamines (Dmytryk and Chojnacka 2018).

There is proof that the hormone-related effects of *Ascophyllum nodosum* extracts are mainly explained by the up- and downregulation of hormone biosynthesis and to smaller extent by the hormones present in seaweed extracts (Umanzor et al. 2020). Additionally, antistress benefits have been noted, and protective seaweed extract components such as regulators of endogenous stress-responsive genes may play a role (Saa et al. 2015). Additionally, it is recognized that plant active substances, sometimes known as allele chemicals, which are being given increased attention because of sustainable crop management in mediating the interactions of plants within ecosystems (Craigie 2011).

2.4 Inorganic Compounds

Beneficial elements are chemical substances that aid in stimulation of plant development and are necessary for some species but are not necessary for all plants (Schiavon and Pilon-Smits 2017). Gramineous species contain various helpful elements including Al, Si, Se, Co, and Na, which can be found in different forms such as soil, plants, inorganic salts, and amorphous silica ($SiO_2.nH_2O$). These play important role in growth and development of these species. These advantageous properties can manifest under specific environmental conditions, or they might be constitutive, such as hardening of cell walls by impregnation of cell wall by silica deposits (Rivas-García et al. 2021). It is possible to suppose that the physiological processes of the beneficial components present in some complex biostimulants, such as extracts of seaweeds, are involved in their bioactivity as shown in (Sani et al. 2022). As fungicides, chlorides, phosphates, silicates, and carbonates, which are inorganic salts of helpful and necessary elements, have been utilized (Back et al. 2010). These inorganic substances affect osmotic, pH and redox balance, hormone signaling, and enzymes involved in stress response (peroxidases). More consideration should be given to their role as biostimulants of plant growth, which is different from their fungicidal activity and from their role as suppliers of nutrients in fertilizers. They act on nutrition efficiency and abiotic stress tolerance (Bonfante and Genre 2010).

2.5 Beneficial Fungi

Fungi form associations with roots in a variety of mechanisms, including parasitism and mutualistic symbiosis (i.e., partners live in close proximity to one another and develop connections that are mutually advantageous) (Aamir et al. 2020). A diverse collection of taxa known as mycorrhizal fungi form symbioses with more than 90% of all plant species. The arbuscular-forming mycorrhiza are a common form of endomycorrhiza having close association with plants (Peter et al. 2020).

There is a growing interest of the use of mycorrhiza for sustainable agriculture (Siddiqui et al. 2010). Hyphal networks connect not only fungi and plants but also specific plants within a plant community (Genre and Bonfante 2010). Fungal conduits permit interplant signaling; this could have substantial ecological and agricultural ramifications (Abirami et al. 2022). The AMF create multilateral connections with plants and rhizobacteria as an additional topic of study that is important in real-world field circumstances (Aamir et al. 2020).

Strategies related to crop management must be designed in such a way as to maximize microorganisms and plants interaction in order to profit from mycorrhizal connections (Gianinazzi et al. 2010). Biostimulants should include any fungus-based compounds applied to plants to improve nutrition effectiveness, stress tolerance, crop output, and quality of products. Their biotrophic nature makes it technically challenging to transmit AMF on a wide scale, which places significant restrictions on their application (Kour et al. 2020). However, other fungal endophytes, such as *Sebacinales* and *Trichoderma* spp. (Rouphael et al. 2018) separate from the mycorrhizal species, are able to colonize roots and transport nutrients to their hosts. They can spend at least a portion of their life cycle outside of the plant (Aamir et al. 2020).

Fungi are becoming increasingly popular as model organism to study how nutrients are transferred with their hosts. Additionally, they are being used as plant inoculants that are easier to cultivate in vitro (keya Tudu et al. 2022). The biotechnological industry has taken the advantage of several of these fungi primarily, *Trichoderma* spp., as sources of enzymes because of their considerable research on them and exploitation of their biopesticides and biocontrol properties (Mukherjee et al. 2022). Numerous plant responses such as improved abiotic stress tolerance, nutrition usage effectiveness, and organ growth and morphogenesis are also produced. These fungi endophytes may be classified as biostimulants based on their actions, despite the fact that they are currently used in agriculture and marketed as biopesticides (Laurent et al. 2020).

2.6 *Beneficial Bacteria*

Bacteria engage in a variety of interactions with plants (Vasseur-Coronado et al. 2021): (i) bacterial niches usually found in the soil and in the cell interior as well, with intermediate locations in the rhizosphere; (ii) connections can be temporary or long lasting, and some bacteria can even spread vertically through seeds; and (iii) activities that affect plant life include participation in biogeochemical cycles, nutrition delivery, improved nutrient use efficiency, development of disease resistance, and improved resistance to abiotic stress (Sani et al. 2022).

Two primary types of biostimulants should be taken into account with reference to their usage in agriculture: (Ahmad et al. 2008) mutualistic rhizospheric plant growth-promoting rhizobacteria (PGPRs) and mutualistic endosymbionts of the rhizobium type. Rhizobium and related taxa are sold as biofertilizers, or microbial inoculants, that help plants absorb nutrients (Babalola 2010).

All elements of plant life, including growth and nutrition, reaction to different stresses and relationship with other species in agroecosystems are influenced by PGPRs, which have multiple functions (Vasseur-Coronado et al. 2021). Many of these functions are typically carried out by the same species, whereas others depend on synergisms between bacteria in bacterial consortia or are strain specific (Gaiero et al. 2013). This complexity together with the varying reactions of the plant cultivars and the receiving settings place restrictions on the application of PGPRs in agriculture. Additionally, the composition of the inoculants' technical challenges leads to variable outcomes in practice (Mishra et al. 2022). Besides this, global marketing for biostimulants is expanding and PGPR are increasingly considered to be a type of plant "probiotics," that is effective provider of nutrition and immunity for plants (Luziatelli et al. 2015).

3 Common Features of Biostimulants

It is only appropriate to refer to the described compounds and microorganisms as biostimulants if they share some crucial traits related to their natures, functions, and/or uses. The basis for any definition would then be such qualities. The following inferences can be made from the review of the literature about biostimulants that they can enhance the crop quality, nutrient uptake and increase efficiency of plants to mitigate environmental stresses rather than these they also decrease demand for fertilizers and water (Philippot et al. 2013).

3.1 *Diverse Nature of Biostimulants*

The chemicals discussed in this review are either inorganic molecules or organic compounds that are created naturally. However, synthetic compounds cannot be disregarded, particularly if biostimulants contain some plant growth regulators (for instance, nitro-phenolates) are marketed as "biostimulants," (Zarzecka et al. 2019). Single strains of microorganisms, such as *Bacillus subtilis* and combinations of other microorganisms that exhibit synergistic effects may be present in microbial inoculants (Chaudhari 2017; Hassan et al. 2019). It must be made clear in any regulation definition whether ingredients and finished products (or both) are truly covered (Gianinazzi et al. 2010).

3.2 Physiological Functions of Biostimulants

We define physiologic function as any impact on plant metabolic process (Tanveer et al. 2015). The preservation of photosynthesis-related materials against photo damage or the formations of lateral roots are two examples of physiological functions controlled by biostimulants. These are controlled by the cellular processes such as the ability of antioxidants to scavenge reactive oxygen and increase auxin transporters production. The "modes of activities" of the biostimulants, taken collectively, can be described as physiological processes and the underlying cellular mechanisms. Finally, these mechanisms of action give explanations for how biostimulants work in agriculture, such as increasing resistance to different abiotic stress (which results in oxidative stress) or increasing nitrogen use efficiency. Eventually, the functions of agriculture may result in gains for the economy and the environment, such as increased agricultural production, fertilizer cost savings, improved crop product quality and profitability, and improved ecosystem services (Mahmood et al. 2021).

All biostimulants have effects that have been scientifically proven to improve the agricultural functions: nutrient utilization, abiotic stress resistance, and/or crop quality attributes. Qualities include grain protein content, shelf life, and nutritional value. Any definition of biostimulants should be based on these convergent activities (Rouphael and Colla 2020). Many of the previously known biostimulants also work as elicitors and plant gene regulators to stimulate the pathogen response (chitosan, laminarin, some PGPRs, etc.). However, regulators and stakeholders are coming to an understanding that it is the best to maintain biostimulation and biocontrol distinct from a regulatory standpoint. As a result, biological stress is excluded from the definition (Yang et al. 2014) (Fig. 24.2).

4 Roles of Biostimulants in Agriculture

In agriculture, biostimulants play a vital role in increasing the yield of various crops in optimum conditions. Recently, innovative techniques have been developed to minimize fertilizers pesticides use and enhance agricultural production. One of the environment friendly techniques for sustainable agriculture is the use of biostimulants (Huang et al. 2021).

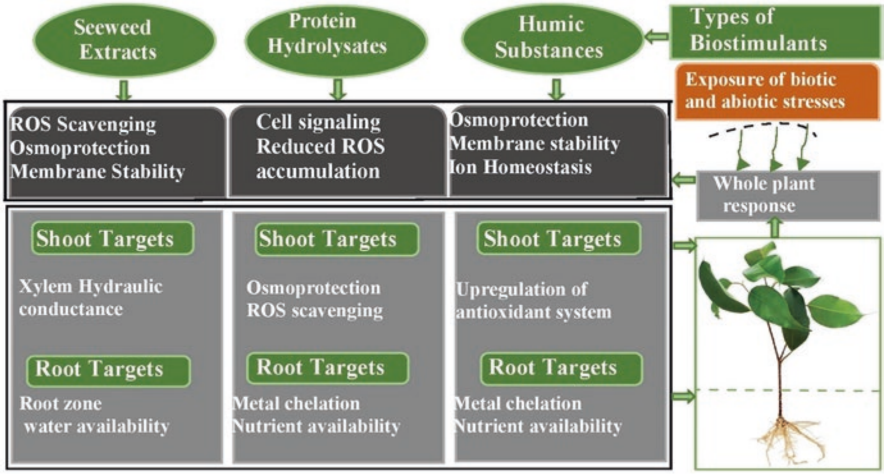

Fig. 24.2 Chitosan stimulates the accumulation of antioxidants in plants (Sani et al. 2022)

4.1 Promote Plant Growth

Recent researchers are focused on the mechanisms underlying plant biostimulants' favorable impacts on plant productivity, such as increasing photosynthesis, growth, nutrient absorption, and water efficiency (Yakhin et al. 2017). Plant metabolism and enzymatic activity can be stimulated by biostimulants, which can also increase crop output and quality (Xu and Geelen 2018). It was shown that humic substances of organic waste origin can function as biostimulants to aid in crop growth, increase enzyme functions, and foster nutrient mobilization in maize (Farooq et al. 2021). For instance, using HSs made from cow waste vermicomposting decreased the amount of total carbohydrates, fructose, and glucose in maize leaves while increasing the amount of starch, indicating that starch plays a role in the metabolism of N and C (Olivares et al. 2015). Worm tea and worm-bed leachate are common names for the leachate produced during the vermicomposting process, which is thought to be a by-product that helps crops develop. Many HSs and other biostimulants are present in the leachate, which may aid in plant development by increasing the number of roots, encouraging macro- and micronutrient uptake, and fostering resistance to diseases and herbivores (Abbas et al. 2015). Vermicomposting could make up for the declining output (Hassan et al. 2018). Results also showed that when compared to conventional compost without the addition of larvae, larvae bioconversion compost had a stronger ability for organic matter to biodegrade.

4.2 Counteract Abiotic Stresses

Plant biostimulants are highly intriguing for commercial uses because just small doses are necessary to boost a plant's resistance to various stimuli (Del Buono 2021). It is widely seen that seaweed biostimulants, especially understressed chlorophylls, can increase the color content (Akladious and Abbas 2013). Similar outcomes were observed with orange and citrus, where the algal-based biostimulant completely reversed the biomass drop brought on by dryness (approximately 50%) (Goñi et al. 2018). Seaweed extracts improved the transcription of genes involved in stress responses, DNA repair, and plant nutrition seen from the standpoint of transcription (Aamir et al. 2020). When applied to plants, bioconversion compost has some capacity to withstand abiotic stressors and is rich in biostimulants (Tabacchioni et al. 2021; Rasheed et al. 2022). Vermicompost extract, for instance, has been found in tests to boost ROS scavenging enzymes and activate antioxidant enzymes in rice (*Oryza sativa* L.) (Vargas-Hernandez et al. 2017). In conclusion, biomass conversion compost includes a range of biostimulants that can increase plant resistance to abiotic stresses and therefore promote the growth of sustainable agriculture. These stimulants also help in plants growth and development (Fig. 24.3).

5 Conclusions

In agriculture, the use of plant biostimulants as alternative technique over traditional techniques seems to be gaining popularity and studies revealed how beneficial they are. The ability of biostimulants to enhance plant growth and development, nutrient uptake, yield, and water content, as well as the nutritional value and quality of their products make them vital for agriculture sector to enhance growth and yield of

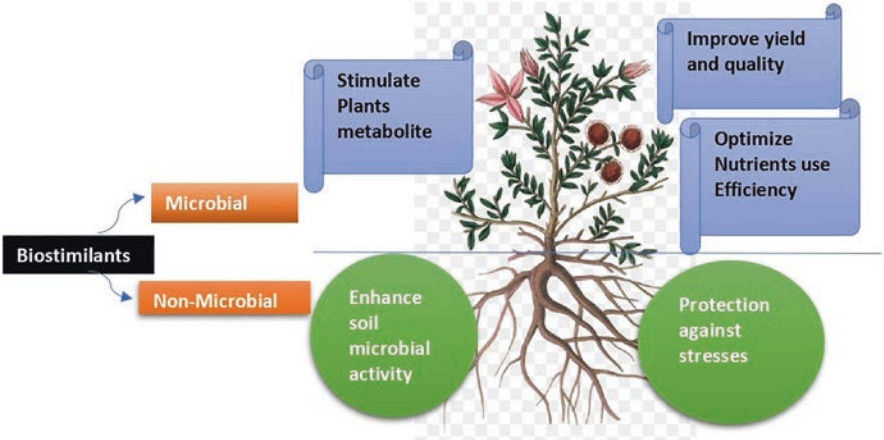

Fig. 24.3 Impacts of microbial and nonmicrobial biostimulants on different parameters of plants (Sani et al. 2022)

plants. Additionally, biostimulants also offer a way to mitigate the inevitable impacts of abiotic stress brought on by soil pollution and climate change in the agronomic sector. The effects of biostimulants vary depending on the crop species, the extraction/production methods used, the amounts of components present, the bioactive used, and even how various biostimulants behave within the same species.

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Chapter 25

Vermicompost for Sustainable Future: Nature-Based Solution for Environmental Degradation, Climate Change, and Food Security

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Abstract With the exponential rise of the world's population, there is great pressure on industry, agriculture, and other associated sectors. High generations of different types of wastes and greenhouse gases (GHGs) from industries, and agriculture sectors have raised several issues such as difficulties in waste handling and global warming. Composting waste into a valuable product can reduce waste handling costs, increase agricultural productivity, and reduce GHGs emissions. However, traditional composting methods have certain limitations, such as it takes a long time, generating low-quality compost, and even releasing GHGs. Contrarily, vermicomposting involves compost preparation with the help of suitable earthworm species, is an efficient and cheap technique, saves time, and emits minute quantities of GHGs. Vermicompost has the potential to be used for efficient waste management, soil rehabilitation, biogas generation, and agricultural sustainability. Moreover, vermicompost has great potential to rehabilitate soils having several issues, such as heavy metals (HMs), drought, and salinity. Food security can be achieved by using vermicompost because it boosts yield, nutritional quality, and biochemical compounds while reducing the pest attack on the plants. The usage of vermicompost not

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only reduces the emissions of GHGs but also improves carbon sequestration in the soil. The biogas generated during vermicomposting can be collected and used to replace other nonrenewable resources. However, further research is needed to augment the quality of vermicompost, methods for its preparation, and optimum doses to obtain more precise results.

Keywords Global warming · Vermicomposting · Biogas · Heavy metals · Carbon sequestration

Abbreviations

$^\bullet HO$	Hydroxyl radical
$^1O_2$	Singlet oxygen
$CaCO_3$	Calcium carbonate
CH_4	Methane
CO_2	Carbon dioxide
GHG	Greenhouse gas
H_2O_2	Hydrogen peroxide
HMs	Heavy metals
MSW	Municipal solid waste
N_2O	Nitrous oxide
$O_2^{\bullet-}$	Superoxide anion
OM	Organic matter
PGRs	Plant growth regulators
ROS	Reactive oxygen species

1 Introduction

The United Nations prediction report about population shows that approximately 9.7 billion people will inhabit the planet by 2050. The Food and Agriculture Organization estimated that over 1.3 billion tons of food are wasted annually (Zaman and Yaacob 2022). Moreover, the amount of waste from industries, residential zones, and agribusiness has significantly increased over the last couple of years (Kaur 2020). These different types of organic waste forms are accumulating at an alarming rate and must be treated properly to avoid environmental damage (Kakati et al. 2022). Unfortunately, billions of tons of greenhouse gases (GHGs) are also produced from this organic waste, which negatively influences the environment. The food waste is decomposed anaerobically and releases methane (CH_4), having several times more hazards than carbon dioxide (CO_2) (El Bilali and Ben Hassen 2020). According to reports, municipal solid waste (MSW) in residential areas is the third-greatest origin of anthropogenic CH_4 release and accounts for 11% of entire CH_4 release worldwide (Singh et al. 2018a). Unfortunately, CH_4 is a significant GHG contributing to global warming (Tiwari et al. 2020).

Another source of GHG emissions is chemical fertilizers used in agriculture to enhance crop yield and plant growth (Allam et al. 2022). Chemical fertilizers have been used for decades to meet the world's increasing demand for agricultural supplies. However, excessive and improper use of these fertilizers has created several environmental threats such as soil nutrient depletion, acidification, eutrophication, reduced biological diversity, and significantly increased amount of GHGs in the atmosphere (Walling and Vaneeckhaute 2020; Sun et al. 2019). Using chemical fertilizers decomposes the organic matter (OM) and deteriorates the structure of the soil, which results in the loss of nutrients through leaching, fixation, and gas emission (Roba 2018). Furthermore, chemical fertilizers damage soil organisms and limit the mycorrhizal colonization of plant roots (Bhatt et al. 2019). The roots of the crops only up take roughly half of the nitrogen (N) they receive from fertilizers. At the same time, the remaining is released into the atmosphere in the form of nitrous oxide (N_2O) by volatilization and denitrification (Meyer and Newman 2020). Currently, there is a serious issue of global climate change. The industrial revolution has also played a pivotal role in the emission of GHGs (CO_2 and CH_4), which caused a steady rise in the planet's average yearly temperature and contributed to global warming (Mikhaylov et al. 2020).

The concept of recycling garbage into vermicompost may be a novel approach. Vermicompost sometimes is referred to as "Black Gold." Additionally, using vermicompost prepared from waste promotes the restoration of essential nutrients to the soil. The nutrients found in vermicompost are easily assessable by the plants (Singh and Singh 2017). As the population increases and food supplies become limited, vermicompost keeps the ability to assure practicability in agriculture, which is crucial since it is one of the ways to meet food demands (Zaman and Yaacob 2022). Vermicomposting is an efficient, and ecologically beneficial approach, currently attracting much attention from researchers worldwide. Moreover, recent studies have shown that the controlled vermicomposting process lowers GHGs emissions (Lv et al. 2018; Rini et al. 2020).

2 Vermicompost

2.1 Characteristics and Processing of Vermicompost

The excreta produced by earthworms are called vermicompost, which can improve soil nutritional quality and health (Begum and Bora 2018). Vermiculture is a process in which biodegradable wastes such as kitchen wastes, farm wastes, horticultural residues, animal wastes, and food production wastes are transformed into nutrient-rich vermicompost after passing through the worm gut. The vermicompost contains a high concentration of macronutrients and micronutrients. Additionally, vermicompost benefits soil microorganisms and enhances soil hormones (cytokinin, gibberellin, and auxin) (Yatoo et al. 2021). In some aspects, vermicompost varies from composting. Vermicomposting is a mesophilic method that employs earthworms and microbes operative at temperatures ranging from 10 to 32 °C (temperature of moist organic material in a pile) (Wako 2021). The process of vermicomposting is quicker than other composting methods. The substance changes its characteristics as it goes through the worm's stomach. The end product has higher microbial activity, plant growth regulators (PGRs), and pest-repellent properties (Kaur 2020). In brief, earthworms may convert waste into "gold" through biological alchemy (Begum and Bora 2018).

2.1.1 Environmental Conditions and Precautions During Vermicomposting

The most suitable condition for vermicompost to thrive is in a dark place with a humid environment to avoid direct sunlight, with an ambient temperature, pH, C: N ratio, and moisture content. Moreover, the salt content needs to be lower than 0.5%, and ammonia (NH_3) should be <1 mg g^{-1} (Kaur 2020). Depending on the budget, vermicomposting can be done in cement tanks, wooden boxes, or clay pits lined with plastics. Composting in pits, bins, and piles is the most systematic and simple vermicomposting method. Covering the chamber with wet cloth in all vermicomposting processes is critical to avoid contact with the sunlight and preserve moisture (Kakati et al. 2022).

During vermicomposting, the following precaution should be taken (Barman et al. 2020):

- *Eisenia fetida* and *Eudrilus eugenae*, two African earthworm species, are most suitable for vermicompost processing. The majority of Indian species are unsuitable for the task.
- Vermicompost should only be prepared from organic resources such as leaves, vegetable peelings, or grass.
- Animal-derived materials such as bone, eggshells, chicken excreta, and flesh are not ideal for vermicomposting.
- Birds, termites, ants, and rats should be kept away from earthworms.
- During the procedure, sufficient moisture should be maintained. Earthworms might be killed by either stagnant water or a lack of moisture.
- When the vermicomposting is completed, it has to be collected and replaced with new organic waste material.

2.2 *The Most Suitable Types of Worm for Vermicomposting*

Various earthworm species can help with waste stabilization and management. Choosing the proper worm species is essential because it affects the rate of waste stabilization (Kundariya et al. 2021). Earthworm species can colonize in organic waste, rapid digestion of OM and assimilation, and large production of cocoons help them resist various stresses present in the environment (Itelima et al. 2018; Singh et al. 2020a). According to the research, *E. fetida* is an African earthworm species with the potential for vermicomposting. It generates many cocoons during composting and can withstand various environmental conditions (imbalance temperature and moisture content) (Singh et al. 2018b). *Eisenia fetida* and *Lumbricus rubellus* are two common banded earthworms used in vermicomposting. They have alternating red and buff stripes and are usually seen in old manure piles. Several studies have been conducted to use epigeic earthworms such as *E. eugeniae*, *E. andrei*, *E. fetida*, and *Perionyx ceylanesis* to convert organic waste into worm excrement, which may be used as a soil conditioner or organic fertilizer (Soobhany 2019; Tauseef et al. 2021; Karmegam et al. 2019; Kauser and Khwairakpam 2022). *E. eugeniae* is extremely effective in quickly decomposing a variety of organic materials such as water hyacinth (Snehalata and Rao 2018), rubber leaf litter (Getachew et al. 2018), neem leaf litter (Martin et al. 2020), and sewage sludge (Avili et al. 2018) into vermicompost.

3 Environmental Remediation

3.1 *Solid Waste Management*

In the age of urbanization and rising consumption, the amount of MSW production in emerging nations has increased massively. About 1.30 billion tons of waste annually is produced in urban areas worldwide. The figure is expected to rise to about 2.20 billion tons by 2025 (Ram et al. 2021). Adequate segregation, processing, and organic waste recycling can all assist in alleviating the growing problem of MSW in the environment. Vermicomposting is a low-cost method for recycling MSW. The composting period of different worms to compost various wastes has been shown in Table 25.1.

3.2 *Wastewater Treatment*

Rapid urbanization, population growth, industrialization, and other human activities result in the significant exhaustion of basic materials (Singh and Singh 2017). Due to inadequate wastewater treatment, the amount of clean water for agriculture,

Table 25.1 Time period to compost various wastes with different worms

Type of waste	Amendment/ waste	Species of earthworm	Composting period	References
Food waste	Clinoptilolite zeolite	*Eisenia fetida*	70 days	Zarrabi et al. (2018)
Medicinal herbal residues	Cattle drug	*Eisenia fetida*	49 days	Chen et al. (2018).
Ruminant excreta	–	*Eisenia fetida*	90 days	Sharma and Garg (2017a)
Milk industry sludge	Cattle drug	*Eisenia fetida*	90 days	Singh et al. (2017b)
Paper cup waste	Cow drug	*Eudrilus eugeniae*	90 days	Arumugam et al. (2018)
Urban plant litter	–	*Eisenia fetida*	60 days	Wu et al. (2018)
Kitchen vegetable waste	Paddy straw	*Eisenia fetida, Eudrilus eugeniae, and Perionyx excavatus*	50 days	Hussain et al. (2018)
Food and vegetable waste	Buffalo dung	*Eisenia fetida*	90 days	Sharma and Garg (2017b)
Shredded paper, cattle manure, and lawn clippings	–	*Perionyx excavatus, Eudrilus eugeniae, and Dichogaster annae*	56 days	Martin and Eudoxie (2018)
Tea factory coal ash	Cow dung	*Eisenia fetida and Lampito mauritii*	60 days	Goswami et al. (2014)
Sewage sludge	Grass clippings, sawdust, and MSW	*Eisenia fetida*, *Eisinea andrei*, and *Dendrobaena*	45 days	Suleiman et al. (2017)
Sugar industry wastes	Farm manure	*Lumbricus rubellus*	45 days	Shah et al. (2015)
Municipal sewage sludge	Sewage sludge-derived biochar	*Eisenia fetida*	42 days	Malińska et al. (2017)
Dewatered sludge	–	*Bimastus parvus*	60 days	Fu et al. (2015)

residential use, and other activities has been reduced (Singh et al. 2017a). Treating wastewater through treatment plants is a traditional technique of wastewater management, but it produces a large amount of sludge as a byproduct. Moreover, in recent years, the cost of maintenance and operations of wastewater treatment plants has been the main issue in managing the treatment of wastewater (Li and Yang 2018; Shen et al. 2020). The biological procedure is more effective than other wastewater treatment methods regarding temperature, pH, and organic loading rate adoption. Furthermore, aerobic biological systems are more effective than anaerobic systems (Singh et al. 2017a). Interestingly, vermifilter was initially used to treat household sewage but is now also used for industrial wastewater treatment (Ghasemi et al. 2020). According to a study, vermifiltration technology sought to lessen the downstream pollution caused by sewage (Manyuchi et al. 2018). The treatment of wastewater using the

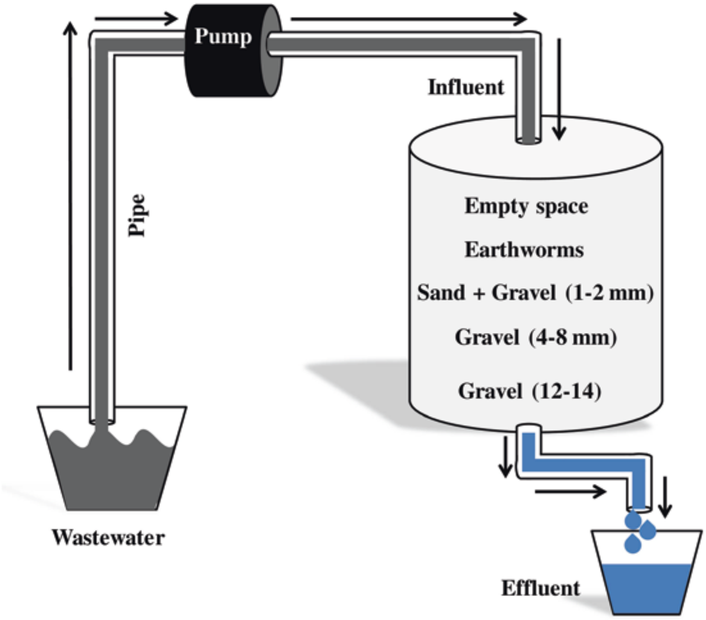

Fig. 25.1 A model vermifilteration setup for the treatment of wastewater

vermifiltration process results in vermicompost and clean effluent, which can be used as biofertilizers (Singh et al. 2020b). The vermifiltration technique requires the optimization of several aspects, such as hydraulic loading rate, hydraulic retention duration, recirculation ratio, earthworm abundance, organic loading rate, and reactor type OM (Lourenço and Nunes 2017). Another hybrid approach for treating wastewater is the combined usage of a macrophyte filter with earthworms. This technique is very cost effective for treating wastewater in underdeveloped nations (Samal et al. 2018). Using natural components such as glass balls, mud balls, river bed material, and wood coal enhances vermifiltration efficiency. The indicator organisms, such as total coliform, fecal streptococci, fecal coliform, and *Escherichia coli*, were reduced by river bed debris. The vermicompost collected at the end of the procedure has higher phosphate and nitrate contents and can be utilized in sewage farming (Kumar et al. 2015). A model vermifilteration setup for wastewater treatment is shown in Fig. 25.1.

3.3 Mitigation of Soil Stresses

3.3.1 Remediation of Heavy Metals Polluted Soil

It is common knowledge that industrialization and urbanization play a major role in the direct or indirect damage to the environment. The most notable pollutants are heavy metals (HMs) and organic pollutants, which constitute a major issue on a global scale. Vermicomposting and vermicompost itself may have other beneficial environmental impacts, such as remediation (Bhat et al. 2018). There is a need for gentle and environmentally friendly solutions even though there are several physical, biological, and chemical ways to manage these pollutants in water and soil. According to research, vermicompost has the potential to be an environmentally friendly alternative to several harsh treatment techniques (Shi et al. 2020). The HMs are nonbiodegradable and have the propensity to enter food chains, posing a potential threat to all living things. Understanding how bacteria and earthworms can impact HMs availability and bioaccumulation during vermicomposting is crucial. According to a study, adding vermicompost lowers the amount of HMs transferred to the wheat plant after immobilizing nickel (Ni), lead (Pb), and cadmium (Cd) in the soil (Kheir et al. 2021). Similarly, a study concluded that Cd availability was lowered after the treatment of the soil with vermicompost under acid rain (Wang et al. 2018). Several humic compounds and soluble salts are found in mature vermicompost, which has different functional groups (-CO, -COOH, -NH, and -OH) (de Aquino et al. 2019; García et al. 2013). Humic acids can combine with HMs ions to generate organometallic complexes. Because of the coordination sites for metal ions provided by carboxylic and phenolic groups, humic compounds from vermicompost can effectively bind HMs (Chen et al. 2015; Vuković et al. 2021). In sediments, adding vermicompost immobilized the Cd, chromium (Cr), and Pb. It was also noted that different humic compounds produced organometallic complexes with all three HMs (Zhang et al. 2019).

3.3.2 Reclamation of Saline Soil

Plants treated with vermicompost become more resistant to salt stress (Makkar et al. 2022). The reduction in the salinity depends upon the amount of vermicompost added to the soil (Kiran 2019; Sorkhi 2021). The vermicompost treatment significantly enhanced soluble proteins, K/sodium (Na) ion ratio, and Ca/Na ion ratio. Vermicompost also decreased salt-induced crop loss (Iqbal et al. 2020). According to a study by Bidabadi et al. (2017), spraying of vermicompost leachate on *Punica granatum* reduced the quantity of Na ions uptake during germination by promoting salt tolerance. Salinity is known to reduce the photosynthetic activity of the plant. Incorporating vermicompost into the soil also improves the chlorophyll fluorescence parameters of the leaves (Benazzouk et al. 2018).

3.3.3 Coping with Drought-Stressed Soil

According to recent studies, supplying vermicompost to plants under water-deficit conditions improved plant development (Makkar et al. 2022). Vermicompost improved leaf-soluble carbohydrates and nutrient absorption in *Matricaria* *chamomilla* L. (German chamomile) (Salehi et al. 2016). Similarly, plant osmotic processes were maintained by high sugar content in the leaves of sugarbeet (Ghaffari et al. 2022). Vermicompost enhanced green bean productivity and minimized the impact of drought (Nouriyani 2018). Furthermore, Hosseinzadeh et al. (2017) reported that using vermicompost under moderate and severe water stress improved chickpeas' morphological parameters and fruit quality (*Cicer arietinum*). Under drought stress, oxygen radicals, phenols, and enzymes decrease the chlorophyll concentration, while vermicompost treatment invariably increases the chlorophyll and other pigment content (Salehi et al. 2016). So, vermicompost might indemnify watering disruptions, alleviating drought impacts (Aguilar et al. 2017).

4 Food Security

4.1 Crop Yield and Growth

The addition of the vermicompost has shown the enhancement of the fresh/dry weight and shoot height of tomato (*Solanum lycopersicum*) (Awadhpersad et al. 2021), cucumber (*Cucumis sativus* L.) (Tith et al. 2021), hot pepper (*Capsicum annuum*) (Aminifard 2022), kale (*Brassica oleracea*), and radish (*Raphanus sativus*) (Calderon and Mortley 2021). The biochemical and morpho-physiological parameters were improved by vermicompost leachate (Adamipour et al. 2019). Vermicompost has been shown to increase soil microbial activity and nutrient availability, as well as control the process of producing PGRs. During vermicomposting, microbial diversity and earthworms contribute plant growth hormones-like compounds such as humic acid/fulvic acid to organic materials (Wong et al. 2020). The PGRs present in the vermicompost have been proposed as one of the variables that may contribute to improved yield and plant growth (Blouin et al. 2019). These PGRs are synthesized by bacteria and are already present in vermicompost. After adding aqueous extracts of vermicompost, the growth patterns of a few ornamental plants resembled those achieved by natural plant hormones such as cytokinin, gibberellin, auxin, and, particularly in *Coleus*, *Petunia*, and *Begonia*, indicating that earthworms are responsible for producing plant hormones (Makkar et al. 2022). Direct secretions of PGRs by earthworms and microbes in soil may have a cumulative impact (Ahmed and Al-Mutairi 2022). Yatoo et al. (2021) demonstrate that supplementing vermicompost with cow manure and other organic additives resulted in nutrient-rich vermicompost, which could positively favor agricultural productivity.

4.2 Nutritional Quality of Plants

The microorganisms are introduced into the plant's rhizosphere using vermicompost, which boosts the availability of N, phosphorus (P), and potassium (K) by altering their bioavailability (Turp et al. 2021; Elhaissoufi et al. 2021; Dubey et al. 2019). The geranium (*Pelargonium* species) nutrient contents were increased with the addition of vermicompost (Gong et al. 2018). The K and calcium (Ca) contents increased in the root and leaf of chickpea under various water-deficit conditions after applying vermicompost in the soil (Hosseinzadeh et al. 2018). Vermicompost improved the accessibility of major nutrients in tomatoes (*Lycopersicum esculentum*) (Ebrahimi and Ghorbani 2020), as well as P, K, and Ca contents in weeds (Aung et al. 2020). The addition of vermicompost showed to enhance the nutrients (N, P, K, zinc (Zn), iron (Fe), and manganese (Mn)) in the shoot and bulb of the sweet fennel (*Foeniculum vulgare*) (Abd El-Rheem et al. 2019). Vermicompost application increased the N, P, and Ca contents in kale (*Brassica oleracea*), N and K contents in radish (*R. sativus*), and N, P, K, and Fe contents in tomato (*L. esculentum*) (Calderon and Mortley 2021). Nitrogen, P, K, Zn, and Fe contents increased in the chicory by adding vermicompost (*Cichorium intybus*) (Gholami et al. 2019). Similarly, the nutrients (Cu, Fe, Mn, Zn, magnesium (Mg), Ca, N, P, and K) contents were boosted in three different species of rose (*Pegasus patio, Pelargonium peltatum, and Vinca rosea valiant*) after treatment of soil with vermicompost (Esringü et al. 2022). Vermicompost improves the soil conditions, resulting in greater K and Ca concentrations in the roots and leaves of lentils (*Lens culinaris* Medik.) (Hosseinzadeh and Ahmadpour 2018).

4.3 Biochemical Compounds in Plants

In a field experiment, researchers discovered the impacts of tea made up of poultry fertilizer and vermicompost on the biochemistry of basil. The highest phenol concentration and antioxidant activity were achieved when vermicompost tea was diluted in the soil. Organic compost tea may boost secondary metabolites in fragrant medicinal plants (Javanmardi and Ghorbani 2012). Fertilization using vermicompost has the power to enhance a plant's bioactive qualities. When vermicompost was added to the soil, it was found that date palm had higher amounts of phenolic compounds. This is caused by humic acid and the gradual liberation of nutrients accessible to plants. Plants use their phenolic content as a defense strategy against harmful bacteria (Al Jaouni et al. 2019). Vermicompost-treated plants exhibited much greater phenolic and flavonoid contents than plants cultivated with mineral fertilizers (Yusof et al. 2018). A study reveals that after treating the soil with vermicompost, the content of carotenoid in chickpeas (*C. arietinum* L.) was enhanced under various water stress conditions

(Hosseinzadeh et al. 2018). Correspondingly, a study found that adding vermicompost under water-deficit and waterlogging conditions boosted the protein content in *Moringa oleifera* (Guzmán-Albores et al. 2020). The rice had higher carotenoid contents after adding vermicompost (Ruan et al. 2021). Lahbouki et al. (2021) reported in a study that vermicompost-conditioned soil showed enhancement in the contents of protein and soluble sugar in prickly pear cactus (*Opuntia ficus-indica*).

4.4 Reducing Oxidative Stress in Plants

During the whole lifecycle, plants are subjected to several environmental pressures. Stress tolerance and plant growth necessitate reactive oxygen species (ROS) (Huang et al. 2019). Chloroplasts, plasma membranes, peroxisomes, and mitochondria are the primary sources of ROS. Although ROS synthesis is a normal aspect of plant cellular metabolism, the excessive buildup can harm cellular components such as DNA, lipids, carbohydrates, and protein (Kumar et al. 2019). Excess ROS components, such as superoxide anion ($O_2^{\bullet-}$), hydroxyl radical ($^{\bullet}OH$), hydrogen peroxide (H_2O_2), and singlet oxygen ($^1O_2$), can lead to oxidative stress and induce cell death or damage. Under optimum conditions, antioxidative defense mechanisms can scavenge excess ROS. A material that reduces, stops, or eliminates oxidative damage from a specific molecule is known as an antioxidant. To regulate ROS formation, vermicompost enhances the level of bioactive components and antioxidant enzymes in plants (Zaman and Yaacob 2022). Nonenzymatic antioxidants such as phenols, glutathione (GSH), ascorbic acid (AsA), alkaloids, and flavonoids can scavenge ROS directly or indirectly. To prevent ROS overproduction, nonprotein amino acids interact with antioxidant enzymes such as peroxiredoxins (PRXs), peroxidase (POX), catalase (CAT), polyphenol oxidase (PPO), and superoxide dismutase (SOD) (Hasanuzzaman et al. 2020). Figure 25.2 shows the pathways through which vermicompost boosts plant antioxidant activity against free radicals under water deficit. After retrieving $O_2^{\bullet-}$, a nonradical ROS (H_2O_2) produces SOD enzymes. The hydroxyl radicle is one of the most dangerous ROS produced when H_2O_2 undergoes the Fenton and Haber–Weiss reactions. To prevent this harmful route, vermicompost treatment can boost several plants' bioactive characteristics and antioxidant enzymes, allowing them to neutralize ROS (Kamanga et al. 2018). The antioxidant activity was boosted by applying vermicompost to the tea plant (Singh et al. 2020a). The date palm fruit demonstrated greater antioxidant activities after treating the soil with vermicompost because of the increased synthesis of bioactive chemicals such as flavonoids, ascorbate, phenolic, and steroid (Al Jaouni et al. 2019). The activities of SOD were observed higher in the strawberry plant after the vermicompost treatment (Zuo et al. 2018).

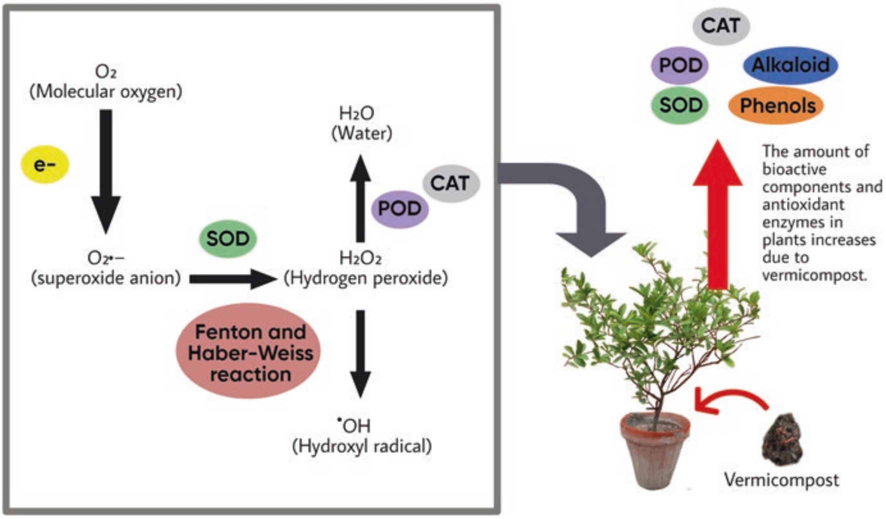

Fig. 25.2 The pathways through which vermicompost boosts plant antioxidant activity against free radicals under water deficit

4.5 Supersession of Plant Diseases and Pests

Certain antibiotics found in vermicompost aid in increasing plant tolerance against diseases and pests. According to a recent study, worm casting helps repel hard exoskeletons pests. It happens because the worm produces chitinase responsible for chitin degradation in the external skeleton of insects (Zaman and Yaacob 2022). When pepper, tomato, and cabbage plants were grown in vermicompost-treated soil, there was a significant reduction in insect population and less plant damage (Adhikary 2012). Vermicompost applied to crops has also been demonstrated to reduce soil-borne plant diseases and nematodes. Furthermore, vermicompost treatment remarkably reduced the prevalence of numerous plant diseases in okra, including powdery mildew, yellow vein mosaic, and collar rot (Zaman and Yaacob 2022). The abundant microbes in vermicompost would defend plants by competing for scarce food sources with pathogens, for example, by malnourishing them and engaging all accessible locations to block their accessibility to plant roots (Adhikary 2012). Vermicompost boosts the fertility of the soil by increasing microbial activity, forcing plants to produce more enzymes and plant growth-regulating hormones. Likewise, microbes can deviously manage plant pests, nematodes, and diseases, lowering crop loss (Pathma and Sakthivel 2012).

5 Climatic Benefits of Vermicompost

5.1 Carbon Sequestration

Several species of earthworm, particularly the *Lumbricidae* family, are real biomineralizers because they have specialized calciferous glands that produce calcium carbonate ($CaCO_3$) granules (Boonchamni et al. 2019). The calcite is produced in a higher amount from the granules, with tiny amounts of aragonite, vaterite, and amorphous $CaCO_3$. The earthworms' calciferous glands produce the calcite granules by converting CO_2 into bicarbonate and carbonate, which change into amorphous $CaCO_3$ before solidifying as calcite (Brinza et al. 2013; Kavehei et al. 2018). The earthworm's esophagus receives the calcite granules created in the calciferous glands. Later, the particles go to the gut and are eventually released into the soil (Hodson et al. 2015). The possibility of carbon sequestration is one of the causes that granule secretion has been suggested.

Furthermore, earthworms are employed in the vermicompost process to transform OM into a humus-like substance (vermicompost) (Muralikrishna and Manickam 2017). Organic matter humification has been shown to speed up by 40 to 60% more than during natural composting (Sharma and Garg 2018). Vermicompost qualifies as a climate-smart soil management technique because of its low CO_2 emissions and slow decomposition rates (Hossain et al. 2017). Once the OM is consumed by earthworms and turned into humus, a significant amount of the OM is transferred to the soil pool (Wong et al. 2020). The earthworm's feeding and digging activities, together with the strong microbial activity taking place in its stomach, fragment, aerate, and turnover of OM, which speeds up the humification process (Edwards and Arancon 2022; Lemtiri et al. 2014). Additionally, adding vermicompost to the soil increases carbon sequestration, thus lowering the release of GHGs into the atmosphere (Lim et al. 2016).

5.2 Reduction of Greenhouse Gases and Global Warming

Vermicomposting is a mesophilic process that begins in the active phase and ends in the maturation phase, according to the nature of the earthworm and microorganisms. Microorganisms release GHGs and volatile compounds during vermicomposting (Yasmin et al. 2022). In a study, N_2O emissions were higher, but CH_4 emission was reduced during the preparation of vermicompost from sewage sludge (Lv et al. 2018). Additionally, earthworms activate denitrifying bacteria that produce N_2O because they have a large population of them inside earthworms intestines, both aerobic and facultative anaerobic, and in casts of worms (Swati and Hait 2018). Additionally, the wastes pass through the gut, broken down by bacteria and enzymes, becoming simpler forms like humic compounds and emitting considerable amounts of CO_2 (Sharma and Garg 2019). The early stages of vermicompost also produce CO_2 emissions much higher than CH_4 emissions. Compared to simple composting, vermicompost reduces CH_4 emissions (Lv et al. 2018). The aerobic conditions, which are sustained by earthworm burrowing activities during the preparation of vermicompost, are what cause the reduction in CH_4 emissions (Swati and Hait 2018). According to another study, the emission of CH_4 and N_2O was less during vermicomposting as compared to traditional composting (Nigussie et al. 2016).

Similarly, less emission of CH_4 was observed during the vermicompost process at low temperatures (Chan et al. 2011). In addition to successfully transforming duck manure into organic fertilizer, the combined precomposting and vermicomposting with additions of reed straw and zeolite also dramatically reduced the emissions of CH_4, NH_3, and N_2O during the biodegradation of duck manure (Wang et al. 2014). In conclusion, vermicomposting is a viable option for reducing the emissions of GHGs in low-income countries where the prevailing solutions are not cost effective and have difficulties in their implementation (Nigussie et al. 2016).

5.3 Production of Biogas

The majority of gases emitted by landfills can be utilized as biogas, a sustainable origin of energy (Singh et al. 2018a). Anaerobic digestion of organic waste results in the spontaneous generation of biogas, a type of biofuel. Carbon dioxide, hydrogen sulfide (H_2S), and CH_4 are the main components of biogas (da Silva et al. 2017). According to the European Union, biogas has the possibility to provide 25% of renewable electricity. It may be used to heat buildings, produce electricity, and replace other energy sources that release GHGs. This biofuel can protect the environment from pollution by limiting the quantity of waste broken down in the open air and lowering the chance of alluring disease-harboring sources. It has been discovered that pretreating the wastes with vermicompost before anaerobic digestion can assist boost biogas generation (Zaman and Yaacob 2022). Vermicompost pretreatment of cornstalks boosted biogas generation (63–65% CH_4) in comparison to corn stalks digested independently (Chen et al. 2010). Vermicompost accelerates the rate at which organic wastes decompose while expanding the surface area on which anaerobic bacteria may hold onto nutrients. These enable more effective chitin degradation by the anaerobic microorganisms and boost biogas generation (Singh and Singh 2017).

6 Conclusions and Recommendations

Vermicompost has shown its efficacy in agriculture to produce humic acid, generate PGRs, enhance plant nutrient availability, and improve soil health. Furthermore, vermicompost helps the plants overcome several stresses (drought, salinity, and HMs), suppress various diseases, minimize pest activities, and improve plant yield.

Apart from it, vermicompost also has the potential to reduce the amount of solid waste by converting it into a nutrient-rich soil amendment and minimizing the emission of various GHGs. On the other hand, vermicomposting can also help collect biogas that can replace other nonrenewable resources. Therefore, vermicompost can be referred to as a sustainable and eco-friendly soil amendment recommended for sustainable agriculture and climate change mitigation. Further research is needed to improve the quality of vermicompost, methods, and application doses to obtain more precise results.

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Chapter 26
Biofertilizer: Boon for Sustainable Sugarcane Production

Varucha Misra and Ashutosh Kumar Mall

Abstract Agriculture is one of several human activities that contribute to chemical pollution through chemical fertilizers for increasing growth, production, and productivity. Indiscriminate use of chemical fertilizers had been rapidly increased all through the world, increasing their contribution to soil and water pollution. Arbitrary usages of fertilizers are also causing contaminants to add up in the soil. These soil contaminants (arsenic, lead, copper, chromium, etc.) are also causing soil infertility for crops. Furthermore, the cost of fertilizers as well as energy has also been raised due to its over-demand. The application of chemical fertilizers in crops, besides giving benefits in terms of yield and productivity, is also causing a substantial negative impact on human health. To end up the drawbacks of chemical fertilizers, biofertilizers came into light with more positive and beneficial aspects for crop production and productivity. These biofertilizers involve the usage of beneficial microbes and are eco-friendly, less expensive, and are renewable sources of nutrients. Biofertilizers are a solution to the use of fertilizers that act as a source for soil contaminants, which increase in time and get highly accumulated. There are different types of biofertilizers, and the different crop needs the application of different biofertilizers for high yield and productivity. In accordance with this, one important cash crop is sugarcane, which is used for the production of sugar. Usage of *Azotobacter* and *Azospirillum* on this crop revealed a higher yield of 24–42 tonnes per ha when the planting method adopted was raised bed planting. Adding to it, using biofertilizers for any crop is beneficial when its exact mode of action is known. Therefore, this chapter will highlight the contaminants emerging through indiscriminate use of fertilizers, biofertilizers as a solution, their mode of action, and its comparison with chemical fertilizers, besides its usage and effect on sugarcane crop.

Keywords Sugarcane · *Azotobacter* · *Azospirillum* · Contaminants · High yield · Fertilizers · Biofertilizers

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1 Introduction

Nutrients (quantity and balance) are important for optimum plant growth (Chen 2006). Fertilizers are the ones that play an important part in supplying an adequate amount of nutrients to plants and helping them in growth and good harvest. But fertilizers at times contain raw material from unknown sources, and this may cause effects that are not known to us or may give rise to contaminants that harm the soil and crop in another way when used on a long-term basis. The use of fertilizers on crops causes a strong impact on soil health and regulation of ecosystem function through an effect on primary productivity (Singh 2018). Applying fertilizers over crops, though causes benefit, but, on other hand, gives rise to several contaminants that add up to soil. Phosphatic fertilizers are in queue to such fertilizers, which are known to add up contaminants in soil (Khan et al. 2018). Several studies had revealed that even some certified fertilizers may contain trace elements that act as contaminants (Srivastav 2020; Westfall et al. 2005) when accumulated in large amounts. This could happen only when its application over crops increases (Jiao et al. 2012). Furthermore, Jiao et al. (2012) showed that in areas where intensive use of fertilizers has been done, elevation in trace elements such as arsenic (As), cadmium (Cd), and lead (Pb) may cause serious threats to soil contamination, which may further accentuate other negative effects on the crop as well as on human health. Excessive application of fertilizers not only provides soil contamination but even elevates the concentration of a particular element in soil or substance which is of importance to the environment. Such a condition may be correlated to a process known as eutrophication, which involves excess nutrients, but the main concern is the accumulation and availability of nutrients/elements that are toxic to plants and soil as well (Dudka and Miller 1999). Contaminated soil becomes a source of harmful emerging contaminants in the soil such as, Cd, chromium (Cr), nickel (Ni), Pb, copper (Cu), and zinc (Zn). The excessive transfer of these elements to the food chain is controlled by soil–plant barrier, but a few elements including cadmium cause this barrier to fail which in turn causes toxic effects on plants (Dudka and Miller 1999). Emerging contaminants occurring through the use of chemical fertilizers are causing soil infertility, which is known to restrict plant growth (Khosro and Yousef 2012). Restoration of soil infertility can be achieved by the adoption of integrated soil fertility management practices involving a combination of management measures such as biological nitrogen fixation and natural resource conservation (Vlek and Vielhauer 1994). Biofertilizers are also a crucial component of such management practices as they are essential for playing part in soil production and sustainability (Bisen et al. 2015). Furthermore, it acts as a supplement against chemical fertilizers for achieving sustainable agriculture.

In this chapter, the focus is on contaminants occurring by the use of fertilizers, the importance of biofertilizers in this respect, the effect of biofertilizer on sugarcane crops, its mechanism of action, and its comparison with chemical fertilizers.

2 Contaminants Occurring Through the Use of Chemical Fertilizers

For successful growth of crop and high yield, several factors are involved such as variety, disease, and insect management, weather conditions, and most important the quality of soil in which it is grown. In regard to soil quality, farmers often use chemical fertilizers and mineral fertilizers to improve the soil and obtain higher crop yields (Bres and Politycka 2016). Stewart et al. (2005) revealed that though the use of chemical fertilizers provides macronutrients to crops causing a positive effect on crop yield, but the negative effect it causes on the environment such as hypoxia, harmful algal blooms, and eutrophication is the main drawback of using chemical fertilizers (Savci 2012). There are various important sources of causing heavy metals in soils such as irrigation water, pesticides, and organic products, and these sources not only cause accumulation in the soil through leaching and surface off process but also in plants and thus affect the food chain of the ecosystem (Adriano 2001; Nicholson et al. 2003). The problem in the use of mineral fertilizers over crops is the emergence of cadmium contaminants in top soil, particularly with phosphate fertilizers (Lugon-Moulin et al. 2006; Cheraghi et al. 2012; Gonçalves Jr et al. 2014). The uptake of this mineral depends on soil pH, and cadmium solubility increases as soil acidity increases (Bres and Politycka 2016). The phosphate fertilizers are a major source of emerging contaminants in soil due to their existence of origin, and there are several products such as mono-ammonium phosphate (MAP) and diammonium phosphate (DAP) that are adding contaminants to soil (Khan et al. 2018). Robarge et al. (2004) revealed that concentration of Cd as a contaminant has been observed, and the range of Cd in MAP and DAP varies from 22 mg kg^{-1} and 19 mg kg^{-1}. Rigorous and continuous use of these fertilizers further accumulates these contaminants in the soil causing harm to the environment as well as human health (Atafar et al. 2010; Hariprasad and Dayananda 2013; Yargholi and Azarneshan 2014). This gets further increased with time (Loganathan et al. 1995; Chen et al. 2007). In many plants, correlation of phosphorus (P) in fertilizer with Cd has been observed (Loganathan et al. 1995). The accumulation of cadmium due to P fertilizer application had been much of interest and concern when it has been known that about 54 to 58% of cadmium is present in soil and the reason owes to the use of P fertilizer application to crops (Tirado and Allsopp 2012). Another fertilizer is lime fertilizers, though rich in calcium or magnesium but is contaminated by heavy metals such as Cd, molybdenum (Mo), Zn, As, Pb, copper (Cu), mercury (Hg), cobalt (Co), nickel (Ni), Cr, and As (Conceição et al. 2013; Breś et al. 2009; Gabe and Rodella 1999; Nicholson et al. 2003). Haiyan and Stuanes (2003) had also shown that these are not only causing single contaminants in soil but further interaction with elements is causing multiple contaminants which are toxic in nature. Sternbeck et al. (2011) revealed the range (0.04 to 0.06 g Cd ha^{-1} year^{-1}) in which cadmium gets added to soil due to lime fertilizer. Against chemical fertilizers, organic fertilizers are being recommended but even their rigorous use on long-term basis showed elevation in metal content, soil organic matter, and cation exchange capacity with further reduction in soil pH (Khan et al. 2018).

To end up the losses and emerging contaminants occurring through chemical fertilizers, biofertilizers are the ones which are the solutions to this problem (Mahapatra et al. 2022). Biofertilizers are known to be containing living microbes, which when used on various parts of the plant such as seed and plant surface, help in encouraging proper plant growth by conversion of important nutrients found in plants in unavailable condition to available condition (Rokhzadi et al. 2008; Roy 2020). These eco-friendly products are gaining importance due to much awareness of soil health as the usage of chemical fertilizers is causing soil and water pollution resulting in ultimate harm to human health (Youssef and Eissa 2014). These promote the growth of plants by increasing nutrient contents in plants and also cause hormone production in plants. Furthermore, these even provide immunity from disease-causing pathogens (Bhardwaj et al. 2014). Another important role of biofertilizer is in biocontrol, wherein *Tricoderma*-based fungicides are used for improving plant growth against various diseases (Kumar et al. 2017; Asad 2022). On an overall basis, it has been revealed that 60 to 90% of total fertilizer applied for plant growth is unused to plants, while plants uptake only 10–40% of total fertilizer which opens up the importance of biofertilizers application to plants (Ju et al. 2018).

3 Biofertilizers: Its Importance and Types

Biofertilizers are biologically active products that involve the use of microorganisms (bacteria, algae, or fungi strains) that helps in providing essential nutrients to plants when applied into the soil (Rehman et al. 2022). They cause either direct or indirect impacts on plant growth and yield by adopting different mechanisms (Pal et al. 2015). They work via two ways either through symbiotic association or through solubilization of nutrients found in soil like P. These are known to be low in cost and effective in usage. On basis of classification, biofertilizers are of the following types: Nitrogen-fixing P biofertilizers, phosphate-mobilizing fertilizers, plant growth-promoting biofertilizers, and enriched compost biofertilizers (Roy 2020). Nitrogen-fixing biofertilizers include *Rhizobium*, *Azotobacter*, and *Azospirillum*, while P biofertilizers include *Bacillus*, *Pseudomonas*, and *Aspergillus*. phosphate-mobilizing fertilizers include mycorrhiza and plant growth-promoting biofertilizers include *Pseudomonas* and enriched compost fertilizers include *Aspergillus flavus, C. olivaceum*, *A. nidulans, Chaetomium bostrychodes, A. niger, Fusarium solani, Humicola fuscoatra, A. ochraceus,* and *F. oxysporum*. Of all the microbes in fertilizers, the most widely accepted is *Rhizobium* nitrogen-fixing biofertilizers. They possess the ability to organize important compounds from usable to nonusable forms (Rajendra et al. 1998).

There are a number of reasons why biofertilizers are important for the crop. These are as follows:

1. Increase in yields after harvest: Studies had reported that on average, and the application of biofertilizer had shown a 20–30% increase in yield (Simarmata et al. 2016). In the case of the application of algae-based fertilizers, it has been shown that in rice crop, yield is improved by 10–45%.
2. Soil structure improvement: The application of microbial biofertilizer is known to ameliorate soil structure by causing an impact on soil particle aggregation.
3. Enhancement in water retention capability.

3.1 Nitrogen-Fixing Biofertilizers

These contain several inoculants having microbes as a single entity or in the group that possesses the capability of converting atmospheric nitrogen into compounds of organic forms. Later on, these bacteria convert organic compounds into unstable forms in plants (Abbey et al. 2019). The modes of action of these biofertilizers are to fix nitrogen from the atmosphere and then make available this nitrogen to plants. This in turn causes a rise in nitrogen content in the soil thereby making the soil more fertile. The following table mentions the various nitrogen-fixing microorganism (Nosheen et al. 2021) used in biofertilizers depending on the crop cultivated (Table 26.1).

3.1.1 Azospirillum

These are non-nodule forming, gram-negative, and aerobic bacteria having the capability to fix nitrogen. These bacteria belong to the Spriliaceae family (Mehnaz 2015). Among the number of *Azospirillum*, the most beneficial ones are two species, namely, *Azospirillum lipoferum*, and *A. brasilense* (Mishra et al. 2013). These bacteria form symbiotic associations with C4 plants as they possess the capability of fixing nitrogen on organic salts (Mishra and Dash 2014). Inoculation of these bacteria causes an impact on root development and exudation (Trabelsi and Mhamdi 2013).

Table 26.1 Nitrogen-fixing microorganisms used as biofertilizers in various crops

Microorganism associated with biofertilizers	Crop on which it is used
Azolla	*Oryza sativa* (rice)
Azospirillium	*O. sativa*, *Saccharum officinarum* (sugarcane)
Azotobacter	*Triticum aestivum* (wheat), *O. sativa*, *Saccharum officinarum*
Blue green algae (BGA)	*O. sativa*
Rhizobium	Pulses, oilseeds, and fodder crops

3.1.2 Azotobacter

These bacteria are aerobic, free-living heterotrophs and belong to Azotobacteriaceae family. In soil, these microbes rarely increase to 10^4 to 10^5 g^{-1} as there is a deficiency of organic matter and antagonistic microbes. These bacteria cause the inhibition of many pathogenic fungi in the roots of sugar beet by stimulating antifungal antibiotics in soil (Bhat et al. 2015). Azotobacter colonizes the roots of plants, and it penetrates inside the roots for its proliferation without forming any nodule formation on root tissues (Bhat et al. 2015). Bangar and Sharma (1997) revealed that the use of this bacteria causes 7.7–15.2% higher cane yield than the ones where the use of *Azospirillum* was considered while when *Azotobacter* was applied as a supplement material then marginal increase in sugarcane and sugar yield was seen.

3.2 P-Solubilizing Biofertilizers

These include microbes such as bacteria, fungi, and yeast. They belong to non-nitrogen-fixing biofertilizers. Kalayu (2019) revealed that these microbes belong to the beneficial microbes category as it possess hydrolyzing capability of organic and inorganic insoluble P. Furthermore, these microbes help in overcoming the P deficiency occurring in the soil in eco-friendly way (Kalayu 2019). It is known that about 25–30% of P is only available in most of the soils in India for plants, but plants are unable to uptake insoluble form of P without using these microbes (Ju et al. 2018). Bagyaraj et al. (2015) revealed that P which is taken up by plants for its growth is available only in two forms, i.e., monobasic form and dibasic form. Many soil-borne bacteria and fungi possess the ability to convert this form of P into soluble one by excreting out organic acids that help in solubilizing rock phosphate and tricalcium phosphate. This is done by the decline in particle size and causes a lowering of soil pH (Gupta 2004). An interesting feature of the application of this sort of biofertilizer is that they are not sticked to one type of crop and can add an advantage to any crop. This type of biofertilizers is applied to a crop by farmers to overcome the P deficiency occurring in soil (Sharma et al. 2013). These biofertilizers include *Azotobacter*, *Bacillus*, *Erwinia*, *Enterobacter*, *Rhizobium*, and *Serratia*.

3.3 Vesicular Arbuscular Mycorrhiza Biofertilizers

These biofertilizers contain the mycelium of fungi as an important ingredient and are non-nitrogen-fixing biofertilizers. These fungi form symbiotic associations with the roots of plants. This is known as vesicular arbuscular mycorrhiza (VAM). Now, these biofertilizers are known as arbuscular mycorrhiza fertilizers (AMF) (Anand et al. 2022). This causes a rise in plant growth and an increase in nutrient accumulation in plants like P, Cu, and Zn (Berruti et al. 2015). There are several benefits of using such biofertilizers for plants (Abbasi et al. 2015). These are as follows:

- Rise in plant tolerance capability against several abiotic and biotic stresses. This so happens by increasing the root surface area by the production of antimetabolites and hormones (Igiehon and Babalola 2017).
- Had a potential as an applicant for increasing the growth of plants and as a substitute against harmful chemical fertilizers.
- Possess vital functioning in encouraging mineral cycling.

4 Advantages of Usage of Biofertilizers

As stated earlier, biofertilizers are important for improving soil fertility as well as the production and productivity of crops (Pal et al. 2015). The application of biofertilizers on crops possesses several beneficial aspects in comparison to synthetic fertilizers (Roy 2020). These are as follows:

(i) Eco-friendly compounds causing no harm to the environment (Itelima et al. 2018).
(ii) Increases crop yield by 20–30%.
(iii) Cost effective and cheap. Application of this causes a reduction in the consumption of chemical fertilizers on crops. This helps the plant in providing nutrients at a very lower price.
(iv) Causes biological nitrogen to make available to plants in direct form. Also, they enhance P uptake by plants as they solubilize P. It is essential in functioning as a recycler of nutrients.
(v) Sustaining soil fertility and improving properties of soil. It also improves the texture and water-holding capacity of the soil. Thus, it maintains overall soil health.
(vi) Increases plant growth as it stimulates the release of hormones, vitamins, etc., e.g., *Azospirillum* and *Pseudomonas* (Hazarika and Ansari 2007).
(vii) Helps in suppressing diseases related to soil-borne. It acts as an antagonist to soil microbes by producing antibiotics/bacteriocins (Hazarika and Ansari 2007).
(viii) Helps in propagating and reproducing soil microorganism that is beneficial to plants and soil.
(ix) It helps in solubilizing and mobilizing nutrients in the soil and also acts as a renewable source of nutrients to the soil.
(x) Helps in secreting antibiotic/fungicide substances in soil.
(xi) It helps in the decomposition of plant residues, particularly organic matter, adding more fertility to the soil and stabilizing the carbon nitrogen ratio in the soil.

(xii) Uptake of ions, such as P, Zn, sulfur, is increased when mycorrhiza/arbuscular mycorrhiza are used as biofertilizer. Furthermore, they also improve resistance to root diseases and even augment the hardiness to transplanted plants (Pal et al. 2015).

5 Mechanism of Action

In general, various biofertilizers have different modes of action (Fig. 26.1). The basic mechanism of action of biofertilizers is that they fix the atmospheric nitrogen or even soluble P in soil mainly in leguminous crops (in root nodules) which get available to plants when they are in need. They even solubilize insoluble forms of P into soluble ones, such as aluminum, iron, and tricalcium. This is mainly seen in phosphate-solubilizing biofertilizers. In the case of biofertilizers containing *Azospirillium*, these bacteria cause plant growth-promoting substances, which increase root hair development and root biomass, accentuating indole acetic acid

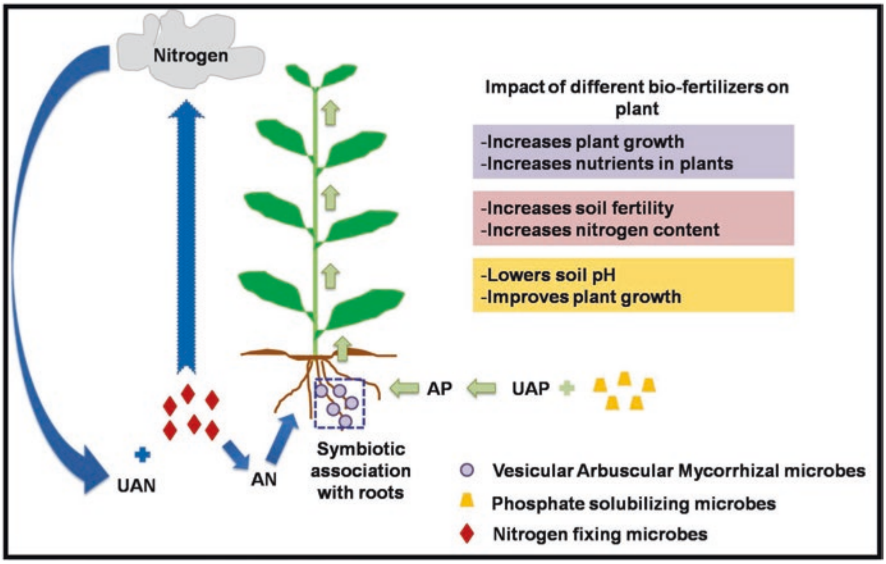

Fig. 26.1 Mode of action of various biofertilizers and their impact on plants. In nitrogen-fixing biofertilizers involvement of nitrogen-fixing microbes captures atmospheric nitrogen and is stored in soil that gets available to plants due to these microbes (mode of the action depicted in blue and its impact in red). The second type of fertilizer is phosphate-solubilizing bacteria (mode of action depicted in green and its impact in yellow), which makes available P to plants that are present in the soil as unavailable. The third type of biofertilizers is vesicular arbuscular mycorrhizal (VAM) biofertilizers involving VAM microbes causing symbiotic association with roots (its impact depicted in purple). AP available phosphorus; UAP unavailable phosphorus; AN available nitrogen; UAN unavailable nitrogen

oxidase (IAA) activity as well as endogenous IAA activity. Furthermore, these bacteria compete with harmful microbes present in the rhizosphere (Pathak et al. 2022).

6 Biofertilizers in Sugarcane

Sugarcane has been found to fix atmospheric nitrogen with the help of nonsymbiotic-fixing microorganisms. As a sustainable substitute for mineral fertilizers in sugarcane and other crops, biofertilizers have gained popularity (del Carmen et al. 2008; Molla et al. 2012; Nunes Oliveira et al. 2017; Yadav and Sarkar 2019). *Azotobacter* and *Azospirillum* are the two main groups of bacteria that fix atmospheric nitrogen in association with the roots of crops and widely occur in soils of tropical and subtropical areas. These organisms increased the sugarcane yield significantly (Serna-Cock et al. 2011). However, *Azospirillium* sp. is more effective in clay solid with adequate irrigations while *Azotobacter* sp. in sandy soils. In addition, there are many other bacteria, namely, *Beijerinkia*, *Derxia* sp., *Azomonas* sp., and *Closteridium*, which fix nitrogen in the soil. The rate of biofertilizers applied in sugarcane crops for high yield is 5 kg ac^{-1} or 12–15 kg ha^{-1}. For *Azospirillum* or *Azotobacter*, 4.0 kg ac^{-1} is required for sugarcane good growth and yield in two splits. Biofertilizers are applied for 30 and 60 days in fields where chemical fertilizers were applied for 45 and 90 days, respectively, in two splits while for three splits 30, 60, and 90 days of chemical fertilizers usage, *Azospirillum* (or) *Acetobacter* and two kg phosphobacteria are to be applied (Serna-Cock et al. 2011). The usage of biofertilizers over sugarcane crops is also of utmost importance to achieve a better yield. A mixture of biofertilizers with farmyard manure (500 kg) is recommended near the base of the clumps of sugarcane for good yield and production which should be followed up by earthing up and irrigation. Besides, the combination of PGPR and biofertilizer can increased the bacterial and fungal interactions in sugarcane crop (Qiu et al. 2022).

7 Effect of Biofertilizers on Sugarcane Yield and Response of Various Varieties to Biofertilizers

Different methods are employed for the application of biofertilizers to sugarcane crops, namely, smearing steeping of setts and bacterial suspensions and soil application. At Padegaon, it has been observed that inoculation with *Azotobacter* sp. at the time of sugarcane raised bed planting and later treatment of roots in bacterial suspension at the time of transplanting gave 24–42 t ha^{-1} more cane yield over control. However, in another study at Sugarcane Breeding Institute, Coimbatore, it has been reported that *Azotobacter* and *Azospirillium* biofertilizers application as sett treatment or soil application did not show any significant difference in cane yield but the treatment was effective in terms of reduction in nitrogen fertilizer dose by 25 percent. Usage of biofertilizers in sugarcane crops had increased cane yield ranging between 10 and 25 percent. When *Azotobacter/Azospirillum* was used at the rate of 2.5 kg ha^{-1} on sugarcane, it improved growth, yield, and its components in the plant as well as ratoon canes (Shankariah and Gururaj 2001). Substantial saving in nitrogen fertilizer with the use of biofertilizer has been found by many workers. Application of *Azotobacter* sp. culture helped in Adsali plantation. The research work at VSI, Pune revealed that sugarcane yield was increased by 32–29 t ha^{-1} over control with a saving of 25% nitrogen. Application of *Azospirillium* (7 kg) on Co 6304 as a source of nitrogen as a supplement along with 225 kg of nitrogen per hectare had shown the same cane yield as that obtained from 300 kg nitrogen per hectare, indicating a cutback of 75 kg of nitrogen per hectare (Durai and Ravichandra 1996). Hence, it is essential to use *Azotobacter* sp. and *Azospirillium* sp. Biofertilizers as a supplemental source of inorganic fertilizers to economize cultivation in sugarcane. The application of inorganic fertilizers and other chemicals to sugarcane has an antagonistic or stimulatory effect on the efficiency of biofertilizers. Heavy doses of nitrogenous fertilizers decreased *Azotobacter* sp. population. The addition of lime to acidic soil increases *Azotobacter* sp. population. *Azotobacter and Azospirillium* were high in unfertilized soil as compared to fertilized soil. Research on the same line carried at VSI, Pune revealed that nitrogen dose up to 400 kg ha^{-1} had no inhibitory effect on *Azotobacter* and *Azospirillium* and neem cake-coated urea up to 400 kg ha^{-1} encouraged their growth as compared to urea treatment (Singh 2016). Furthermore, Bangar and Sharma (1997) had shown that the application of phosphate-solubilizing bacteria even on low levels (60 kg P_2O_5 ha^{-1}) on sugarcane causes an increase in its yield due to the presence of solubilization of insoluble phosphate. More benevolent microorganisms accumulated in the sugarcane rhizosphere soil as a result of applying biofertilizers have been reported by Liu et al. (2021).

Varietal response of sugarcane to biofertilizers was studied by testing 51 sugarcane varieties at SBI Coimbatore and found that nine cane varieties, namely, Co 418, Co 740, Co 775, Co 853, Co 62,175, Co 8143, Co 8012, Co 8018, Co 5150 gave a positive response to *Azotobacter* sp. and ten varieties, namely, Co 1148, Co 7204, Co 7704, Co 7717, Co 8005, Co 8015, Co 8017, Co 8145, Co 8208, Co 8209 to *Azospirillium* sp., while twenty varieties were found to be nonresponsive. Out of 8 sugarcane varieties tested for *Azotobacter* sp., only BO 91 gave a maximum positive response. Thus, it is evident that *Azotobacter* sp. and *Azospirillium* sp. are potentially effective in increasing the yield and quality of sugarcane and also bringing out nitrogen economy by reducing nitrogen dose. However, these effects vary greatly due to the efficacy of strains and the variety of cane. Hari and Srinivasan (2005) had shown that sugarcane varieties respond differently to the application of nitrogen biofertilizers when their nitrogen levels are different. In the case of good yield from *Azospiriullum*, Co 8014, Co 8122, and Co 6304 performed best, while *Gluconacetobacter* Co 8021 performed the best. Co 6304 was superior to *Azotobacter* (Hari and Srinivasan 2005). Furthermore, the application of VAM on sugarcane plants grown in soil modified with rock phosphate and the mixture of diammonium phosphate and super phosphate showed a maximum increase in sugarcane biomass (Prasad and Bilgrami 1995). Also, the combination of VAM with rock phosphate had successful results on sugarcane growth and yield (Stamford et al. 2015).

8 Production of Biofertilizer in Sugarcane

In sugarcane, production of biofertilizer involves the following steps:

(i) Maintenance of stock culture of beneficial microbes such as *Gluconoacetobacter* and *Azotobacter* by preserving in glycerol at −20 °C.
(ii) Multiplication of biofertilizer by reculturing the stock culture in the right medium.
(iii) Transfer of multiplied stock culture in a right liquid medium and thereafter for proliferation once again transfer it in right liquid medium for proper growth of microbes.
(iv) Mixing liquid culture containing microbes with carriers such as press mud and farmyard manure.
(v) Packaging of biofertilizer in polybags with complete information sticked/labeled on it. The polybag should possess the following information: date of packaging, amount of biofertilizer, date of expiry, mode of application, and type of biofertilizer.

9 Conclusion

Biofertilizers involve the usage of living microbes, and their application to plants causes improvement in plant growth. Though biofertilizers possess great potential as a nutrient source yet it lacks in achieving popularity as per their capability due to constraints such as establishment, favorable conditions and expertise (Yadav et al. 2019).

Application of these biofertilizers had a direct or indirect impact on plant growth and crop yield either by symbiotic association or by dissolving nutrients present in the soil. Both these mechanisms help in increasing yield and productivity. In nitrogen-fixing biofertilizers, *Azospirillium* and *Azotobacter* are the two of the various microbes used that help in fixing nitrogen and making available nitrogen to plants through soil. In P-solubilizing biofertilizers, microbes involved cause unavailable P (present in the soil) to available P (for plants). Though the application of biofertilizers has been made on various crops, we had discussed here one important cash crop, namely, sugarcane, which contributes to sugar production in the world. It has been reported that in raised bed planting, inoculation with *Azotobacter* sp., and treatment of bacterial suspension with cane roots at the time of transplanting had 24–42 t ha^{-1} more cane yield than untreated ones.

The way chemical fertilizers and pesticides are being used, more production of such fertilizers is being encouraged, without being known about the hazardous implications caused by them on humans and also the imbalance it might cause in the environment. Although indiscriminate usage of these chemical fertilizers has caused better production, it has also caused soil and water contamination to a large extent. They also caused contaminants such as cadmium, As, and Pb to emerge in soil. Furthermore, they have caused damage to beneficial microbes that made crops more disease prone. Besides, soil fertility has also been reduced by its usage. But people are now aware of the drawbacks that chemical fertilizers and pesticides cause, so the use of biofertilizers is now in practice. To apply in modern agricultural use, the useful aspects of biofertilizers should be known for better growth of plants, particularly the presence of beneficial microbes and absence of emerging contaminant. The role of these biofertilizers in the future will help to increase crop production, productivity, and soil sustainability. Furthermore, due to their eco-friendly nature, they will cause no harm to the environment as well as to people's health.

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Chapter 27

Beneficial Role of Microbial Diversity for Sustainable Agriculture

Sandeep Sharma, Kailash Chand Kumawat, and Pritpal Singh

Abstract Drastic climatic perturbations and agricultural malpractices have spiked up the consequences of abiotic and biotic stress resulting in serious damage to crop plants, limiting productivity and eventually causing ecological degradation all of which translate to a loss of more than ~50% in global agriculture production. Agricultural scientists have been on the quest for finding natural alternatives for augmentation of agriculture produce as well as pressing issues such as sustainable management of agriculture waste. One prevailing alternative would be to use technologies involving the use of indigenous microbial diversity, which have previously been applied globally for the extraction of essential minerals, waste management, and to accrue the agriculture production under sustainable conditions. Indigenous microbiomes constitute a group of innate microbial communities that inhabit the rhizosphere and all biotic surfaces with amassed potential for phytohormone production, biodegradation, bioleaching, biocomposting, symbiotic nitrogen fixation, antagonistic activities, and enhancing soil fertility along with as soil health. The plant–microbiome interactions, environmental restoration, and safeguarding target via the indigenous microbiomes to turn out the good-for-nothing and useless waste into productive bioresources is the primary concern of this chapter. Therefore, keeping in view the promising future of beneficial microbes, this chapter has focused on discussing the microbe-mediated amelioration mechanisms action with summarizing current progress in this field.

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1 Introduction

World population is increasing explosively day by day, and it requires intensifying the existing agricultural production system. Inappropriate use of synthetic, fossil fuel-based agrochemicals have undoubtedly increased agricultural production; however, the growing continuum of awareness and concern regarding adverse effects of these chemicals on the soil productivity and environmental quality are irrefutable (Singh et al. 2011; Sharma et al. 2022a). Their exorbitant nature and exigency due to extensive use have steeply deteriorated the environment leading up to novel endeavors to develop alternative strategies to increase productivity, with beneficial microbial communities playing an critical role in these efforts (Vaxevanidou et al. 2015; Kumar and Gopal 2015; Singh et al. 2014, Singh et al. 2019a, 2019b; Singh and Benbi 2020). The distinctive nature of indigenous microflora coupled with apparently mercurial biosynthetic abilities, displayed in precise environmental conditions, has made them highly suitable for solving particularly arduous problems in a number of fields. The responsible use of the indigenous microbial diversity to get economic, social, and environmental benefits drives an evolution of probing and investigation into traditional technologies to look for an efficient way to protect and monitor the environment (Cai et al. 2013).

The biodiversity of microbial world on earth is largely unexplored and the small fraction whose nature and identity are known makes up only (<10%) of microscopic landscape while also aggregating the largest life mass on the planet (Bhattacharyya et al. 2016; Sharma et al. 2020). Out of these, indigenous microorganisms constitute the smallest form of life and yet play a pivotal role in varied spectrum of activities within a living organism that contribute to the. Therefore, innovations and research in microbial ecology are a principal frontier in modern biological sciences. Bacteria, fungi, algae, protozoa, actinomycetes, and the infectious agents such as viruses are key components within the extensive resources of activities observed in microbial diversity (Andreote et al. 2014; Sharma et al. 2021a). Microbial diversity interacts with various plants and consociate through different direct and indirect mechanisms.

There is growing evidence that above ground plant diversity the microbial diversity that dwells under the ground primarily through root exudation and rhizodeposition (Morella et al. 2020; Sharma et al. 2022b). Simpler carbohydrates that are released into the soil feed the indigenous microflora and are found abundantly near the root surface gradually diffusing along a gradient with increasing distance (Gunina and Kuzyakov 2015). The microbial population is more abundant and complex in the rhizosphere, defined as the narrow zone that surrounds plant roots (10^9 colony-forming unit per gram of soil, comprising ~10^6 taxa) (Lakshmanan et al. 2017). Plant residues comprise chiefly of lignin, hemicelluloses, and cellulose, which are degraded by decomposer fungi which actively break down theses intransigent compound into forms that are more readily taken up by other beneficial microbiomes (Singh and Benbi 2018; Singh et al. 2021a, b). A conversion of this sort is largely dissociated from those conventional agricultural practices, for this latter account to substantial losses of organic matter content to the system and an unregulated carbon (C) flux (Craven and Ray 2019), stable isotope labeling (SIP) nutrient fluxes with technique that hold great potential of resilient, functioning and beneficial microbiomes that can pave way for holistic agriculture in a few years' time. Therefore, new technologies can facilitate the application of diverse and methodical rhizospheric microbiome to promote sustainable agriculture through contribution of economic, social, and environmental sustainability (Ray and Craven 2016; Ray et al. 2020; Singh et al. 2021b, c).

Historically, potential microbial diversity that are involved in promoting plant growth and aid nutrient acquisition have largely been employed in agriculture fields as a form of single strains to offset such fertilizer inputs as nitrogen (N), phosphorous (P), and other essential nutrients. However, researches in the field biotic population have largely held an opinion that diversity of microbes with distinctive function niches have critical roles in adherence and de-absorption of inorganic nutrients to physical surfaces along with breakdown of organic residues, their incorporation into the soil (Kumar and Dubey 2020; Kumawat et al. 2021; Finkel et al. 2017). It has now become evident that improving plant performance in a sustainable manner is a result of complex interactions, which are beyond the ones between host plants and specific indigenous microbes or a consortium thereof. These referred interactions require modeling for improving predictable outcomes. This chapter highlights the current state of art for incorporation of specific beneficial plant growth-promoting microorganisms and further discusses the principles and management of micro-biome-based approaches for sustainable agriculture for that benefit not only the scientific communities but also stakeholders.

2 Agriculturally Important Microflora in Sustainable Agriculture: Past, Present, and Future

Beneficial microbes have myriad applications in fields of agriculture, horticulture, and forestry. They interact favorably in the plant rhizosphere resulting in beneficial outcomes, which are sometimes rather unpredictable. Table 27.1 shows the beneficial aspects of rhizospheric microbiome with respect to a selective number of plant species. *Azotobacter*, *Bacillus*, *Pseudomonas*, *Rhizobium*, *Acenatobacter*, *Enterococus*, *Proteus*, *Serratia*, *Azospirrilum*, *Burkholderia*, *Paenibacillus*, *Klebsiella,* and *Bradyrhizobium,* etc., have proven their efficacy in promoting plant growth, symbiotic association, and improving soil health in sustainable manners. Potential beneficial microbial diversity plays important role in plant protection through induced systemic resistance against phytopathogens and exhibit antagonistic activities or actias biotic elicitors against

Table 27.1 Diversity and plant growth-promoting attributes of rhizospheric microbiomes in different agricultural crops

Dominant genera of rhizospheric microbiomes	Crops	Functions	Main finding on rhizospheric microbiomes	Reference (s)
Bacteriodetes, *Verrucomicrobia*, *Actnobacteria,* and *Proteobacteria*	*Phaseolus vulgaris*	Improve plant growth and health of common bean	Significant association between rhizobacterial community composition, crop genotype, and specific root phenotypic traits were recorded	Pérez-Jaramillo et al. (2017)
Bradyrhizobium sp., *Pseudomonas oryzihabitans, Leclericia adecarboxylata,* and *Pseudomonas aeruginosa*	*Glycine max*	Enhance plant growth, nutrient acquisition, nodulation efficacy, and improve soil health	Significant improvement in plant growth promotion, nutrient uptake, nodulation, legheamoglobin content, chlorophyll content, and grain yield as well as improved soil health	Kumawat et al. (2019a, b)
Actinobacteria, *Acidobacteria*, *Chloroflexi*,*Cyanobacteria*, *Tenericutes*, *Deferribacteres*, *Verrucomicrobia*		Growth promotion andnutrition	Selection of the microbialcommunity in therhizosphere based onniche-based processes and improve plant growth promotion and symbiotic parameters and soil health	Mendes et al. (2014)
Comamonadaceae, Flavobacteriaceae	*Hordeum vulgare*	Traits related to pathogenesis, plant microbial interaction, and nutrient mobilization/mobilization and ACC deaminase activities are enriched in the barley root-associatedmicrobiota	Host genotype has asignificant effect on thediversity of root-associatedbacterial communities	Bulgarelli et al. (2015)

Proteobacteria, Bacteroidetes, Actinobacteria, Acidobacteria, Planctomycetes		Plant growth, soil health, improve crop domestication, and productivity	Host genotypedetermines specific bacterialgroups in microbiome ofrhizosphere. Plant cell wallfeatures serve as sufficientcolonization (up to 40%) ofroot-associated microbiota Jasmonic acid plant defensepathway may mediateplant–microbial interactionsin the rhizosphere and alters thecomposition of rhizospheremicrobiomes	Bulgarelli et al. (2012)
Bacillus sp., *Planococcacea* sp., *Lysinibacillus* sp., *Pseudomonas* sp.	*Arabidopsis thaliana*	Induced systemic resistance(ISR)	Different developmental stages of plant influence rhizosphere microbiome. Plant can select a subset of microbes at different stages of development, presumably for specific functions	Carvalhais et al. (2013)
Acidobacteria, Actinobacteria, Bacteroidetes, Cyanobacteria		Plant growth promotion and antagonistic activities		Chaparro et al. (2014)
Olpidiaceae, Mortierellaceae,Pleosporales, Preussia sp., *Fusarium* spp., *Conocybe* sp.	*Helianthus annuus*	Indigenous microflora has symbiotic association and plant growth promotion	Plant-associated fungal communities are strongly influenced by host geneticfactors than bacterial communities	Leff et al. (2017)

(continued)

Table 27.1 (continued)

Dominant genera of rhizospheric microbiomes	Crops	Functions	Main finding on rhizospheric microbiomes	Reference (s)
Rhizobium sp. *LSMR-32* and *Enterococcus mundtii LSMRS-3*	*Vigna radiata*	IAA, P, and Zn solubilization, exo-polysaccharide production, siderophore production, cell wall degrading enzymes, ACC deaminase	Improve plant biomass, symbiotic efficacy, soil enzyme activities, macro and micronutrient uptake, tolerance to salinity, and enhanced grain yield	Kumawat et al. (2021)
Oxalobacteraceae, *Burkholderiaceae*, *Sphingobacteriaceae, and Sphingomonadaceae*	*Beta vulgaris*	Plant growth promotion, antagonistic activities thatrestrict pathogencolonization and infection	Invading pathogenic fungus and plant stress responses directly influence the shift inrhizobacterial community in microbiome composition	Chapelle et al. (2016)
Proteobacteria, Alphaproteobacteria,Sphingomonadales	*Solanum lycopersicum*	Degradation of plantpolysaccharides; ACC deaminase activities, P, K, and Zn solubilization carbohydrate utilization and protein metabolism and biological nitrogen fixation	Rootendophytes andrhizobacteria hadsignificantly differentcommunity structures andspecies abundance	Tian et al. (2015)

Azospirillum, Gluconacetobacter,Rhodospirillum acidovorax, Alcaligenes,Burkholderia, Klebsiella, Enterococcus, Enterobacter, HydrogenophagaFrancisella, Moraxella, Pantoea, Photorhabdus, Pseudomonas, Xanthomonas, Mogibacterium, Bacillus and *Peanibacillus, Actinomyces, Corynebacterium,* and *Propionibacterium*	*Poaceae* crops such as *Zea mays* L; *Zea mays* sp., *Parviglumis; Sorghum bicolor cv. Arprim; Triticum aestivum* L. cv. *Fiorina*	Improve plant growth, plant biomass, grain yield, and soil health	Bacterial communitycomposition in therhizosphere is different fromthat in bulk soil. Rhizobacterial communitycomposition differedaccording to the *Poaceae*genotype. The extent ofdiversification of eukaryotichosts can be a significantfactor for selection of theirassociated bacterialcompartment	Bouffaud et al. (2014)
Proteobacteria, Bacteroidetes, Acidobacteria,Planctomycetes, Nitrospirae, Actinobacteria,Verrucomicrobia, Firmicutes, Cyanobacteria,Chloroflexi, Gemmatimonadetes,Ascomycota, Basidiomycota, Zygomycota	*Triticum aestivum, Hordeum vulgare, Oryza sativa*	Glycan, limonene, andpinene degradation;nitrogen and sulfurmetabolism; plant growthpromotion	*Triticum aestivum* and*Hordeum vulgare* hadshown much strongerselection effects than *Oryzasativa* for the rhizosphere microbial community	Lu et al. (2018)
Proteobacteria (mainly *Alpha-, Beta-, andDeltaproteobacteria* classes), *Acidobacteria,Actinobacteria,* and *Chloroflexi* phyla. *Archaeal*communities composed of *Crenarchaeota,Thaumarchaeota,* and *Euryarchaeota* phyla	*Oryza* sativa	Growth promotion anddisease inhibition	Rhizosphere microbiome is shaped by soil- and plant-related conditions such as geographic location, soil type, rice genotype, oxic and anoxic interface, agricultural management, and growth stages	Ding et al. (2019)

various adverse climatic factors and biotic stresses. Effective microorganisms are usually denoted as a group of microbes identified with potential plant growth-promoting activities that are effective in their role as microbial inoculants without causing harmful impact on the environment (Bhattacharyya et al. 2016) that can also be used to improve propitious indigenous microbial diversity in the plant rhizosphere.

Potential microbes with beneficial effect are also pivotal in management of invertebrates and vertebrates' pests, plant diseases, weeds, and other pests that usually pose the potential to damage the agricultural as well as horticultural crops. Mycorrhizal association can be colonized in the diverse plant species and provide it beneficial impact to abiotic as well as biotic stresses such as drought, salinity, resistance toward insects and various serious plant diseases (Singh et al. 2011; Nagpal et al. 2020). Therefore, the uniqueness of rhizospheric microbiomes and their unpredictable biosynthesis capability make them quite adaptable in specific agroecosystem in order to provide suitable solutions to various problems related to productivity and disease suppression. Diverse groups of rhizospheric microbiome have a key role in eliminating environmental problems associated with inappropriate use of agrochemicals, which are widely accepted alternative approaches under sustainable agriculture system (Russo et al. 2012). Microbial bioinoculants and their applications in sustainable agricultural development with a focus on improvement of environmental health are getting better attention.

Since the early 1800s, the United States Department of Agriculture has recommended the use of diverse rhizospheric microbiome to improve efficacy of biological nitrogen fixation ability in the leguminous crops. Such microbiological and biotechnological approaches are believed to significantly improve global food supplies and to adequately reduce the area of arable land required to meet the challenging productivity goals. Diverse array of potential microbes not only play significantly role in the plant growth promotion in cereal and legume crops but also in an improving various aspect of host plant resistance against the abiotic and biotic stress conditions (Ray et al. 2020; Olenska et al. 2020; Azad and Kaminskyj 2016). In similar context, agricultural microbiologists globally for the last decade have conducted research on plant rhizospheric microbiome, such as plant growth-promoting rhizobacteria (PGPR), root-associated mycorrhizal fungi, actinomycetes, endophytes, across a wide range of cereal as well as legumes encompassing diverse ranges of agroclimatic conditions. Brundrett and Tedersoo (2018) have recently demonstrated 135 years of research on mycorrhizae and found that only non-mycorrhizal vascular plants make up ~8% of the total suggesting that most crop plants with mycorrhizal associations were favored over the course of evolution in plant kingdom.

Further, the focus of the majority of these research works has been only on the application of microbial inoculants to facilitate specific plant growth-promoting and symbiotic traits, i.e., nutrient solubilization/ mobilization, ACC deaminase, biofilm formation, exo-polysaccharide, biological nitrogen fixation (Sarkar et al.

2018; Kumawat et al. 2019a, b; Kumawat et al. 2021), siderophore, phytohormone production, hydrogen cyanide production, intrinsic antibiotic spectra (IAR), cell wall degrading enzymes, and biotic and abiotic stress tolerance or resistance. (Singh et al. 2019a, b, c). These rhizospheric microbes carry the potential to impart plenteous benefits to promotion of plant growth and fitness under not only greenhouse but also field conditions (Parnell et al. 2016). Recently, next-generation biotechnological approaches have revolutionized our understanding of rhizospheric microbial community and their metabolic activities which coupled with improved culturing techniques has tremendously facilitated the use of biologically active agents under field conditions (Mueller and Sachs 2015).

Specifically, culture impendent approaches such as metagenomics have helped uncover vast, previously veiled population density of microbes that might have new or improved PGP properties useful for sustainable agriculture, bioremediation, and human health. Such new researches certainly reveal a role for indigenous microbiome in defending host plant from phyto-pathogens and open new horizons for the development of probiotics to ameliorate plant stresses under sustainable agriecosystem (Kwak et al. 2018). Though it has been demonstrated recently via research the mechanism how microbes work in changing climatic conditions before and how decades of agrochemicals use have diminished their abilities to enhance plant fitness and soil health. Therefore, designing potential microbial inoculants after carefully screening with plant growth-promoting traits and evaluating the relationship between inoculants and indigenous microbiome would sustainably improve plant growth-promoting attributes and resilience of agricultural bioinoculants to encourage plant growth.

3 Role of Indigenous Beneficial Microbes Under Ideal Agricultural System

Green revolution from better agricultural approaches that ensued in mid-twentieth century has recently acquired high-yielding varieties as well as reduced agroecological cost and thereby a greater contribution toward environmental pollution, unfavorable climatic change conditions, loss of beneficial rhizospheric microbial biodiversity, and decreased the soil health in the intensive cropping system (Sharma et al. 2021b). Sustainable agriculture system is beneficial both economically and spiritually producers and consumers while also focusing on soil health as well as human health. There should be an active preservation of natural and environmental resources under changing climatic conditions to enhance food production for increased world population through efficient nutrient utilization and recycling of energy via biogeochemical cycles (Scherr and McNeely 2008).

4 Nutrient Management

Nutrient management of essential nutrients is the agricultural science related to appropriate utilization of rhizospheric soil, temperature, pH, various environment factors, and essential nutrients (N, P, K, Zn, and Mn) with diverse agricultural conservation techniques that directly or indirectly help in increasing nutrient utilization for improving food grain quality and soil health. Crop plants generally absorb essential nutrients from root exudates secreted in the rhizospheric soil and classified in the three main classes, i.e., (1) low molecular weight (2) high molecular weight, and (3) volatile organic compounds (VOCc) (Ortiz-Castro et al. 2009). Root exudates consist of carbohydrate, polysaccharides, amino acids, vitamins, phenolics, various organic acid, mucilage, and certain VOCs, i.e., alcohol, aldehyde, and various secondary metabolites. The rhizospheric root exudation mainly depends on the various environmental factors such as temperature, soil pH, soil type, age of plants, and their photosynthesis activities (Badri and Vivanco 2009). These root exudates compounds can be act as signaling molecule for microbial interactions with plant or might be used as carbon sources for microbial metabolism under changing climatic conditions (Nihorimbere et al. 2011; Sharma et al. 2020).

Agricultural production all over the globe slowed down recently due to intensive agricultural system. It is a matter of utmost urgency to maintain high crop production, with strictly limited or little alteration in the agroecosystem. Further, to ameliorate agricultural productivity with quality product is the need of the hour owing to increase in population all over the world and shrinking agricultural land, raising labor cost, input cost, and a shortage of farm workers. To enhance the sustainability of preexisting intensive cropping system and maintaining ecosystem as well as biodiversity with produce more quality products, beneficial rhizospheric microbes used as biofertilizer/bioenhancer (Singh et al. 2010). Microbial diversity mostly present in soil and atmosphere play an essential role in the nutrient management though biogeochemical cycles (Adhya et al. 2015; Sharma et al. 2022b). Rhizospheric microbes, particularly bacteria, fungi, and actinomycetes, may act directly by facilitating essential plant nutrient accumulation through decomposition and recycling of organic matter or influencing phytohormone levels, essential nutrient solubilizing ability, or indirectly attenuating the harmful impact of phyto-pathogens (Glick 2012; Sharma et al. 2016; Sarmah et al. 2005). Potential diversity of microbes, i.e., *Aspergillus*, *Trichoderma*, *Azospirillum*, *Azotobacter*, *Enterococcus*, *Enterobacter*, *Bacillus*, *Pseudomonas*, *Klebsiella*, *Bradyrhizobium*, *Rhizobium*, *Proteus*, *Serratia*, *Paenibacillus*, and *Burkholderia*, involved in enhancement of plant growth promotion, biological nitrogen fixation, along with suppression of the phyto-pathogens are reported (Phukan et al. 2012; Bhattacharyya and Jha 2012; Bhattacharyya et al. 2015; Sharma et al. 2016; Kumawat et al. 2021).

Beneficial rhizospheric microbiomes also have the ability to make symbiotic association with plant roots through plant microbial interaction that ultimately increase supplying of essential nutrient such as N, P, K, Fe, and Zn. Plant symbiotic associations of arbuscular mycorrhizal fungi (AMF) are well-established systems present in ~90% of plant diversity with evidence of early colonization via external hyphae. AMF was successful in improving the fitness of host crop plant by scavenging mineral such as P, water, and essential macro- as well as micronutrients in turn of exchange for fixed carbon and ultimately make them available for the various plant species. Symbiont AMF (endomycorrhizae) such as *Chrococcus*, *Phormidium*, *Anabaena*, *Osillatoria*, and *Aphanocopra* that exhibit the capability for symbiotic association with other advantageous microbes may be applied as bioinoculants in the various crops, i.e., cereals, pulses, oilseeds, and fruits crops to increase plant growth promotion through enhance nutrient utilization efficiency (Brundrett 2002; Shridhar 2012; Hasan 2013; Salvioli et al. 2016).

5 Recycling of Organic Matter, Efficient Nutrient Utilization, and Preservation of Bioresources

Photosynthesis is the vital process and mainly depends on the chlorophyll synthesis by plants through utilization of solar power for fixing atmospheric carbon dioxide (CO_2) into different types of carbohydrates and biosynthesis of essential amino acid and protein for plant metabolism. Photosynthesis activities are extremely low due to the climatic changing conditions. Therefore, an integrated efficient solar energy utilization mechanism is urgently needed to be explored in enhances the level of photosynthesis activities, so that maximum amount CO_2 might be converted into available form of nutrient for plant growth promotions. Exploration of diverse microbes is an indispensable tool in most of the sustainable agricultural ecosystem, including efficient utilization of solar energy and make available nutrients for plant growth promotion through biogeochemical cycling (Bhattacharyya and Jha 2012; Aislabie and Deslippe 2013; Saharan et al. 2019). Rhizospheric microbiomes are key factors responsible for maintaining soil structure, soil fertility, soil health, and soil quality for efficient plant growth promotion through interconversion of different forms of N, K, P, Zn, and Fe interline with biogeochemical cycles (Prosser 2007). However, efficient utilization of nutrient for plant growth under sustainable agroecosystem is a relative difficult task because microbial enzymes activities in the rhizospheric soils execute C losses from the atmosphere through bioremediation, soil respiration, and methanogenesis. Recent advanced technologies that could be improving nutrient utilization efficiency of organic system with appropriate use of agrochemicals are urgent need to develop sustainable agricultural system.

Organic matter such as agricultural, industrial, and municipal wastes has become a huge threat for ecosystem pollution in the developing or developed countries. Chemical-based organic matter decomposition of agricultural methods has also significantly contributed to the degradation of environment as well as impediment of natural resources. Recycling of diverse xenobiotic compounds and organic matter through utilization is an area that needs to be further developed for a well-functioning system of sustainable agriculture. Inoculation of various microbes with greater biodegradation capabilities may prove to be suitable approaches in conservation of natural resources and maintenance of environment and soil health (Verstraete et al. 2007). Recently, Kumawat et al. (2021) reported that *Enterococcus*, *Rhizobium*, *Proteus*, *Pseudomonas*, and *Bacillus* sp. examined to assess its suitability under diverse agroclimatic condition as bioenhancer/ bioprotectants along with biofilm formation and exo-polysaccharide production might paid a potential incorporation to develop ecologically sound approaches for the sustainable agriculture.

6 Direct and Indirect Mechanism of Rhizospheric Microbiomes

6.1 Phytohormone Production

Diverse rhizospheric microbiomes including bacteria, fungi, actinomycetes, and algae are responsible for producing metabolically active compounds including various types of plant growth regulators that can exert significant physiological impact on plant growth promotion and development (Ahemad and Kibret 2014). Beneficial PGPRs might be alterations of root architecture, which promote plant growth development through synthesis of auxins (Indole acetic acid; IAA), gibberellic acid (GA), and cytokinins (Kloepper et al. 2007; Perez-Montano et al. 2014). Auxins constitute IAA and are synthesized actively by various rhizospheric microbiomes in the proximity of root and may evoke a number of physiological/metabolic alterations leading to improved length and surface area of root. Many of symbiotic bacterial species, namely, *Rhizobium*, *Bacillus*, *Pseudomonas*, *Bradyrhizobium*, *Nostoc*, *Azotobacter*, *Klebsiella*, *Stenotrophomonas, Rahnellas*, *Azospirillum*, *Burkholderia*, *Herbaspirillum*, and *Gluconobacter* can produce many VOCs and N-acyl-L-homoserine lactones (AHLs), which trigger the production of phytohormones in plants. IAA affects processes such as cell division and differentiation along with the capacity to uptake essential nutrients through vascular bundles. It has a significant impact on seed germination and pigment formation and results in increased photosynthesis activities (Fig. 27.1).

Under abiotic stresses, various possible mechanisms involved in the production and regulation of plant growth regulators show tolerance toward adverse climatic changing conditions (Iqbal and Ashraf 2013; Alqarawi et al. 2014). The ability of crop plant to acclimatize salinity stress depends on their interaction with potent and advantageous rhizospheric microbes that can produce phytohormone such as cytokinin, IAA, and GA (Berg et al. 2013; Bhise and Dandge 2019). Therefore, it is imperative to search for potential rhizospheric microbial consortia, which effectively colonizers colonize roots relatively early and can inhibit any kind of stress posed by excess of abiotic stresses on plants. Recently, Kang et al. (2019) demonstrated that production of auxins by salt-tolerating *Leclericia adecarboxylata* strain MO1 has linkages with synthesis of carbohydrates, chlorophyll fluorescence

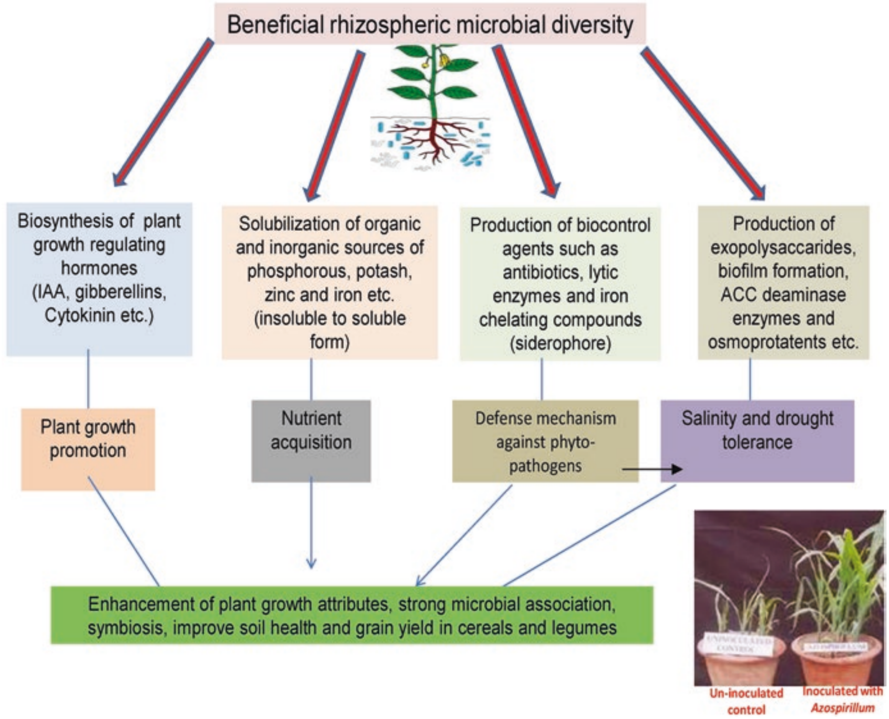

Fig. 27.1 Systematic diagram represented direct or indirect mechanism of plant growth promotion by rhizospheric microbiomes

improvement (F_v/F_m), expression of *ipdc* gene, and organic acid production in tomato. Similarly, coinoculation of *Rhizobium leguminosarum* bv. *viciae* with induced auxin biosynthesis pathway resulted in production of efficient nitrogen fixing root nodules with up to 60-fold more IAA as compared to nodulation in wild-type strain in *Vicia hirsulta* (Camerini et al. 2008). Gibberellins producing potential rhizospheric microbes such as *Azospirillum* sp., *Bacillus pumilus*, *B. licheniformis,* and *Pseudomonas fluorescens* were also reported by Boltini et al. (2004). Increased endogenous levels of GA in the PGPR, i.e., *Promicromonospora* sp. SE188, *Burkholderia cepacia* SE4, and *Acenatobacter calcoaceticus*, proved to promote plant growth attributes in under conditions of abiotic stress in cucumber with enhanced production of proteins, reducing sugars, ribonucleases, and antioxidant enzymes (Kang et al. 2014; Bhise and Dandge 2019). Cytokinins that are critical for tissue differentiation and proliferation of cells are produced in many beneficial microbes such as *Bacillus*, *Arthrobacter*, *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Halomonas*, and *Stenotropho monas* species (TrParray et al. 2016). Accelerated cytokinine production is known to decrease the stress hormone ethylene leading to decrease in leaf senescence in cereal and legumes supplementing plant growth (Pallai et al. 2012; Kapoor and Kaur 2016).

6.2 Phosphate Solubilization

Phosphorous is the second most crucial macro-nutrient (after N), which is pivotal in multiple physiological processes including root stalk development, flower and seed formation, and biological N fixation along with providing resistance to phyto-pathogens. In spite of being in abundance, large amount of P is present in insoluble form (organic or inorganic), which occurs when it forms a complex with Al or Fe in acidic soils or C in calcareous soil. Rhizospheric microorganisms act as rescue system causing acidification of soil due to production of organic acid and mineralization of organic P by acid phosphatases hence essential mechanism to solubilizing inorganic phosphate. Phosphorus-solubilizing microorganisms belonging to different genera such as *Bradyrhizobium*, *Cladosporium*, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Enterobacter*, *Flavobacterium*, *Enterococcus*, *Stenotrophomonas*, *Serratia*, *Chryseobacterium*, *Erwinia*, and *Agrobacterium* are prominent (Rodriguez and Fraga 1999; Khan et al. 2009; Bhattacharyya and Jha 2012; Sharma et al. 2016; Saharan et al. 2019).

A recent estimate suggests that phosphate-solubilizing bacteria (PSB) constitute ~1–50% of normal soil microflora, while fungi belonging to the same category constitute a population of about ~0.1–0.5% (Bhattacharyya et al. 2016). These PSBs provide available P to plant and also helps to increase the efficiency of BNFs and availability of micronutrients through synthesis of plant growth-promoting regulators for metabolic activities (Zaidi et al. 2009). Rhizospheric microbes that possess the ability of phosphate (PO_4^{3-}), Zn and K solubilization, N fixation, ACC deaminase, and phytohormone production aid in mobilization of nutrients thereby making it available to the plant even under abiotic stress conditions (Bhise and Dandge 2019). Therefore, it can be concluded that beneficial PGPs traits in bioinoculants are mediated by direct solubilization/mineralization of inorganic or organic source of P and stimulation of root growth by alteration root architecture as well as formation of mycorrhizal associations.

6.3 Potassium Solubilization

Potassium being an essential nutrient is required for numerous plants metabolic activities, cellular osmoregulation processes, resistance to biotic and abiotic stresses, and enhancing nutrients use efficiency (Sparks and Huang 1985; Bertsch and Thomas 1985). The water soluble-K, exchangeable, nonexchangeable, and structural or mineral are stay in dynamic equilibrium in soil and range from 3000 to 1,00,000 kg ha^{-1} (Meena et al. 2016). Potassium-solubilizing bacteria (KSB) are capable of solubilizing minerals that contain K such as biotite, feldspar, illite, muscovite, orthoclase, and mica and can convert insoluble K to soluble forms and making it easily accessible to plants as a part of available nutrient pool. Rhizospheric microbes such as *Acidithiobacillus ferrooxidans*, *Bacillus circulans*, *Arthrobacter*, *Azotobacter,* *Frateuria*, *Klebsiella*, *Bacillus edaphicus*, *Peanibacillus*, *Bradyrhizobium*, *Rhizobium*, *Pseudomonas*, *Stenotrophomonas*, and *Bacillus mucilaginous* have been reported as KSBs and their essential role in mobilization of insoluble sources of potassium native to the soil into forms suitable for nutrition (Lian et al. 2008; Liu et al. 2012; Bhattacharyya et al. 2016; Saharan et al. 2019). Potassium is mainly available for plant nutrition by dissolving silicate minerals, production of organic acid, acidolysis, polysaccharide production, chelation, and various exchange metabolic reaction of beneficial microbes. The KSBs are found in the all type of soil and their K solubilization ability mainly depending on the soil structure and various environmental factors. Therefore, KSB would serve as effective biofertilizers, which when integrated with reduced level of inorganic K fertilizers would in turn improve crop productivity under minimum cost in a sustainable manner. The knowledge on biodissolution by KSBs/KMBs is also essential to develop alternative technology, i.e., biomineralization, and bioremediation to reduced dependence on the agrochemicals (Saharan et al. 2019).

6.4 Zinc Solubilization

Zinc is an essential micronutrient and has a vital role in nutrition of both prokaryotic and eukaryotic population. Zinc acts as a cofactor for certain metabolic activities of plant as well as microbes and provides resistance against biotic stresses and aids in photosynthesis, maintaining cell membrane integrity, protein biosynthesis, pollen formation, and enhances the antioxidant enzyme activities (Gurmani et al. 2012; Hussain et al. 2015). According to Prasad (2010), ~75% exogenous application of inorganic Zn sources such as $ZnSO_4$ and ZnO get fixed in the rhizospheric soil at Indian conditions under intensive cropping system. Mostly Zn is fixed in soil at $pH > 7.0$ and increases with rise in level of carbonate, thus becoming unavailable to plant and can be solubilized by Zn-solubilizing bacteria in the available form for plant nutrition.

The main mechanism for Zn solubilization is by organic acid produced by rhizospheric microbes in the soil, which sequesters Zn cations by chelation, reduces pH of soil, and ultimately enhances Zn solubilization efficiency for plant growth promotion and also reduces malnutrition in human masses (He et al. 2010; Saravanan et al. 2007; Sharma et al. 2016). Zinc-solubilizing bacterial genera such as *Pseudomonas*, *Rhizobium*, *Bacillus*, *Azospirillum*, *Oidiodendron*, *Gluconobacter diazotrophicus*, *Burkholderia*, *Serratia*, *Acinetobacter*, *Thiabacillus thiooxidans* and *Thiobacillus ferrooxidans* have been shown to enhance plant growth and significantly improve Zn acquisition in plant tissues (Sharma et al. 2016; Kamran et al. 2017; Saharan et al. 2019). Application of potential indigenous Zn solubilizes enhanced Zn content in shoot and root in soybean and wheat crops when compared to uninoculated control, as demonstrated by He et al. (2010) and Madhaiyan et al. (2010). Similarly, augmentation in plant biomass accumulation and acquisition of Zn through inoculation of Zn solublized rhizospheric microbiomes has been noticed (Rana et al. 2012).

6.5 *Siderophore Production*

Iron (Fe) is the fourth most abundant micronutrient in the earth's crust is necessary for synthesis of cytochrome oxidase, ribonucleotide reductase and also acts as cofactor or metal activator for over 140 enzymes in the metabolic processes. Under aerobic conditions (in an abundance of oxygen), it exists as Fe^{3+} (Ferric), insoluble hydroxides and oxy-hydroxides which are unavailable to plant and rhizospheric microbes (Rajkumar et al. 2010). Beneficial rhizospheric microbiome produce Fe-chelating compounds, i.e., siderophore, thus overcoming low Fe availability, resulting in high solubility of Fe hydroxides (Schalk et al. 2011). They also form stable complexes with heavy metal (Al, Cd, and Cu) and radionuclides (U and Np) and possess biocontrol activities by scavenging Fe making it nonavailable for phytopathogens (Ahemad and Kibret 2014; Saharan et al. 2019).

Siderophore producing native rhizospheric microbes are beneficial for increasing plant height and also enhance nutrient accumulation, prevent damage by phytopathogens using antibiotics along with Fe scavenging metabolic activities (Shen et al. 2013). Parray et al. (2016) demonstrated the role of siderophore producing *Pseudomonas* strain GRP-3 in iron nutrition by siderophore production in *Vigna radiata* decreasing chlorosis and improved chlorophyll content over control treatment. Similarly, Rajkumar et al. (2010) reported that different strains of *Ensifer meliloti* having siderophore producing ability that suppressing *Macrophomina phaseolina*, causing charcoal rot of groundnut. Mycorrhizae also play a role in biosynthesis of low molecule weight iron chelating compounds, i.e., siderophores and organic acids such as oxalic acid and citric acid and provide proton for mobilization of available Fe present in rhizospheric soil and may also prove to be beneficial for Fe uptake in various plant crops (Winkelmann 2007; Bharadwaj et al. 2012).

6.6 *Ethylene, ACC Deaminase: Strategy to Mitigate Salt Stress*

Ethylene (ET) is an essential stress hormone, produced in plants which regulates many physiological processes including seed emergence, senescence, and organ abscission and are also key in upregulation response crucial for dealing with biotic and abiotic stress tolerance (Etesami and Beattie 2017). Low-concentration ethylene has been reported as a crucial defense against the abiotic stresses, whereas high concentration of ethylene may cause ethylene stress hindering plant growth, i.e., senescence, leaf abscission, and chlorosis (Dodd et al. 2010; Yoon and Kieber 2013; Glick 2014). Rhizospheric microbiomes have the ability to assimilate ACC deaminase enzyme, converting ethylene into ammonia and α-ketobutyrate which provides both nitrogen and energy under abiotic and biotic stress conditions (Kumawat et al. 2021). Indigenous rhizospheric with ACC deaminase activity has been studied for their ability mitigate stress due to ethylene and an improvement in growth of tomato and rice was observed even under abiotic stress conditions (Bal et al. 2013). Aslam and Ali (2018) also documented ACC deaminase activity in rhizospheric microbial genera of *Brevibacterium*, *Arthrobacter*, *Pseudomonas*, *Virgibacillus*, *Rhizobium*, *Gracilibacillus*, *Stenotrophomona*s, *Bacillus*, S*alinicoccus*, *Exiguobacterium*, *Enterobacter*, *Klebsiella*, *Methylobacterium*, *Planococcus*, *Acidovorax,* and *Variovorax,* etc. ACC deaminase plays an important role in enhancing infection thread, persistence which is adversely affect by ethylene under salt stress in legume crops during nodulation (Nascimento et al. 2016). Shaharoona et al. (2006) documented that coinoculation of ACCD possessing PGPR with *Bradyrhizobium* in mungbean enhanced symbiotic traits by reducing ethylene as compared to single *Bradyrhizobium* treatment. Similarly, microbial strains *B. iodinum* RS16, *Z. alba* strain RS-11, and *B. licheniformis* RS 56, which produce ACC deaminase and are halotolerant, have reportedly reduced secondary ethylene peak in red pepper plant at 150 mM NaCl concentration (Zafar-ul-Hye et al. 2014; Qin et al. 2018).

6.7 Rhizospheric Microbiome Antagonistic Activities

Soil-borne phyto-pathogens negatively affect agricultural productivity worldwide. Rhizospheric microbiomes play an important role to control these pathogens as they increase competition for colonization sites, synthesize antimicrobial metabolites (antibiosis), secrete Fe scavenging proteins, and induce systemic resistance. They also produce cell wall-degrading enzymes (chitinase, cellulase, protease, xylanase, and pectinase, etc.) against pathogens causing cell contents to leak out leading ultimately to collapse of the evading phyto-pathogens due to failure in marinating cellular integrity. Microbial diversity of disease suppressive soil is often dominated by antagonistic microorganisms which produce a diverse array of antibiotics with biostatic as well as biocidal effects on the soil-borne pathogens (Mohseni et al. 2013; Rahul et al. 2014). Beneficial microbes are known to promote plant growth by suppressing pathogens, namely, *Sclerotium rolfsii*, *Rhizoctonia solani*, *Botrytis cinerea*, *Phytophthora* sp., *Fusarium oxysporum,* and *Phythium ultimum,* by producing antifungal metabolites, i.e., HCN, protease, cellulase, chitinase, and pectinase (Bhattacharyya and Jha 2012; Nadeem et al. 2013).

6.8 Rhizospheric Microbes as Biotic Elicitors

Most elicitors are obtained from beneficial rhizospheric microbiomes discounting their nature and type and are involved in plant defense mechanisms (Thakur and Sohal 2013). Exogenous applications of these defense signaling molecules such as methyl jasmonate, 2–3-butanediol acetoin, salicylic acid, and nitric oxide (NO) induce accumulation of a wide range of secondary metabolites such as phytoalexins, indoleglucosinolates, and alkamides (Ortiz-Castro et al. 2009). Biotic elicitor signal transduction pathway in crop plant is the first committed step for signal perception and uses specific elicitor-binding proteins a knowledge of which is important for a clear understanding of molecular basis of signal exchange between host plant and phyto-pathogen that eventually cause the host defense system to activate against the diverse range of pathogen associated with host plant (Bhattacharyya et al. 2016).

7 Impact of Rhizospheric Microbes in Stress Agriculture

A huge challenge in agricultural sector is to find an alternative approach for abiotic stresses (drought and salinity) that are harmless to the soil and also impart agriculture sustainability increasing crop production in an eco-friendly manner (Hamilton et al. 2016). It is a known fact that halo-drought-tolerant rhizospheric microbiomes have an inherent capability under soil salinity and drought conditions (Gepstein and Glick 2013; Glick 2014). The application of bioenhancers/bioprotectants not only enhances crop productivity but also improves plants survival under extreme conditions of salinity and drought through different pathways (Palacios et al. 2014).

The enhancement of plant growth by using drought and salt-tolerating rhizospheric microbiomes in abiotic-stressed conditions is accredited to several physiological mechanisms that include improvement in plant nutrient by means of biological nitrogen fixation, siderophore production, phytohormone synthesis, nutrients solubilization/mobilization (Etesami and Beattie 2017; Etesami 2018; Nagpal et al. 2019), lowering the levels of ethylene by ACC deaminase enzyme activity (Saharan and Nehra 2011; Kumawat et al. 2021), synthesis of exopolysaccharides and biofilm formation that prevent the accumulation of Na^+ ions by plant roots (Qin et al. 2016; Etesami and Beattie 2017), maintenance of a relatively high K^+/Na^+ ratio (ion homeostasis) by a stringent regulation of expression of ion transporters in order to protect against the ion toxicity (Islam et al. 2016; Etesami 2018; Etesami and Beattie 2018), supplement accumulation of osmo-protectants such as glycine betaine, trehalose, and proline (Creus et al. 2004; Arora et al. 2012), upregulating antioxidant enzymes such as superoxide dismutase, catalase, ascorbate peroxidase, and glutathione reductase to provide defense against oxidative stress (Islam et al. 2016; Qin et al. 2016), and maintenance of increased levels of photosynthesis as well as stomata conductance (Del Amor and Cuadra-Crespo 2012).

Recently, Damodaran et al. (2019) reported that improved seed germination, plant growth promotion rice, and wheat grain yield can be achieved by use of *Lysinibacillus* sp. While also mitigating harmful impact of salinity due to osmoprotectant accumulation, the regulation of gene expression is associated with saline stress and antioxidative enzymatic pathway. Harmful effects of salinity on leguminous crops (soybean, mungbean, groundnut, pigeon pea, and common bean) have previously been investigated by a number of soil microbiologists along with possible solutions to the same by the use of drought-tolerating microorganisms (Dardanelli et al. 2008; Meena et al. 2017; Yasin et al. 2018). Similarly, Gupta and Pandey (2019) demonstrated that the deleterious impacts of salinity or drought stress were alleviated by microbial consortium of *Aneurini bacillus aneurinilyticus* and *Paenibacillus* sp. leading to increased root–shoot ratio, plant biomass, and chlorophyll content of french bean seedling under conditions of increased salinity.

8 Mycorrhizal Association: A Critical Component of Healthy Soil Rhizosphere

Mutualistic associations of mycorrhizae that develop among soil fungi and plant root gradually evolve to provide equal benefits for both fungal and host plant partners (Brundrett 2002). The beneficial effects are generally brought about by exchange of photo-synthetically derived carbohydrate from crop plant for essential soil nutrient provided by foraging mycorrhiza. Mycorrhizae are essential for shaping plant communities and also for sustaining the functional diversity of rhizospheric microbiome through transports of photo-synthetically derived carbohydrate into the soil in the form of diverse range of sugar, amino acid, and polyols (Tarkka et al. 2018). Mycorrhizal association shows many diverse interactions within the rhizosphere “myco-rhizosphere” including such as phyto-pathogens and mutualisms that fix atmospheric nitrogen, mobilization of phosphorous, produce vitamins, plant growth regulators, and protect against the phyto-pathogens (Tedersoo et al. 2020). Vesicular arbuscular mycorrhizae also support large diversity of rhizospheric microbiomes that further accelerated minerals weathering by excreting organic acids, accumulation of siderophore, and antibiotic against the pathogens (Ray et al. 2020). Sultana and Pindi (2012) reported that application of consortium (AMF, *Rhizobium* sp., and PGPRs) significantly enhance plant growth, nutrient acquisition, N_2 fixation, and alteration of root architecture as for better nutrient absorption in the cotton plant as compared to uninoculated control.

9 Future Prospects and Challenges

Rhizospheric microbiomes and their extensive physiological activities are of significant importance for the agricultural sustainability and also for sustaining life on earth. Conservation of ecological diversity is an essential in the maintenance of microbial species for better management strategies such as plant disease management, restoration of degrade ecosystem, and nutrient management through biogeochemical cycles (Classen et al. 2015). Potential microbial inoculants are used to enhance soil health and to remove soil contaminants through the process of bioremediation and control of pest and disease of crop plant through application of *Trichoderma* formulations (Kumar et al. 2014). Extensive research programs also need to be developed in the wake of changing climatic conditions to enhance alternative microbial remediation technologies that use decontaminated soil and groundwater for sustainable agriculture purposes. Microbial bioinformatics/genomics-based approaches can expedite effective research strategies to explicate mechanisms of microbial pathogenicity and their potential impact toward the sustainable agriculture development. As bioinformatics studies accrue, constructing a precise framework of the biology behind genetic regulation that brings about complex interactions in microbial world still remains a challenge and so are the studies concerning proteomics and genomics of the diverse microbial population that are advantageous to the cause of sustainability. Farmers who tend to struggle to adapt to smart farming techniques to increase crop production under changing climatic conditions can potentially act as proficient stress alleviators in agricultural crops and promoting sustainable management.

10 Conclusions

Due to imprudent use of agrochemicals, intensive agriculture system faces diverse challenges including a stark decline in soil structure and soil microflora and gradual loss of water, air, and nutrients. Environmental sustainability has now become a contemporary challenge that is being widely researched upon by scientists. The applications of effective and beneficial potent rhizospheric microbiomes are the alternative way to overcome such type challenges. As stated earlier, native rhizospheric microbiome-based technology is a novel approach and has provided solutions that range from biodegradation, bioleaching, biocomposting, biological nitrogen fixation, to improvement of soil health and crop production leading to a more sustainable agricultural system without causing environmental pollutions.

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Chapter 28
Crop Production and Soil Management Interventions for Increased Organic Carbon Sequestration in Soils

Pritpal Singh, Sandeep Sharma, Shahida Nisar, Rajeev Kumar Gupta, and Sukhwinder Singh

Abstract Water, energy and labor scarcity, and increasing cost of production are major challenges faced by the farmers under intensive agriculture production system. To address these challenges, various soil and crop management practices viz., crop rotations, crop residue management, tillage and fertilizer application are advocated to ensure food security and environmental protection to achieve ecosystem sustainability. Crop residue burning has become a significant contributor to atmosphere pollution coming third after industrial and vehicle emission has caused serious environmental implications. Nonetheless, crop residue burning has been equally detrimental to the soil's health, because of the huge loss of essential plant nutrients and reduces microbial activities due to increased soil temperature to ~42 °C up to a depth of ~2.5 cm. Crop residue management strategies could reduce soil organic carbon (SOC) loss and risks of water and wind erosion by altering soil surface cover. As a result, these strategies may also alter soil characteristics. This chapter aims to discuss the impact of in-situ and ex-situ crop residue management strategies viz., integrated nutrient management (INM), crop residue management, cover cropping, cropping systems and biochar on C sequestration, and their role to mitigate the emission of greenhouse gases (GHG). Since organic C in the soil is a central determinant of soil physical, chemical properties and biological activity of soil, therefore, the adoption of crop residue management practices that increase C input to the soil and reduce C losses for the improvement of soil fertility and its functions, while controlling erosion, and to sustain the crop productivity in intensive cropland ecosystems is required.

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1 Introduction

Soil is an important sink of carbon (C) and plays a major role in its cycling in terrestrial ecosystems (Sharma et al. 2020a). On a global scale, soils contain 1500 Pg (1 Pg = 10^{15} g) organic C in the top 1 m of soil profile. In the top 30 cm soil layer, the total C stored is times that of total C in vegetation (Powlson et al. 2011). However, C stored in soil is vulnerable to losses as carbon dioxide (CO_2), and has caused depletion of the total organic C pool by ~25%–75% (equivalent to 10–30 Mg C ha^{-1}) in most soils of the agroecosystems C (Lal 2004a). This historic loss of soil organic C (SOC) has rendered the cultivated soils as a potential sink for C sequestration. The C sequestration in soil is net effect of C input through various management practices and its loss as CO_2, which is mediated by microbial decomposition (Benbi et al. 2012; Singh and Benbi 2018a, b; Singh and Benbi 2021; Sharma et al. 2020a, b, 2021a, b). It has been estimated that decomposition of soil organic matter (SOM) contributes about 50 Pg C to the atmospheric carbon (Paustian et al. 2000). Soils contributed ~1/4th of the historic anthropogenic CO_2 emission during the past two centuries (Duxbury 1994). Nonetheless, the potential of soils to offset C emission is estimated to be 1.15–3.30 Pg C $yr.^{-1}$ (Cole et al. 1997). Therefore, soil C sequestration with adoption of various soil and crop management practices is considered a promising approach to mitigate atmospheric load of CO_2 (Singh and Benbi 2020a, b; Madiwalar et al. 2023). Soil C sequestration is strongly influenced by cropping systems (Singh and Benbi 2020a; Sharma et al. 2020a, b) management practice including nutrients and organic manures (Singh and Benbi 2023), and land-use type or change (Kaur et al. 2008; Benbi et al. 2012, 2015; Brar et al. 2013; Mandal et al. 2022; Avtar-Singh et al. 2022). Increasing C sequestration in agricultural soils not only would help to mitigate rising atmospheric CO_2 concentration (Lal 2004b; Ghosh et al. 2012; Singh and Benbi 2020a, b; Singh et al. 2021a, b) but would also lead to improvement in soil physical, chemical and biological properties (Haynes 2005; Singh and Benbi 2016; Sharma et al. 2020a; Sharma et al. 2021a; Singh et al. 2023a, b).

Cropping systems and nutrient management practices such as balanced application of nutrients and integrated nutrient management are advocated as important factors affecting the amount of SOM returned to the soil (Singh et al. 2021a). The high biomass producing crops and increased crop productivity under intensive agriculture return higher crop residues and root biomass to the soil (Mandal et al. 2007; Majumder et al. 2007a, b; Purakayastha et al. 2008; Ghosh et al. 2012; Sharma et al. 2020a, b; Singh and Benbi 2021). Rice, wheat and maize significantly influence the degradation and accumulation of SOM because these crops are grown under contrasting soil conditions such as wheat and maize under well-aerated conditions and rice under anaerobic conditions (Singh and Benbi 2020a, b, 2023). The contrasting soil moisture regimes under these crops considerably influence the rates of SOM decomposition and its stabilization in various C pools (Benbi et al. 2015; Singh and Benbi 2020a, 2020b). The cropping systems also differ in their rooting behavior and thus result in differential input of C to soil (Singh and Benbi 2020a, b; Singh et al. 2021a). Soil management practices associated with crop production often influences both quality and quantity of SOC, and its turn-over rates (Majumder et al. 2007a, b; Benbi et al. 2012; Ghosh et al. 2012; Das and Maiti 2016; Singh and Benbi 2018a; Sharma et al. 2020a, b). This has grown an interest in C sequestration through soil and crop management practices (Russell et al. 2005; Wilson and Kaisi 2008; Sharma et al. 2022a, b, c) to mitigate rising concentrations of atmospheric CO_2 and improve soil quality for agricultural sustainability (Sharma et al. 2020a, b). Among the advocated agricultural management practices, application of balanced fertilizers (Halvorson et al. 2002; Banger et al. 2010; Sharma et al. 2022a), organic amendments (Kaur et al. 2008; Banger et al. 2010; Brar et al. 2013), land-use type/change (Lawal et al. 2009; Benbi et al. 2012; Sharma et al. 2022b, c, d) and cropping systems (Singh and Benbi 2020a, b) are the important practices that significantly contribute toward soil C sequestration and consequently mitigate C emission (Benbi et al. 2016). Soils under rice–wheat cropping systems of subtropical parts of India have depleted ~30%–60% of its SOC (Swarup and Yaduvanshi 2000; Lal 2004a; Mulvaney et al. 2009). Contrary to the rice–wheat system, soils under soybean–wheat system have shown lesser depletion SOC due to greater C input into the soil through continuous falling of soybean leaves (Manna et al. 2013). The information on the effect of different crop production and soil management practices on C sequestration potential has been extensively studied. The information on impact of different management practices on C sequestration potential is presented under following subheadings.

2 Crop Residue Burning Vis-à-Vis Carbon Loss

Burning of crop residues is a major environmental concern, especially in Indo-Gangetic Plains (IGPs) of South Asia with rice–wheat system (RWS) as predominant cropping sequence (Bhatt et al. 2019, 2021; Sharma and Singh 2023; Sharma et al. 2023). Recently, it is estimated that annual production of rice residues is highest in India about 242 million tons (Mt), followed by china 97 Mt., Thailand 22 Mt., and 11 Mt. by Philippines (Liu et al. 2011; Gadde et al. 2009). Globally, ~3.5 Pg year^{-1} (1Pg = 10^{15} g) of crop residue in produced, of which only ~50%–60% is returned into the soil (Lal 1999). Residue burning in RWS has been related to highly mechanized system involving mechanical harvesting of crops, leaving behind huge residue biomass of ~30%–60 cm high stubble remained in the fields (Sidhu et al. 2007). Residue burning in fields in often incomplete, producing huge quantities of greenhouse gases (GHGs) such oxides of C (CO and CO_2), N (N_2O) and sulfur (SO_2), volatile organic compounds (VOC), dioxins and furans, carcinogenic polycyclic aromatic hydrocarbons (PAH), and fine inhalable particulate matter ($PM_{2.5}$)

(Jenkins et al. 2003; Oanh et al. 2011). About 25% of India's black C, organic matter and CO, 9%–13% of its $P.M_{2.5}$ and CO_2 emissions, and ~ 1% of its SO_2 emissions were ascribed to open field residue burning. The C and N in crop residue emit 57%–81% as CO_2-C, 5%–9% as CO-C, 0.43%–0.90% as CH_4-C and 1.2%–1.5% as N_2O-N (Miura and Kanno 1997). Estimates revealed that open field burning of 1 Mg rice residue release of 13 kg particulate matter, 1460 kg CO_2, 1.0 kg CH_4, 0.06 kg N_2O, 60 kg CO, 3.2 kg nonmethane hydrocarbon (NMHC) and 3.5 kg NOx, 1.6 SO_2 (Gadde et al. 2009; Silalertruksa and Gheewala 2013; NAAS 2017). As compared to the conventional method of rice cultivation coupled with open field residue burning in north-western India. Crop residue burning leaves high C footprints and also lowers the amount of C input to the soil organic C pool (Singh et al. 2020, 2021b, c). On the other hand, Singh et al. (2020) reported that residue retention reduced C footprints by ~14.1% and energy footprints by ~12.9% in rice–wheat cropping system of north India.

3 Cropping Systems, Cover Crops and Intercropping Vis-à-Vis Carbon Sequestration

The C sequestration in soils depends upon crop rotation such as, intercropping, cover cropping and ratoon cropping (Makumba et al. 2007; Wilson and Kaisi 2008; Wang et al. 2010a, 2010b; Bhatt et al. 2022). Saskatchewan, Canada, Campbell et al. (1995) reported higher gain of ~2.0 Mg C ha^{-1} in 0–15 cm brown Chernozem soils in continuous wheat (*Triticum aestivum*) cultivation than in fallow–wheat cropping sequence during 12 years. Similar to this Halvorson et al. (2002) reported that in dry land soils of North Dakota, wheat (*Triticum aestivum*)–fallow system for 12 years, even no-tillage (NT), resulted in loss of SOC. This was due to high microbial activity that increased decomposition of SOM with no C input of crop residue in fallow period. Comparing annual and perennial cropping systems, Kroodsma and Field (2006) reported that C sequestration was lowest (55 g C m^{-2} $yr.^{-1}$) in annual cropping system of rice and increased when switched from annual crops to perennial crops of vineyards that sequestered 68 g C m^{-2} $yr.^{-1}$ and in orchards C sequestered was 85 g C m^{-2} $yr.^{-1}$. Low C sequestration in soils under rice cultivation was attributed to the rice residue burning after harvesting which decreased C input through residues. Cover crops considerably affect the C sequestration through biomass accumulation. Bell bean (*Vicia faba* L.) sequestered higher C than white clover (*Trifolium repens*) in fine sandy soils of United States during winter season and sun hemp (*Crotalaria juncea* L.) accumulated higher C (481 g m^{-2}) than castor bean (*Ricinus communis*) which accumulated 102 g C m^{-2} (Wang et al. 2010b).

In long-term studies (>10 years) gliricidia–maize cropping system accrued 0.8–4.8 Mg C ha^{-1} compared to 0.4–1.0 Mg C ha^{-1} in sole maize cropping (Makumba et al. 2007). In this study, sole maize system resulted in a net decrease of 6.0–7.0 Mg C ha^{-1} in top 20 cm soil layer over initial C content. In 200 cm soil profile, gliricidia–maize system stored 123–149 Mg C ha^{-1} through root biomass and pruning application (Makumba et al. 2007). Intensive pruning of gliricidia trees may add 4.0–5.0 Mg dry biomass ha^{-1} to the soil (Makumba et al. 2006). Higher SOC stocks in the MWS than RWS were due to application of FYM in the maize. Kukal et al. (2009) reported higher SOC stocks in RWS than MWS due to submergence of the rice in the former cropping system and due to production of higher biomass in rice as compared to maize. Quantification of C sequestration in different cropping systems in subtropical region, Brar et al. (2015) reported that gain in SOC stocks after 8 years was highest in maize–potato–onion (7.3 Mg ha^{-1}) than groundnut–toria–gobhi–sarson (3.4 Mg ha^{-1}) cropping system.

Multiple crop rotations including green manure alfalfa, maize–oat–alfalfa and corn–oat–alfalfa had more SOC stocks than double crop sequence without alfalfa such as corn–soybean cropping sequence which in turn stored higher SOC stocks than continuous corn (Russell et al. 2005). Lower SOC stocks in continuous corn had highest CO_2 emissions compared to corn–soybean cropping system (Wilson and Kaisi 2008). In north-west India, Singh and Benbi (2020b) reported that in rice–wheat cropping system the higher yield scale C emissions measured as greenhouse gases intensity (GHGI) were significantly higher than maize–wheat and cotton–wheat cropping system. The MWS has the higher C emission ratio of 9.6 than the rice–wheat (8.1) and cotton–wheat (7.0), which revealed that MWS had higher capabilities to fix atmospheric C per unit of the amount of C emitted to the atmosphere.

4 Nutrient Management Vis-à-Vis Carbon Sequestration

Fertilizer application increases the plant biomass and residue returned to soil that adds C into soil. Improved nitrogen (N) management is of utmost importance for C sequestered in soils to ensure mitigation of GHGs (Six et al. 2004). In cropping systems such as cotton (*Gossypium hirsutum* L.)–cotton–corn (*Zea mays* L.) and rye (*Secale cereale* L.)/cotton–rye/cotton–corn application of fertilizer-N increased crop mediated C due to increased biomass (Sainju et al. 2008b). However, Halvorson et al. (2002) reported that the addition of N fertilizer did not significantly affect the soil C sequestration even though higher N fertilizer increased crop residue production of spring wheat (*Triticum aestivum* L.)–winter wheat–sunflower (*Helianthus annuus* L.) and spring wheat–fallow cropping system. The SOC stocks increased from 37.2 Mg ha^{-1} in unfertilized N-control to 38.8 Mg ha^{-1} in plots receiving 270 kg N ha^{-1} (Wilson and Kaisi 2008). This was in accord with Russell et al. (2005) who reported that N application though increased corn yields but did not significantly influence the SOC stocks in 15 cm soil depth. On the other hand, Halvorson and Reule (1999) reported that application of N fertilizer for long-term under no-tillage in dry land annual cropping leads to higher C sequestration.

In different forest ecosystems, Adams et al. (2005) reported C sequestration higher by ~24.7% when N was added over the control. Kukal et al. (2009) studied effect of N on C sequestration and reported that SOC stocks increased by ~38% in RWS and ~14% in MWS. Sharma et al. (2020a) reported higher C sequestration with recommended application of N fertilizer and decreased when N rate was applied more than recommended dose. In hot humid tropic region, recommended application of N to wheat–jute rotation significantly increased C sequestration in 60 cm soil profile over fallow and unfertilized control. After 11 years of N fertilization in rice–wheat system at different rates, Benbi et al. (2016) reported that application of N fertilizers at different rates did not significantly influence SOC stocks.

5 Agriwaste Management Vis-à-Vis Carbon Sequestration

Agricultural wastes viz., crop residue, poultry litter, farmyard manure, compost and green manures have a pivotal role to either increase or maintain SOC content. These wastes also improve production by recycling the mineral nutrients, improving physical, chemical and biological properties of soil, increasing fertilizer use efficiency and decreasing soil erosion (Tables 28.1, 28.2, 28.3, and 28.4). However, the potential of added crop residue to increase SOC is largely influenced by the composition of these residues such as C content, C/N ratio, lignin content and the amount of C input in the soil system (Kaisi and Grote 2007). Increase in SOC has a linear relationship with the amount of C input to the soil through crop residues. In RWS, a significant and strong positive linear relationship ($R^2 = 0.980$) between SOC sequestration and cumulative C input from added organic sources was obtained after 19 years of the study (Ghosh et al. 2010). Similarly, Fortuna et al. (2003) reported that application of compost for 6 years increased resistant C pool by 30% and slow pool of C by ~10%. Application poultry litter for 10 years resulted in C sequestration rate of 510 kg C ha^{-1} $yr.^{-1}$ compared with −120 to +147 kg C ha^{-1} $yr.^{-1}$ in 20 cm soil layer with application of N fertilizer without poultry manure (Chan et al. 2008). The higher in SOC sequestration rate with application of poultry litter compared with inorganic N fertilization was due to supplementation of C input at the rate 1.7 Mg ha^{-1} $yr.^{-1}$ from poultry litter (Sainju et al. 2008a). Integrated application of NPK along with farmyard manure (FYM) for 45 years increased SOC by ~115% compared to ~3.0% when NPK was applied alone (Raji and Ogunwole 2006). This resulted in improvement in SOC stocks from 4.95 to 7.30 Mg C ha^{-1}. In another study, Kaur et al. (2008) reported higher gain in SOC stocks with conjoint application of recommended NPK and FYM for 34 years due to higher crop mediated C input in MWS compared to sole application of recommended NPK fertilizers. Banger et al. (2010) reported that integrated use of inorganic NPK plus FYM and sole application of FYM enhanced SOC by 33.4 and 36.3% over the unfertilized control, respectively. It has been estimated that C loss from soils could not be compensated through plant-mediated C inputs through plant photosynthates to maintain SOC levels which is evident from the negative value of C sequestration in soil (−410 to −193 g C m^{-2}) in different crops such as grass, cereals and pulses (Mu et al. 2006). In RWS, Benbi and Senapati (2010) studied the effect of different sources of

Table 28.1 Soil organic C sequestration in different cropping systems, cover crops and intercropping

Cropping system (s)	Soil type	Climate	Soil depth (cm)	Study period (years)	C sequestration (Mg C ha^{-1})	Reference
Continuous corn Corn soybean	Calcareous loam	Temperate	0–15	2	37.6 39.4	Wilson and Kaisi (2008)
Fallow–wheat Continuous wheat	Chernozem	Temperate	0–15	12	22.3 30.4	Campbell et al. (1995)
Spring wheat–winter wheat–sunflower	Fine silt	Temperate	0–30	12	CT; 65.6 NT; 62.9	Halvorson et al. (2002)
Spring wheat–fallow					CT; 64.1 NT; 70.6	
Continuous maize Gliricidia–maize	Sandy clay	Subhumid	0–20	10	19 30	Makumba et al. (2007)
Corn–soybean Continuous corn Corn–corn–oats–alfalfa	Fine loam	Temperate	0–15	48	34.1 37.8 38.8	Russell et al. (2005)
Agroforestry Maize–wheat Rice–wheat	Sandy loam	Subtropical	0–15	5–6	16.1 13.9 8.5	Benbi et al. (2012)
Maize–wheat Rice–wheat	Sandy loam	Subtropical	0–60	32	21.3 29.6	Kukal et al. (2009)
Rice–wheat Maize–wheat Maize–wheat–summer mungbean Maize–potato–summer mungbean Maize–potato–onion Cotton–wheat Groundnut–toria–gobhi–sarson	Loamy sand	Subtropical	0–60	8	4.4 5.9 6.5 6.9 7.3 4.4 3.4	Brar et al. (2015)

Acronyms: *CT* Conventional tillage, *NT* No tillage

organic amendments viz., rice straw and FYM and their combination on C sequestration. They concluded that soils of RWS in subtropical region require a minimum amount of 7.6 Mg C ha^{-1} annually to maintain C concentration. This much amount cannot be met mere by plant C through roots and stubble, but external application of amendments like FYM, rice straw, vermi-compost and straw compost plays a great role in maintaining SOC.

Table 28.2 Soil organic C sequestration at different levels of fertilizer-N in different cropping systems

Cropping system	Nitrogen rate (kg ha^{-1})	C sequestration (Mg ha^{-1})	Reference
Spring wheat–fallow	34 67 110	36.2 37.6 35.6	Halvorson et al. (2002)
Spring wheat–winter wheat–sunflower	0 22 45	35.9 36.6 36.8	
	0 135 270	37.2 39.2 38.8	Wilson and Kaisi (2008)
Corn–soybean	0 90 180 270	31.4 34.1 32.8 34.4	Russell et al. (2005)
Continuous corn	0 90 180 270	35.1 37.8 38.4 39.8	
Corn–corn–oats–alfalfa	0 90 180 270	39.0 38.8 38.5 40.5	
Forest ecosystem	0 224	335 418	Adams et al. (2005)
Rice–wheat	0 120	21.4 29.6	Kukal et al. (2009)
Maize–wheat	0 100	18.7 21.3	
Fallow control wheat–jute	Fallow=0 Control=0 Wheat-jute=180	56.9 48.9 60.6	Majumder et al. (2007a, b)
Rice-wheat	0 90 120 150	9.6 11.5 11.1 10.4	Sharma et al. (2020a)
Rice–wheat	0 60 120 180	7.45 7.71 7.77 7.81	Benbi et al. (2016)

Table 28.3 Effect of fertilizer-P on soil C sequestration in soils (contd.)

Treatment	Cropping system	Soil depth	C accumulation	Reference
NP PK NPK	Rice–wheat	0–15	4.47 g kg^{-1} 4.87 g kg^{-1} 4.89 g kg^{-1}	Singh and Benbi (2018a)
Control N NP	Rice–cowpea	0–30	3.51 g kg^{-1} 3.83 g kg^{-1} 3.81 g kg^{-1}	Banger et al. (2010)
Control N NP NPK	Wheat–wheat–maize	0–20	10.1 g kg^{-1} 10.3 g kg^{-1} 10.1 g kg^{-1} 10.5 g kg^{-1}	Su et al. (2006)
Control N NP NPK	Maize–wheat	0–15 cm	3.1 g kg^{-1} 3.3 g kg^{-1} 3.4 g kg^{-1} 3.8 g kg^{-1}	Kaur et al. (2008)
Control P	Pasteur grazed land	0–60 cm	47.5 Mg C ha^{-1} 59.5 Mg C ha^{-1}	Coonan et al. (2019)
Meta-analysis of soil organic C response to P fertilizer				
			SOC response (%)	
Cropping system	Rice–rice single Rice–wheat Maize–wheat	0–20 cm	1 3 7 8	Zhao et al. (2017)
Experimental duration	<10 10–20 >20	0–20 cm	2 3 7	

6 Agriwaste Management Vis-à-Vis Carbon Pools

Soil organic C pools characterized by chemical methods such as water soluble C (WSC), hot water soluble C (HWSC), $KMnO_4$ oxidizable C, biological C pools such as microbial biomass C (MBC) and physically fractionated C pools such as particulate organic matter (POM), mineral associated C (MinOC) and light fractions of C (LFC) were higher with sole application of organic amendments followed integrated application of NPK and FYM and lower in sole application of NPK fertilizers (Banger et al. 2010). Labile C fractions which represent oxidizable C pool increased by ~28% with application of inorganic fertilizers (NPK) in conjunction with rice straw and by ~25% in NPK along with green manure (*Sesbania sesbania*) for 19 years over unfertilized control in rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system of IGPs of India (Ghosh et al. 2010). Higher oxidizable or labile C fraction in rice straw amended plots has been ascribed to higher content of polysaccharide (cellulose and hemi-cellulose) in crop residue resulting in higher production of labile C fractions compared to GM (Ghosh et al. 2010). Application of vermi-compost, FYM and rice straw compost for 10 years showed that compost

Table 28.4 Agriwaste management and C input vis-à-vis C sequestration in soils

C input source	Carbon input (Mg C ha^{-1} yr^{-1})	C/N ratio	C sequestration (Mg C ha^{-1} yr^{-1})	Reference
Corn	2.32	109.2	0.80	Kaisi and Grote (2007)
Soybean	1.69	22.9	0.84	
Switch grass	8.40	72.3	0.90	
Vermi-compost	8.94	14.6	0.85	Nisar and Benbi (2020)
FYM	18.44	37.9	0.91	
Rice straw compost	13.07	23.9	1.22	
NH_4NO_3 fertilizer	–	–	0.14	Sainju et al. (2008a, b)
Poultry litter	–	–	0.46	
NPK	–		0.026	Raji and Ogunwole (2006)
NPK+FYM	–	–	0.81	
Fallow	0.12		2.5 g kg^{-1}	Kaur et al. (2008)
Control	0.32		3.1 g kg^{-1}	
100%NPK	0.73		3.9 g kg^{-1}	
100%NPK+FYM	1.05		4.5 g kg^{-1}	
Control	9.5		9.8	Benbi and Senapati (2010)
FYM+N	42		12	
Rice straw with N	46.8		10.1	
Rice straw with FYM	66.8		12	
Rice straw with N+FYM	85.4		13	
Rice straw	4.8	116	18.3	Benbi and Brar (2021)
Biochar	5.7	28.9	19.3	
Biochar+FYM	6.6	37.9+28.9	18.5	

application enhanced mineral associated C (resistant C pool) higher than FYM, and FYM increased more of labile C as POC than resistant C pool due to higher lignin content in compost (Nisar and Benbi 2020).

7 Phosphorus Fertilization and Carbon Sequestration

Phosphorus (P) is one of the macro primary essential elements for plant growth. High rate of P application may have negative influence on soil organisms such as mycorrhizae development (Ortas 2003) and heterotrophic respiration via a decrease in the availability of C as substrate for microbial growth (Raiesi and Ghollarata 2006; Rowe et al. 2014). However, it is unclear whether P fertilization contributes to C accumulation in soil. Singh and Benbi (2018a) reported no significant effect of P fertilization on C accumulation in soil in RWS. Similarly, in MWS, Kaur et al. (2008) reported that after 35 years of fertilizer management, addition of P fertilizer did not make a significant difference on change in SOC compared when P fertilizer was absent. In rice–cowpea rotation, Banger et al. (2010) reported SOC accumulation of 3.83 g kg^{-1} in sole application of N fertilizer and 3.81 g kg^{-1} in combined application of N and P fertilizers in 30 cm soil profile. In a triple cropping rotation (wheat–wheat–maize), Su et al. (2006) reported that absence of P fertilizer for 23 years did not significantly affect the SOC accumulation. Change in SOC with P fertilization depends on experimental duration, cropping system, geographic region and fertilization rate. Nonsignificant change in SOC with and without application of P fertilizer was due to optimum availability of P in soils. In P-limited pasture grazed soils, SOC stocks increased by ~4% with application of P fertilizer in 0–60 cm soil depth (Coonan et al. 2019). From a meta-analysis of 84 long-term experiments, Zhao et al. (2017) reported increase in SOC in 0–20 cm soil depth by ~10%, 5% and 5% with application of NPK, N and P fertilizers, respectively compared to the unfertilized control. Experiments that were older than 20 years showed prominent effect of P fertilization than short-duration studies (Coonan et al. 2019). Double cropping system shows a greater effect of P fertilization on SOC compared to single crop due to increase in the root density in the former case (Ibrikci et al. 2009; Thorup-Kristensen et al. 2009). In the soil, fertilizers increase SOC sequestration by impacting root biomass and arbuscular mycorrhizal fungi (AMF). Roots release C accounting for ~15%–29% of the total photosynthate and at least 5% of the photosynthate left directly in the soil (Qian et al. 1997; Nguyen 2003). In P-limited soils, addition of P fertilizer increases biomass of AMF, which acquire C from the host plant and release C into the soil (Treseder and Allen 2002; Soudzilovskaia et al. 2015). Moreover, AMF promote aggregation in soil and thereby protect soil C against decomposition (Wilson et al. 2009).

8 Tillage Intensity Vis-à-Vis Carbon Sequestration

Conservation agriculture (CA) with reduced or minimal tillage intensity has been the most credible option for increased C sequestration due to reduced C emissions. Management practices that increase C sequestration in soil by reducing SOM decomposition or soil respiration are RT or NT practices, mulch farming, and reducing bare fallow (Halvorson et al. 2002). The adoption of CA has been advocated as agriculturally best management practice due to high C sequestration potential and low C emissions. Tillage operations accentuate decomposition of SOM through the physical disturbance and exposure of encapsulated C within the soil aggregates (Cambardella and Elliott 1993). Intensive tillage decrease SOC by exposing this encapsulated C within aggregates to microbial decomposition (Oades 1984; Elliott 1986; Beare et al. 1994). An inverse relationship between tillage intensity and soil C sequestration suggested that C sequestration in 0–15 cm soil depth increased with decrease in tillage intensity from conventional tillage (CT) > minimum tillage (MT) > no-tillage (NT) in spring wheat–winter and wheat–sunflower (Halvorson et al. 2002). In tropical and temperate soils, C sequestration rate increased by ~325 ± 113 kg C ha^{-1} $yr.^{-1}$ under NT than CT in (Six et al. 2002). Due to tillage sharp increase in C losses at the rate of 6.24 g CO_2 m^{-2} h^{-1} has been reported in a long-term (15 years) CT plots (Lopez-Garrido et al. 2009). These C losses have been reported higher in CT for 3 years (801 g C m^{-2} $yr.^{-1}$) and 15 years (905 g C m^{-2} $yr.^{-1}$) than 764 g C m^{-2} $yr.^{-1}$ in RT and 718 g C m^{-2} $yr.^{-1}$ in NT treatments for 15 years (Lopez-Garrido et al. 2009). Alvarez et al. (2014) reported that C sequestration increased by 5% in NT than RT after 15 years of the experiment. Soil temperature and soil structure, considered important for C sequestration, are greatly affected by tillage (Paustian et al. 1997). Continuous wheat (*Triticum aestivum* L.) cultivation in NT gained about 1.5 Mg ha^{-1} more C compared with continuous wheat with CT (Campbell et al. 1995). In the same study (Campbell et al. 1995), fallow–wheat system in NT soils increased SOC by 0.5 Mg ha^{-1} than fallow–wheat in CT plots. Increase in SOC due to fallow in a cropping sequence shows the effect of crop residues (above and below-ground biomass) and reduced soil disturbance due to tillage. Wright et al. (2007) reported that 0–5 cm soil depth showed highest effect of soil tillage on SOC restoration wheat (*Triticum aestivum*)–sorghum (*Sorghum bicolor* L.) cropping system which extended up to 15–30 cm depth. Wright and Hons (2005) reported higher SOC sequestration at 0–5 cm soil depth in NT than CT under sorghum (*Sorghum bicolor* L.)–wheat (*Triticum aestivum*)–soybean (*Glycine max* L.) cropping sequence. Effect of tillage in 0–10 cm has also been reported. In a *Rhodic Hapludox* of Southern Brazil, NT increased SOC by ~64.6% in 0–10 cm soil layer than CT under various winter crop cover treatments (Calegari et al. 2008). Conversion from originally untilled soils to cultivation lost up to ~20%–40% SOM (Davidson and Ackerman 1993). In degraded Mollisols, SOC in 0–7.5 cm layer higher (27 g kg^{-1}) in NT than the CT (24 g kg^{-1}) after 8 years while in nondegraded soil, tillage did not show any difference in SOC content (Fabrizzi et al. 2003). More accumulation of SOC in the surface layer could be attributed to the presence of crop residue in the top layer and top layer constitutes more to the total root biomass (Kaisi and Grote 2007). Moreover, the role of tillage on SOC sequestration has been referred as time dependent (Six et al. 2004). Newly converted NT systems resulted in higher net global warming potential (GWP) than CT practices in humid and dry temperate climates which reduced GWP significantly for more than 10 years (Six et al. 2004). Rather, 20 years long-term adoption of NT practice could reduce GWP significantly under dry climatic conditions with high degree of uncertainty (Six et al. 2004). Soil organic C sequestration is also affected by intensity of tillage. Bhattacharyya et al. (2009) reported higher C sequestration in continuous NT followed by NT in wheat and CT in soybean which was at par with CT in wheat and NT in soybean and lowest in CT in both the crops. In MWS, residue retention in NT showed higher SOC sequestration than NT only which was in turn higher than CT. Residue retention decreases soil surface temperature and consequently decreases decomposition of soil organic matter (Zhang et al. 2007). Modak et al. (2019) reported similar results of C sequestration higher by 2.1 Mg ha^{-1} in NT than CT in mixed cropping systems (Table 28.5).

Comparison between power-tillage and traditional plough (tractor mounted cultivator) for puddling the rice field in IGPs of India showed that traditional plough built SOC and microbial biomass (Patra et al. 2010). Dong et al. (2008) reported

Table 28.5 Tillage intensity vis-à-vis C sequestration in soils

Tillage	C sequestration (Mg C ha^{-1})		Soil depth	Reference
CT	37.7		0–15 cm	Halvorson et al. (2002)
MT	39.7			
NT	42.2			
CT	0.62		0–60 cm	Nisar et al. (2021)
DT	0.85			
NT	1.16			
	0–7.5 cm	7.5–15 cm	0–15 cm	Campbell et al. (1995)
CT	16.4	16.1		
NT	17.1	15.5		
	Degraded soil	*Non-degraded soil*		
CT	23.8 (N; 0 kg ha^{-1}) 23.5 (N; 120 kg ha^{-1})	32.0 (N; 0 kg ha^{-1}) 33(N; 150 kg ha^{-1})	0–7.5 cm	Fabrizzi et al. (2003)
NT	26.7(N; 0 kg ha^{-1}) 28.9(N; 120 kg ha^{-1})	32.7(N; 0 kg ha^{-1}) 34.0(N; 150 kg ha^{-1})		
NT	14.3		0–10 cm	Lopez-Garrido et al. (2009)
CT	11.9			
RT NT	62 65		0–100	Alvarez et al. (2014)
CT-CT CT-NT NT-CT NT-NT	22.6 23.9 24.0 24.8		0–15	Bhattacharyya et al. (2012)
CT NT NT with residue retention	28.8 33.2 34.2		0–30	Das et al. (2018)
NT CT	28.1 26.2		0–60	Modak et al. (2019)

Acronyms: *CT* conventional tillage, *MT* minimum tillage, *NT* no-tillage, *RT* reduced tillage, *DT* deep tillage

that higher CO_2 efflux from the soil under rotary tillage and moldboard ploughing (MBP) for 5 years as compared to NT soils. Tillage causes more decomposition of SOM to increase CO_2 efflux from soil (Cambardella and Elliott 1993). Thus, adoption of NT practices reduces C losses by offsetting CO_2 emission and checking SOC losses. Adoption of NT in low-fertile tropical soils has resulted as an efficient management practice for improving physical and chemical characteristics of soils (Lal 1997). The NT or RT management improves soil aggregation and decreased soil respiration and thereby builds-up the C in soil (Paustian et al. 1997; Buyanovsky et al. 1987). The C sequestration is largely dependent upon physical protection of SOC within soil aggregates as a major mechanism for C protection in soils (Gama-Rodrigues et al. 2010). The NT management results in 40% higher aggregate stability compared to CT management system (Jung et al. 2008).

9 Carbon Input Vis-à-Vis Carbon Sequestration

Accrual of SOC is influenced more by boot biomass compared to above-ground biomass (Campbell et al. 1991; Kaisi and Grote 2007) because roots release ~40% of total photosynthates as rhizodeposition within an hour of their production by plants in rhizosphere (Kumar et al. 2006). Rhizodeposition contains organic compounds that play a critical role in aggregate stability to stabilize SOC (Chevallier et al. 2004). Carbon efficiency also depends on the amount of C input to the soil. Halvorson and Reule (1999) reported that C in above-ground biomass increased C sequestration efficiency by ~30% compared to only ~11% by considering C in both above and below ground biomass. The application of fertilizers alone or in combination with FYM improved stability of soil aggregates which in turn provide physical protection to SOC from microbial decomposition (Banger et al. 2010). Accumulation of SOC also varies with composition of C input. For example, Nisar and Benbi (2020) reported higher C sequestration with annual application of rice straw compost at 9.5 Mg ha^{-1} compared to FYM at 15.2 Mg ha^{-1} in rice–wheat cropping system. This was due to more chemically resistant C in composted rice straw than FYM. In the same study, the C sequestration was lower with addition of vermi-compost than FYM due to lower C input in the former one. Therefore, quality as well as quantity of C input to the soils has significant role in SOC accumulation.

10 Inclusion of Leguminous Crops Vis-à-Vis Carbon Sequestration

Leguminous green manures (GMs) crops as nutrient source have resulted as viable alternatives compared to the application of mineral fertilizers in in different crops (Becker et al. 1990). The GM on decomposition acts as a chief source of N in soil. The rate of N release is greatly affected by net rate of immobilization-mineralization which is microbial-mediated process converting organic N to ammonium (NH_4^+) and further to nitrate (NO_3^-) in well aerated soils. A quantitative understanding of N mineralization patterns and the processes governing the decomposition and mineralization of diverse GM residues is needed to achieve synchronization of N supply from applied residues and uptake by crop N plants. It is estimated that application of green manure reduces N application by 25 kg ha^{-1}. Estimation of N released from legume/GM comprises three ways, (i) quantification of N released from decomposing substrates by the method described by Ibewiro et al. (2000), (ii) N-difference method involves comparison of soil available N or N uptake by crops in legume incorporated plot compared with the control plots with no legume addition (Baggs et al. 2003), and (iii) measuring the fate of ^{15}N in crops as well as soils from the labeled legume (Glaser et al. 2002; Crews and Peoples 2005).

Several organic compounds as well as nutrients accumulate in soil on decomposition of a GM. Decomposition of GM proceeds in the formation of organic acids and followed by their conversion into gaseous products (Yadvinder-Singh et al. 1992). Formation of gaseous products is faster in the aerobic soils with optimum soil temperature and moisture conditions leaving little amount of organic acids behind. However, in waterlogged conditions, accumulation of organic acids from decomposition of GM is higher than aerobic soils (Ishikawa and Baba 1988). Many workers (Watanabe 1984; Ceccenti et al. 1990) have detected the release of volatile compounds (mainly acetic acid and butyric acid), phenolic acids (mainly p-hydroxybenzoic, vanillic, and ferulic), alcohols (mainly methanol, ethanol and n-propanol) and nonvolatile aliphatic acids (mainly tartaric) during decomposition of GMs under waterlogged conditions. The peak concentration of methanol and ethanol was detected between 1 and 3 days after submergence (Tsutsuki 1984). It has been reported that release of organic acids reduce shoot weight by retarding root elongation to restrict nutrient uptake (Yadvinder-Singh and Khind 1992). Moreover, addition of GM to soil stimulates the formation of ethylene (C_2H_4), a plant growth regulating hormone. Formation of volatile and nonvolatile fatty acids such as $C_2H_{4,}$ and H_2S, significantly impact on the plant growth.

11 Irrigation Water Management and Carbon Sequestration

Residue removal can alleviate some challenges of high residue production but could increase water and wind erosion, evaporative losses, soil C loss, and particularly, alter soil water dynamics among others. Residue management is critical for soil water storage. Changes in water content and hydrology not only affect environmental quality but also crop production. Residue management can also impact soil organic matter, which can correspondingly impact soil hydraulic properties (Sindelar et al. 2019). However, studies often refer to the percentage of the crop residue removed, probably because erosion control is more closely linked to the percentage of soil covered by residue. It should also be noted that the percentage of crop residue is very different from the mass of residue either harvested or returned (Wilhelm et al. 2011). Ensuring sufficient residue retention (at least 50% residue coverage) can retain soil C and thereby maintain soil hydraulic properties. Researches showed that the amount of residue needed to maintain soil C is greater than that required to reduce water and wind erosion (Wilhelm et al. 2004).

The beneficial impact of residue management practices in term of soil quality is evident from improved physical properties such as lower soil bulk density (B_D), higher aggregation, water holding capacity and improved soil structure. Salahin et al. (2017) in Bangladesh reported that B_D under residue incorporated plots was found to be the lowest (1.38 g cm^{-3}), whereas the B_D was 1.40 g cm^{-3} having incorporation of two crop residues. Highest B_D was 1.44 g cm^{-3} in plots without incorporation of crop residue. Similarly, Salahin et al. (2017) showed highest total porosity (~43.2%) and lowest was in the plots with no incorporation of residues. However, nonsignificant effect of crop residue on B_D was reported by Singh and Malhi (2006) in Canada. Salahin et al. (2017) reported increase in moisture content of soil by ~31% among plots receiving residues of all three crops (wheat, rice and mungbean) than plot without crop residue incorporation. The water stable macroaggregates (WSMA) in surface (0–0.2 m) as well as subsurface (0.2–0.4 m) depth, increased in legume-based rotations from cereal-based (rice–wheat) rotation. The percentage of WSMA in surface soil was ~50, 57, and 65% in rice–wheat, rice–chickpea and rice–wheat–mungbean rotations, respectively. The highest mean weight diameter (MWD) and aggregate ratio was also found in grain-legume rotations over rice–wheat rotation. Parihar et al. (2016) advocated that adoption of CA practices such as ZT and PB along with residue retention for 7 years increased water stable aggregates by ~23%–32.5%, MWD by 47.1%–53.4% and geometric mean diameter by 28.5%–33.9% to CT in 0–15 cm soil depth.

12 Biochar Application and Carbon Sequestration

Soil organic matter under semi-arid environments is usually low, which is important because it, besides a source of plant nutrients, has been the major source of negative charge on soil colloidal complex, and is considered significant for cations absorption in the soil solution (Ponamperuma 1982). Lately, observing the recalcitrant of C pool in a black C material (known as biochar), researchers investigated this black-C material as a soil amendment (Topoliantz et al. 2007; Woolf 2008). Glaser et al. (2001) reported that "*black-C*" is highly stable C, because it has polycyclic aromatic C structures, and is therefore capable to resist physical and microbial breakdown and persists in the soil. Although there still exists contradiction for its role in C cycling (Senjen 2009), experimental evidences indicated that biochar application helps improve soil properties (Liang et al. 2006; Chan et al. 2007), and contributes toward crop productivity (Yamato et al. 2006; Chan et al. 2008). Chan et al. (2007) showed that biochar application has been reported to improve physical soil properties, such as increased soil aggregation, water holding capacity, saturated hydraulic conductivity and decreased soil strength (Chan et al. 2007; Asai et al. 2009). The increase of cation exchange capacity (CEC) with the application of biochar has also been shown by Liang et al. (2006). Yamato et al. (2006) showed that the application of biochar made from *Acacia magnum* could increase soil pH, Ca^{2+}, base saturation, and CEC and decrease Al^{3+} saturation. Novak et al. (2009) showed that the application of biochar in the acidic coastal soil of the Southern United States could increase soil pH, soil organic matter, Mn and Ca, and decrease S and Zn. On this sandy soil, the application of biochar did not significantly influence the CEC of the soil. The increase in soil biological activity has been reported by Rondon et al. (2007) for nitrogen fixation in *Phaseolus vulgaris* L. and by Chan et al. (2008) for earthworm and microbial biomass. The increase in crop yield with biochar application has been reported elsewhere for crops such as cowpea (Yamato et al. 2006), soybean (Tagoe et al. 2008), maize (Yamato et al. 2006; Rodríguez et al. 2009) and upland rice (Asai et al. 2009).

Biochar has the potential to affect microbial biomass and composition and the microbes are also able to change the properties of biochar (Lehmann et al. 2011; Thies et al. 2015). Because of the porous nature of biochar, its high surface area and its ability to adsorb soluble organic matter and inorganic nutrients, biochar provides a suitable habitat for microbes (Thies et al. 2015). It is true for bacteria, actinomycetes and AMF from among which some types may preferentially colonize biochar depending on its physical and chemical properties. Abujabhah et al. (2016) reported that microbial abundance was improved after the addition of biochar. Application of 2% and 4% (*w/w*) pine biochar led to a significant decline in AMF abundance in roots by ~58% and ~73%, respectively, but not in soils, which were accompanied by significant decline of ~28% and ~34% in soil P availability (Warnock et al. 2010). In contrast, application of a peanut shell biochar increased P by ~101%, while AMF root colonization and extra-radical hyphae lengths deceased by 74% and 95%, respectively. Similarly, application of mango wood biochar at rates of 23.2 and 116.1 Mg C ha^{-1} increase P availability by ~163% and ~208%, respectively, but decreased AMF abundances in soils by ~43% and ~77% (Warnock et al. 2010). Microbial abundance, diversity and activity are strongly influenced by pH (Rousk et al. 2010). The buffering capacity, that is, the ability of the soil solution to resist changes in pH imparted by biochar CEC may also help maintain appropriate pH conditions and minimize pH fluctuations in the microhabitats within biochar particles (Rousk et al. 2010; Sparkes and Stoutjesdijk 2011). The decomposition rate of biochar in the environment is influenced by the biochar's chemical and physical properties, as well as environmental factors such as temperature and rainfall (Lehmann et al. 2009). The stability of biochar is due to the transformation of the native carbon structure of the biomass to aromatic ring structures that takes place during the thermal treatment of the organic matter (Tang and Bacon 1964).

Biochar application rates and soil type also affected response soil microbial biomass. Explanations for soil microbial biomass change in response to additions of biochar include enhanced available soil nutrients (dissolved organic matter, P, Ca and K), adsorption of toxic compounds and improved soil water and pH status, all of which can influence the activity of soil microorganisms (Lehmann et al. 2011). In addition, microbial properties and enzyme activities are dynamic and highly sensitive to environmental change (Nannipieri et al. 2003), and thus changes in these properties might indicate potential long-term effects of biochar on soil nutrient cycling processes. It has been reported in many studies that addition of biochar to soils leads to immediate release of CO_2 (Zimmerman et al. 2011; Steinbeiss et al. 2009). There is also considerable evidence that biochar inhibits mineralization of organic C (Liu et al. 2011; Dempster et al. 2012). This was in accord with rapid C mineralization initially followed by relatively slower C mineralization in the biochar-amended soils consistent with other studies (Keith et al. 2011; Fang et al. 2014). Higher C mineralization rate with increasing amount of biochar additions in all soils indicate rapid mineralization by dormant microbial communities starving for labile C substrates (Mondini et al. 2006). In addition, differences in the physical nature and position of organic matter and associated microbial communities within the matrix of biochar-amended experimental soils may also have contributed to diversity in accessibility of carbon to microbes. Cheng et al. (2011) also showed that the proportion of the labile fraction of biochar progressively decreases leading to increasing half-life of the remaining biochar during incubation. In addition, another possibility for increased CO_2 emissions in biochar-amended soils could be biochar priming the mineralization of native organic matter. Earlier studies have shown that the C mineralization in biochar-amended soils increases with increasing amount of organic matter in soil (Hamer et al. 2004; Keith et al. 2011). Brodowski et al. (2005) and Cheng et al. (2008) suggested that oxidized biochar surfaces chemically interact with the functional groups of clay minerals and native organic matter in soils and thus decrease mineralization of C through greater physical protection within soil organo-mineral fractions over time (Glaser et al. 2001). Moreover, finer soil particles in high clay soils may fill the pore spaces of biochar, and consequently limit the biotic mineralization of added C. In addition, larger amount of calcium and Fe in clay soils can also stabilize labile C in biochar-amended soils by ligand exchange and calcium bridging (von Lützow et al. 2007).

13 Green Manuring and Carbon Sequestration

Soil organic matter is considered to be a key attribute of soil quality because it influences nutrient cycling, soil structure, water availability and other important soil properties (Carter 2002). Apart from supplying N, GMs improve soil fertility by adding much needed organic matter to the soil, and can help increase the productivity of the succeeding crop (Meelu 1996). Although use of GM is routinely credited for its ability to increase SOM and microbial biomass pools, the actual extent of such changes depends on management, and soil and climate factors as well as GM biomass accumulation (Meelu 1996). Organic matter and microbial biomass in fine-textured soils may show greater and more rapid response potential to GM approaches due to greater silt and clay fractions provided more physical and chemical protection from decomposition than that associated with larger (sand) size fractions. There is some disagreement about whether GM actually provides an increase in the organic content of the soil. It appears that GMs may have a small effect on total levels of SOM under systems of continuous cultivation. Additionally, the annual contributions of GM residues may be relatively small compared with pre-existing SOM pools, especially after residue losses following decomposition. Because of their succulent nature, narrow C/N ratio and low lignin content, GMs decompose faster on incorporation into the soil and only a small quantity of carbon will be converted into stable humus. It would generally require several years of green manuring for appreciable increase in the organic matter level in the soil. Slight increases, which may appear "*negligible*" to some, may be significant. Nonetheless, reported increases of SOM following GM use often range between 0% and 1% of total soil mass (Reddy et al. 2003). The practical effects of such SOM increases may be relatively small; however, larger increases in SOM may be limited by the short-term nature of these studies or from the use of management approaches that do not obtain high biomass accumulation from GM. Because most GM research lasts for 2–5 years, we have little information on the long-term potential of GM use to greatly increase SOM, especially for GM grown in place (not "*cut-and-carry*" studies where GM additions can be adjusted for optimal). Long-term and large-scale studies may demonstrate increased economic crop yield in response to higher SOM (Kanchikerimath and Singh 2001). These authors concluded that realization of greater SOM increases, especially in hot, humid and sandy environments, may require greater or more consistent additions of recalcitrant residue, especially under conventional tillage. A large number of studies have shown considerable build-up of soil organic carbon content due to the addition GMs (Thakur et al. 1999; Chaphale et al. 2000). Mandal et al. (2003) reported that GM increased the SOM content by ~14%–18% over no-GM for 0–15 cm soil depth, and it was 20%–25% for 15–30 cm soil depth at 65 days after transplanting of rice. Similar to organic matter, there was an increase in total nitrogen concentrations of soil in GM plots. An increase of 27.6%–46.5% in available soil N after raising and in-situ incorporation of sunhemp than the fallowed plots in 2 years of study was reported by Reddy et al. (2003). In maize–wheat system, Sharma and Behera (2009) observed significant improvement of soil organic C and $KMnO_4$ oxidizable-N due to growing of summer legumes and incorporation of their biomass over a period of two cropping cycles. Ladha et al. (2003) evaluated long-term (14 years old) effect of urea and in-situ grown *S. rostrata* on soil N pools (both total and available) in rice–rice system· They observed no significant change in soil total N content in the urea treatments, whereas it increased to 344 kg after 27 crops in the GM treatment. Several other workers (Shah et al. 2003; Sharma et al. 2008) have also reported build-up of organic C due to the added source of C through legume biomass in the system. A study by Srivastava et al. (1984) has shown that GM increased the humic and fulvic acid fractions of SOM, with greater contributions toward synthesis of fulvic acid (FA) as compared to humic acid (HA) fraction. Similarly, Azam et al. (1985) found that fulvic acid fraction contained the major part of ^{15}N derived from GM. Sekhon et al. (2009) reported that long-term application of GM along with mineral fertilizers enhanced water-soluble organic C content by 56.5% over mineral fertilizer alone. A maximum increase of 2.5-to 3.4-fold was observed in light fraction C due to combined application of organic manures and mineral fertilizers over control. The increase in surface soil carbon accounted for ~7.0% of the C added through green manure. Ramesh and Chandrasekaran (2004) reported that green manuring significantly increased HA and FA concentration in SOM.

14 Crop Residue Management and Carbon Sequestration

Crop residues management practices help to accumulate SOC stocks and are consequently viewed as a tool for enhancing C sequestration in croplands (Zhang et al. 2010; Maillard and Angers 2014). Residue management and artificial addition of organic material sources, including the production and incorporation of green manure crops, application of livestock manure and crop residue incorporation into the top-soil, are among the more promising methods for improving soil carbon pools, soil structural and aggregation properties (Pathak et al. 2005; Bhattacharyya et al. 2009). The use of organic fertilizers and compost increases SOC, soil microbial biomass and also alters soil C and N dynamics (Smith et al. 1997; Su et al. 2006) and enhance the SOC sequestration to a greater extent compared with application of equivalent amount of inorganic fertilizers (Gregorich et al. 2006). Carbon sequestration potential is influenced by many factors such as climate and soil conditions (Miller Aaron et al. 2004; Chabbi et al. 2009), cropping systems (Jagadamma and Lal 2010) and managements including tillage (Ogle et al. 2005) and fertilization (Bhattacharyya et al. 2010). The change in SOC fractions like labile C, water soluble C and microbial biomass C can be promptly influenced by changes in C inputs (Bolinder et al. 1999). The labile SOC fraction is an important component that determines soil quality for its involvement in soil aggregate stabilization by providing physical barriers between microbes and enzyme and their substrates (Tisdall and Oades 1982). Soil aggregation is enhanced by organic amendments which consequently improve crop productivity and prevent soil degradation. The aggregation process is an important means for conserving and protecting SOC pools, which allows the stored fractions of SOC to function as a reservoir of plant nutrients and energy for microorganisms (Bandyopadhyay et al. 2010; Zhang et al. 2014).

15 Conclusion

Long-term soil management interventions are considered prerequisite for improved soil health and ecosystems sustainability for crop production. There is a need to identify processes of soil C sequestration and assessing the residence time of C thus sequestered. It is important to identify most important site-specific key factors governing C sequestration through different soil management interventions for better crop production. Long-term studies should be conducted with different soil types, cropping systems and residue load under variable environments for improving the knowledge regarding C sequestration potential and soil health by using different soil management interventions for crop production. More studies are needed to quantify of C footprints and GHGs (CO_2, CH_4 and N_2O) emission through the adoption of different management interventions by conducting life cycle analyses of C under diverse soils, cropping systems and ecoregions. We recommend to maintaining and setting up long-term soil management interventions experiments on key soil types and agroecological regions to quantify the influence of green manure, biochar, residue management practices and integrated nutrient management on the soil health including nutrient cycling, C sequestration, ecosystem services and system productivity.

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Chapter 29
Microclimate Modification in Field Crops: A Way Toward Climate-Resilience

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Abstract Increased climate extremes like heat stress, drought, flood, cold waves, cyclones, strong winds, etc. and their exposure are leading to agricultural vulnerabilities, which threaten global food security. Besides adaptation and mitigation of climate change, microclimate modification is a potential way to create the production system that can withstand the extreme weather events and bring positive impact on agricultural productivity. Microclimate, i.e., the climatic variables in the immediate vicinity of the crops, is indispensable because it regulates and affects the physiological processes of the plants as well as the energy exchange activities between the plant and its surroundings. The major microclimate factors, such as soil temperature, soil moisture, soil characteristics, atmospheric temperature, atmospheric humidity, wind, etc., are very significant in agricultural production system. The modification of crop environment may be achieved by controlling the heat load, water balance or wind velocity. Different crop management options from sowing to harvesting, like sowing parameters, tillage, fertilizer management, irrigation management, shading, shelterbelts or windbreaks, various cropping systems and agroforestry, using antitranspirant and modification of weather hazards helps in providing favorable crop microclimate by moderating temperature extremes, conserving soil moisture, and optimizing radiation interception. This chapter reviews an understanding on different microclimate management options that can easily be adopted and influence the agricultural system in the changing climate scenario.

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1 Introduction

Crop production is a function of mainly three factors: genetic makeup of plants, soil environment, and the climatic conditions in which the plant grows. Since the relationship of plants with soil is better understood than climate, detailed investigation of crop–weather relationship is of paramount importance for developing sustainable crop production systems. This complex relationship of weather and crops is now more complicated than ever due to anthropogenic climate change due to increased greenhouse gas emissions. Human activities like burning of fossil fuels, deforestation, industrial activities, etc. have been constantly adding significant amount of greenhouse gases to the atmosphere. New emission peaks are reached every decade, and the highest emissions so far were recorded during 2010–2019 (IPCC 2022a). Moreover, since 1850, the last four decades recorded comparatively warmer temperatures, with the global surface temperature from 2001 to 2020 being 0.99 °C higher than that in 1850–1900 (IPCC 2021). Krishnan et al. (2020) reported that India's average temperature has increased by almost 0.7 °C during 1901–2018. In fact, increased occurrence of extreme weather events due to unpredictable behavior of meteorological parameters is also evident from the recent trend in climate change data (IPCC 2022b). For instance, since the 1950s, there has been a stark increase in the frequency and intensity of hot extremes like heat waves and heavy precipitation events but decline in cold extremes, including cold waves. Likewise, occurrence of tropical cyclones has globally increased for the last four decades along with higher probability of incidence of concurrent heat waves and drought (IPCC 2021). In India, the southwest monsoon is reportedly weakening (Naidu et al. 1999; Zhang and Zhou 2011; Guhathakurta et al. 2015), while the premonsoon rains have increased (Dash et al. 2007). Also, localized heavy precipitation events have become more frequent (Krishnan et al. 2020).

The success or failure of crop production systems depends upon the prevailing weather conditions throughout the life cycle of the crops. Suboptimal climatic conditions reduce crop productivity by adversely affecting the plant physiological and energy exchange processes (Kingra and Kaur 2017). There has been a growing concern over global food and water security because anthropogenic climate change has disrupted the growth rate of agricultural productivity in last 50 years (IPCC 2022b). Crop yield models for Malawi, East Africa, indicated a 14.0% yield decrease in maize by the middle of the century with an eventual reduction of 33.0% toward the end of the century due to climate change (Msowoya et al. 2016). Another global warming model for northeast China predicted 35% decrease in maize production by 2030 when there is an increase in temperature by 1.32 °C from 2008 (Li et al. 2014). Similarly, in the United States, empirical studies estimated 2.5% reduction in average maize yield during 1970–1999 because of global warming. The studies further predicted this decrease to be 20–50% by the 2050s based on current emission levels (Leng and Huang 2017). In Africa, maize yield was found to decrease by about 10% when temperature increased by 2 °C and precipitation decreased by 20% (Lobell and Burke 2010). Model-based yield estimations also show similar declining yield trend in various other crops viz. 3.5–12.9% reduction in wheat (Gammans et al. 2017), 10–15% in paddy (Nelson et al. 2009; Li 2018) and 34.6–35.4% in maize (Li et al. 2014) due to global climate change. A recent meta-data analysis reported that climate change increases global food prices by 26%, thus impairing food accessibility especially in low income countries (Birgani et al. 2022). In the same study, drought emerged as a prime weather disturbance, inflating global food prices by 32.0%. Rise in temperatures deteriorates food quality, thereby diminishing nutritional benefits. Aberrant weather can also lead to new pest and weed outbreaks threatening the food stability. Food availability, accessibility, utilization, and stability collectively make up food security, which are negatively affected by the global climate change (Zewdie 2014). This has already rendered food insecurity for a lot of countries and many more are predicted to join the list soon.

As large-scale modification to the existing weather is not feasible, agricultural systems should be adjusted to suit the existing weather (Mahi and Kingra 2007). Microclimate modification by different methods like shelterbelts, shading, mulching etc. are viable methods to protect the crops from the vagaries of weather. Modifying the weather condition around the crops implies ambient thermal and soil moisture regimes. This, along with providing optimum growing condition to the plants in an otherwise aberrant weather condition, may also improve the soil biota further augmenting crop production. Hence, there is an urgent need to adopt different methods of microclimate modification for ensuring optimal plant growth through sustainable use of natural resources to secure food supply to the vast population (Kingra and Kaur 2017).

2 Concept of Microclimate

Microclimate is simply the climate near the ground where plants and animals live. Thus, it is the local climatic conditions in a small area near the ground covering few meters (~2 m) above and below the surface and also the area around and within plants (Yashino 1974; Maliwal 2011). Microclimate is also a culmination of the prevailing macroclimate. The primary difference between macro- and microclimates is in the rate at which weather elements change temporally and spatially. Huge quantities of energy exchange take place at the soil surface as a result of the evaporation and condensation processes. The first few tens of millimeters above and below the soil surface is the seat of maximum diurnal variation in temperature, irrespective of whether the soil is covered with vegetation or not. Similarly, the rate of change in humidity with elevation is greatest near the surface, whereas wind velocity is considerably decreased due to momentum transfer at the surface level. Hence, there are a wide range of environmental variations near the earth surface which drastically differ from the climate just few meters above, where the weather elements are stabilized and moderated by the active atmospheric mixing processes (Rosenberg et al. 1983).

3 Modification of Microclimate

Since time immemorial, man has tried different methods with the aim of artificially modifying the climate. With the advancement of agriculture, humans developed an understanding on the importance of rain, the occurrence of which was largely erratic. In areas struck by drought and low rainfall, people tried to artificially create rain, and these methods were usually based on different superstitions lacking scientific approach (Hong et al. 2023). Today, understanding of both agriculture and weather has increased with growth and advancement of technology. Hence, technological interventions with an attempt to modify the growing environment favoring plant growth are often employed under suboptimal condition (Kingra and Kaur 2017). This control or modification of the physical environment may be achieved by controlling the heat load, water balance or wind velocity.

3.1 Control of Heat Load

This consists of two methods; one is heat evasion, which finds its importance in tropical and subtropical regions. The other is heat trapping, which is important in the temperate areas with short crop growing seasons. In the tropical regions, the heat load on plants is often higher than optimum. In these situations, heat evasion is done through protective shading using appropriate shading material, which serves as a thermostat and can be removed or used as per need (Mensah et al. 2022). This helps in lowering of the ambient temperature and also regulates evapotranspiration. Trapping of heat involves considering the angle of solar radiation and adjusting the crop accordingly. These adjustments may involve growing crops on the sunny side of furrows or making row adjustments to maximize radiation interception and minimize reflection from the crop canopy. Other methods may involve ploughing, irrigation, use of heaters, mulching, etc. (Kingra and Kaur 2017).

3.2 Control of Water Balance

Optimum soil moisture is a prerequisite for good plant growth, and even small change in moisture at the critical stages might cause significant yield losses. The water balance in soil can be improved by two methods: by increasing the root zone soil moisture and by decreasing evapotranspiration losses. These methods can be accomplished by adopting different techniques such as use of mulches and good tillage practices, increasing infiltration as well as reducing runoff losses.

3.3 Controlling Wind Velocity or Turbulence

Wind direction and velocity both have great impacts on plants, both mechanically and physiologically. Direct impacts of wind include mechanical damage to crops, increase in evapotranspiration, and carbon dioxide intake, whereas indirect impacts include change in heat and cold wave patterns, changes in movement of clouds and fog, etc. Thus, local and regional effects of wind should be modified to meet crop growth needs. This is achieved with the help of shelter belts and windbreaks. Apart from wind speed reduction, shelter belt also has several other benefits. They have a moderating influence on the ambient temperature, moisture status of the soil as well as the atmosphere, thus providing an optimum growing environment for the sheltered crops.

However, in actual practice, most of the techniques employed at the field level are in fact an overlapping of more than one of the three principal techniques discussed above, and some of the important ones are described in the next section.

4 Techniques of Microclimate Modification

Several techniques as well as management practices can be adopted to provide a favorable crop-specific growing environment by reducing the negative effects of weather aberration. Some of them are discussed below (Tables 29.1 and 29.2).

4.1 Shading

Modification of temperature and light intensity in crop fields through use of shade is a traditional practice. Shading mainly involves modification of energy level at the soil or crop level, which is achieved by regulating the reflection through absorption of excess solar radiation and only permitting transmission as required. It affects plant growth by altering microclimatic factors such as light, photosynthetically active radiation (PAR), temperatures, relative humidity, CO_2 concentration, wind speed, soil temperature, and moisture availability (Eckhart et al. 2011). Shading is of two types: natural shading and artificial shading. As the name suggests, natural shading consists of natural shade creation under tall trees and crops such as in intercropping systems, or through use of left-over stubble or fallen leaves. The branches and leaves of the trees block the direct solar radiation and reduce the energy received at the ground level, which in turn lowers temperature as well as emission of

Table 29.1 Different techniques used in field crops for microclimate modification

Technique used	Crop	Result	Source
Time of sowing:			
Sowing on 29th October in Punjab compared to sowing on 12 and 28 November	Wheat	Improved heat use efficiency	Singh et al. (2016)
Sowing on 5th November in comparison to sowing on 20th November and 5th December at Punjab		Lower accumulated stress degree days (ASDD) and highest yield	Singh et al. (2018)
Row arrangement:			
Sowing in different row directions (E-W and N-S)	Wheat	4–5% higher PAR interception in E-S compared to N-S, resulting in higher yield	Dhaliwal et al. (2019)
Time of transplanting:			
Transplanting on different dates; 16th June, 30th June, 14th July, 28th July, in Kalyani, West Bengal	Rice	Highest grain yield recorded from 16th June and reduction by 15%, 31% and 36% respectively	Saha et al. (2019)
Planting methods:			
No till permanent raised beds (PRB)	Maize-Wheat	Improved soil physical characters like total porosity, soil water retention, water infiltration rates and soil organic carbon	Lin et al. (2022)
Shading:			
Growing under paranet shade (0%, 30% and 50% shade levels)	Potato	50% shade level resulted in higher LAI and yield	Mariana and Hamdani (2016)
Mulching:			
Application of wheat straw mulch against no mulch	Maize	More soil moisture and water use efficiency as well as greater yield	Yaseen et al. (2014)
Application of wheat straw mulch and bed planting against no mulch and flat planting		Higher water infiltration rate, greater water productivity, and higher plant growth parameters and biological yield with mulching and bed planting	Shah et al. (2015)
Straw mulching @ 5 t ha^{-1}	Soybean	Increased seed yield	Revathi et al. (2021)
Tillage practice:			
Growing under reduced tillage with chisel cultivator against conventional tillage with mouldboard plough	Soybean	Production from reduced tillage was not significantly different from conventional tillage, reduced drought stress resulting in higher fat and protein content under reduced tillage.	Chetan et al. (2021)

(continued)

Table 29.1 (continued)

Technique used	Crop	Result	Source
Intercropping:			
Maize and soybean intercropping	Maize and soybean	Higher PAR interception and radiation use efficiency in maize and soybean intercropping as compared to sole maize crop	Pandey (2010)
Irrigation management:			
Partial root zone irrigation techniques: alternate partial root zone irrigation (APRI), fixed partial root zone irrigation (FPRI) against conventional irrigation (CI)	Maize	Water saving compared to CI was 28% and 32% with FPRI and APRI methods, respectively.	Barideh et al. (2018)
Antitranspirant:			
0, 1 and 2 antitranspirant sprays and 4 levels of phosphorus (20, 40, 60, 80 kg/ha)	Green gram	2 sprays of antitranspirants and 80 kg ha^{-1} phosphorus recorded highest yield and net income	Avinash et al. (2019)

Table 29.2 Role of antitranspirant in growth and yield of major food crops by microclimate modification

Type of antitranspirant	Material used	Crop	Result	Source
Film forming type	di-1-*p*-menthene	Wheat	Reduced concentration of endogenous ABA under drought stress resulting in increased number of grains per m^2	Mphande et al. (2021)
			Application of antitranspirant gave a yield advantage of 0.66 t ha^{-1} compared to unirrigated and unsprayed plots	Weerasinghe et al. (2016)
	Glycerol	Wheat	Antitranspirant application produced significantly positive impact on the physiological traits	El-Hady et al. (2018)
Reflectant type	Kaolin	Wheat	Kaolin spray resulted in increase in growth parameters, yield attributes, photosynthetic pigments as well as carbohydrate constituents	Abdallah et al. (2019)
Stomatal closing type	Na_2CO_3	Soybean	Application of the antitranspirant at 5% resulted in higher mean seed yield (2862 kg ha^{-1}) over other sprays	Revathi et al. (2021)

long-wave radiation from the earth surface (Kotzen 2003). Artificial shade on the other hand is created artificially through use of structures such as shade nets, roofing or using mulches of organic or inorganic origin. Shade nets are generally employed to lower heat stress in crops (Elad et al. 2007) and can also selectively transmit the desired constituent solar radiations viz. ultraviolet, visible or long wave radiations when made using appropriate materials (Ilić et al. 2022). Cultured shade nets can also change the quality of light reaching the plants. In addition to light duration and intensity, the composition of light viz., blue, red and far-red light affects plant photo-morphogenesis (Ruberti et al. 2012). Varying amount of shade also affects crop phenology. For example, seed germination was faster while flower initiation was delayed in wheat and maize with increase in shading intensity (Singh and Alam 2020). Shading creates suitable microclimate condition for potato resulting in higher leaf water potential, greater plant height, leaf area index and tuber weight per plant (Hamdani and Mubarok 2018). However, shading may reduce net photosynthetic activity in crops due to reduced amount and activity of Rubisco (Taylor et al. 2022). Yield decrease was observed under shaded conditions in rice along with increase in chalkiness and low grain quality (Moula 2009; Chen et al. 2019). Hence, in any attempt at yield intensification through microclimate modification using shade, selecting varieties capable of maintaining favorable photosynthetic and antioxidant functions under low-light intensity is important (Zheng et al. 2011).

4.2 Intercropping

Intercropping generally means growing of more than one crop simultaneously on the same field in a definite row arrangement. The advantages of an intercropping system are manifold ranging from increasing returns from a particular land to weed and pest suppression. It ensures better utilization of the light, water, and other resources by the crops that remain in the field simultaneously for a major part of their lifecycle. Modifying microclimate through use of shade nets can be quite input intensive especially in tropical countries, whereas intercropping is a simple, cheap, and effective method. Intercropping systems achieve species diversification with differential canopy patterns and maturity. This promotes better land coverage during the entire growing season compared to monocropping systems, facilitating higher interception of incident solar radiation. Thus, less solar radiation reaching the ground surface implies lower air and soil temperatures which improves soil moisture conservation due to reduced evapotranspiration (Nandhini and Somasundaram 2020; Setiawan 2022). For example, intercropping of maize with legume crops can significantly improve the soil moisture content relative to sole maize crops (Naresh et al. 2014; Bekele et al. 2021). Potato intercropped with legumes like lima bean and dolichos resulted in higher leaf area index (26–57%), lower soil temperatures in the top 30 cm depth (up to 7.3 °C), as well as higher soil water content (up to 38%), radiation use efficiency (56–78%), and crop water productivity (45–67%) compared to sole potato stands (Nyawade et al. 2019). Intercropping effectively suppresses weed growth and may result in decreasing insect pests. However, the increased humidity within crop canopies can often be conducive to fungal diseases in plants. Nevertheless, it is still one of the most viable options for dodging the ill effects of climate change while maintaining a good profit for the farmers.

4.3 *Shelterbelts or Windbreaks*

Shelter belts are artificially constructed linear arrangement of trees with the primary objective of reducing wind speed which eventually results in further modification of the microclimate in the "sheltered" zone. It is especially useful where frequent high wind causes great mechanical damage to plants. The effectiveness of any shelter belt in reducing wind velocity on the leeward side depends upon the height of the barrier, its permeability or porosity, shape, width and the topography. The area of effectiveness on the leeward side increases proportionally with the height of the shelter belt. Highly dense shelter belts with low permeability are less effective as it creates strong turbulence behind the barrier as air descends abruptly on the ground surface. Similarly, highly permeable or less dense barriers have reduced sheltered area on the leeward side. Medium permeability of about 40–50% is adequate for harnessing the maximum benefits of shelter belts. The orientation of the shelter belts relative to wind direction is also important and the highest effect is achieved when wind hits the shelter belt at 90° (Zhu 2008). Reduction of wind speed due to shelter belts decreases turbulent mixing and affects energy exchange processes which lead to changes in soil and air temperatures. Humidity levels in the sheltered zone, both during day and night time, increased owing to reduced turbulence. Shelter belts also affects the plant water relations which is quite complex. Depending on atmospheric resistance and saturation vapor pressure deficits, transpiration rates can either be reduced or remain unaffected. Rate of evapotranspiration in the sheltered zone is also lower resulting in improved water use efficiency. As a result of more favorable microclimate and improved plant–water relationship, photosynthesis is improved (Vogel 2009; Mensah et al. 2022). Corn yield was found to increase by about 4.63% within 2–5 h, with an average increase of about 2.41% within 1.2–15 h (Liu et al. 2022). Cai et al. (2021) reviewed that rice lodging caused by cyclones was found to be reduced to 16.28% behind shelter belts. Similarly, yield loss and lodging in cotton was found to be reduced up to an area of 27 h on the leeward side of shelter belts. Apart from creating a favorable microclimate, shelter belts help in reducing soil erosion by decreasing wind speed thus preserving the soil quality. They are also potential carbon sinks thus further helping in ameliorating climate change impacts (Mayrinck et al. 2019).

4.4 *Sowing Time*

Global rise in temperature hampers production via reduction in the length of growing season, rapid crop and soil evaporation as well as heat stress at the crop reproductive stages (Luo et al. 2018). Crop growth is accelerated under increased temperature, and this reduces the duration of the phenophases. Altered phenological stages result in impaired physiological functioning (Fatima et al. 2020). Sowing time should be optimized considering the crop cultivar characteristics, the area where it is grown and the predicted climatic conditions during the growing season. Adjusting sowing time so that the phenophases of crops coincide with the duration of favorable weather conditions helps to escape periods of stress by providing congenial microenvironment (Singh et al. 2016). Growing crops when the evaporative demand is least can help increase crop water productivity. In temperate areas of north-eastern China, crop climate models estimated that sowing earlier than the current sowing dates can help boost yields in early and single rice crop types, whereas in Yangtze River basin and other regions affected by substantial heat stress, late sowing should be adopted to prevent damage during reproductive phases (Ding et al. 2020). Studies in Bangladesh found that late transplanting of *Boro* rice helps in optimizing water use by reducing irrigation requirement owing to rainfall received later in the growing season. This however is subject to the limitation of terminal heat stress and heavy rainfall during harvest, which can be dealt with selection of efficient heat tolerant cultivars and early forecasts of extreme weather events (Acharjee et al. 2019). Wheat-based crop climate models imply that late sown wheat will be more affected due to temperature rise and thus normal dates of sowing should be encouraged. Thus, optimizing time of sowing and selection of crop cultivars with photo-thermal adaptability are likely to perform better under changing climate scenario (Kumar et al. 2014; Luo et al. 2018). Similar studies are available for other crops like cotton, maize, barley, etc. that emphasize the significance of time of sowing as a simple yet powerful tool for combating climate change (Dhir et al. 2021; Wu et al. 2023; Yagmur and Sozen 2021).

4.5 Tillage Practices

Tillage is an important step in agricultural production systems, which ensures a good start for healthy growth and better yields in crop. This is mainly achieved through changes in soil pore dimensions. This change is reflected as modified soil physical characters like aeration, moisture status, and temperature, as well as penetration resistance. However, excess tillage can be harmful and often leads to soil erosion, loss of moisture from soil pore spaces and in some cases soil compaction due to heavy machinery use. Besides, conventional cultivation practices disturb the ecological niche in the soil (Mehra et al. 2018). Under global warming scenario, soil water conservation is a prerequisite which is especially important under rainfed growing areas. Thus, the concepts of minimum tillage and residue retention are gaining increasing importance. These resource conserving technologies effectively retain soil moisture from previous crops that can greatly benefit the succeeding crop (Saha et al. 2021). Reduced tillage practices result in overall improvement in resource management, and retaining crop residues on the soil surface deters soil evaporative losses and promotes better water infiltration. Besides, minimum tillage saves time which facilitates timely sowing of crops that prevents further losses due to atmospheric anomalies at the critical stages of the plants (Maji et al. 2019). In an experiment, it was found that rainfed lentil crop grown under zero tillage with retention of rice stubbles resulted in better soil moisture retention compared to conventional tillage practices (Bandyopadhyay et al. 2016). This may be attributed to the standing rice stubbles which acted as a barrier to evaporative losses. Moreover, micropore formation in the soil profile further reduced the loss, eventually resulting in better distribution of soil moisture (Saha et al. 2021).

4.6 Mulching

Mulching is any technique that involves applying or creating a soil cover that checks heat transfer and acts as a moisture barrier that reduces evaporation losses thereby improving the soil moisture status. It helps in achieving better crop growth and yield as well as optimizes water use (Yu et al. 2018). There are mainly five types of mulching: soil mulch (involves loosening the soil to break the continuity of capillaries in soil), straw mulch, stubble mulch, plastic mulch, and vertical mulching (Mahi and Kingra 2007). Based on the types of material used, it can again be classified as organic mulch (where organic or biodegradable materials are used) and inorganic mulch (consists of mainly plastic-based materials) (Kader et al. 2017). These mulch materials beneficially modify the plant microclimate. Retention of residue can impair the transport of water vapor from surface soil into the atmosphere, thus decreasing the loss of moisture through direct evaporation and enhancing the water availability to plants (Xie et al. 2006; Yuan et al. 2009; Fuchs and Hadas 2011). Mulching increases the night time relative humidity due to decreased air temperatures, which encourages dew formation (Tuure 2021). The higher albedo of straw mulch than soil results in lowered surface and air temperatures, mainly in dry soil (Döring et al. 2006). Mulching also increases infiltration of water into the soil. The mulch cover impedes surface runoff by holding water for a longer time on the soil, thus allowing more time for infiltration (Khurshid et al. 2006). The beneficial effects of mulching in controlling temperature and moisture transfer mechanisms is substantial in rainfed farming systems, which are often struck by heat waves and dry spells. However, under wet and favorable conditions, straw mulching was found to have a negative effect on harvest index, grain yield, and water use efficiency of wheat, compared to conventional practice. Nevertheless, under very dry condition, straw mulching increased both grain yield and harvest index (Amato et al. 2013; Pittelkow et al. 2015; Hu et al. 2018). Mulching with plastic sheet is more effective in conserving soil moisture than wheat straw mulch (Li et al. 2013). In China, use of plastic mulch was able to increase production of wheat and maize by about 33.2% and 33.7%, respectively (Chen et al. 2014). Similarly, among different mulch materials, black plastic mulch was found to produce significantly higher grain yield in wheat crop (Rummana et al. 2018). Plastic mulches may, however, result in undesirable negative impacts on the environment as they are difficult to dispose. Moreover, their long-term use often results in deposition of plastic fragments which hinders crop growth. Biodegradable plastic mulches may be a better alternative but are costlier (Divya and Sarkar 2019). Regardless of the mulching material used, mulching can be quite labor-intensive inculcating more input costs. Thus, any use of mulches should be backed by judicious planning and balance should be maintained to ensure maximum benefit.

4.7 Irrigation and Drainage

Importance of irrigation in agriculture is well known and has a wide role in microclimate modification especially under climate change condition. Reduced crop canopy temperatures in irrigated crop, higher latent heat flux, and lower sensible heat are some of the observed changes from irrigation (Kingra and Kaur 2013). Supplemental irrigation, i.e., irrigating crops at the critical stages, is an effective way to reduce heat stress at the vital phenophases. Zhu and Burney (2022) reported that the cooling effect of irrigation considerably extended the thermo-sensitive grain filling period in maize. The authors observed that irrigation induced drought and heat stress mitigation recorded 65 ± 10% and 35 ± 5.3% yield advantages, respectively. Among different irrigation methods, sprinkler irrigation is one of the most popular and widely adapted strategies that aim at higher water use efficiency. Sprinkler irrigation modifies water and energy exchange between atmosphere, crop and soil. These exchange processes results in changes in latent and sensible heat flux at crop canopies. The impacts of sprinkle irrigation on microclimate can last for 5–7 days. It causes substantial decrease in air temperature in the first 1–3 days with the effects subsiding thereafter (Tang et al. 2022). However, excess moisture can be harmful leading to poor microbial activity, nutrient leaching and low soil temperature conditions. Besides water logging affects photosynthesis, leaf nitrogen content, crop development, and senescence (Ebrahimi-Mollabashi et al. 2019). The changing climate scenario witnesses rapid rise in intense rainfall events, often concentrated over a small region. This often leads to water stagnation in the crop fields resulting in heavy losses. This can be avoided and mitigated to some extent by proper land management with adequate drainage facilities in the crop field. Drainage systems can go a long way in improving crop yields, reducing nutrient losses to water resources, improving soil organic carbon, reducing greenhouse gas emissions from crop fields, and, overall, improving crops' resilience to climate change (Castellano et al. 2019).

4.8 Other Agronomic Management Techniques

Making the best out of the changing climate scenario as well as an assured agricultural production can be achieved by basic agronomic management such as altering the planting geometry, fertilizer management, planting method or use of anti-transpirant, etc. Changes in the planting geometry by modifying the planting density by changing seed rate or spacing can help achieve suitable microclimate conditions. Reducing plant density with increased row to row or plant to plant distance or skip row planting can be an effective strategy for better utilization of soil moisture in dryland farming areas (Singh et al. 2012). Suitable planting geometry improves interception of solar radiation through better crop canopy coverage, faster growth rate, and better biomass accumulation, thereby improving resource use efficiency and better phenology of crops (Fatima et al. 2020). Planting methods also play a crucial role in increasing overall crop productivity by inducing favorable microclimate, especially under suboptimal environments. For instance, raised beds can effectively prevent water logging and maintain favorable soil moisture regime in the crop root zone. Also, broad and permanent raised beds can cut down irrigation water requirement by 25–35%, making them a preferred choice under water-stressed environments.

Judicious fertilizer management improves plant vigor and plant implies better capabilities in fighting different environmental stresses. Application of nitrogen after waterlogged conditions promotes good growth. Similarly, phosphorus helps plants overcome freezing injury through its effect on cell division and tissue development. It also helps in canopy adjustment and increases leaf water content under drought situations thus improving photosynthesis. Potassium has a similar positive influence on water regulation and photosynthesis. Micronutrient applications, for example, zinc, have a positive influence on yield and yield attributes under drought situations. However, nutrient application at wrong time may also be harmful. Nitrogen application before a frost incidence promotes growth but increases the plants' susceptibility to frost damage (Debangshi 2021). Thus, proper timing of nutrient application is also vital in reducing climate related fatalities.

Increase in global temperature means increase in frequent drought situations in many parts of the world. In this situation, increasing transpiration efficiency, i.e., more dry matter production per unit water transpired can prove to be vital. This can be achieved by use of suitable agents that help in reducing transpiration. Such antitranspirants include materials like kaolin, phenyl mercuric acetate (PMA), abscisic acid (ABA) etc. However, such antitranspirant materials have the potential to decrease crop yield, and thus, they should be used in moisture sensitive stages of crops to obtain most benefits (Mphande et al. 2020).

4.9 Agroforestry

Agroforestry, i.e. integration of multipurpose trees and shrubs with the crops and/or livestock can be a vital option in alleviating ill-effects of climate change. Agroforestry systems may be of different types. For example, in the alley cropping system, companion crops are grown in the alley ways between rows of widely spaced trees. In the multistrata system, crops like coffee are grown under the shade of tall trees. Other types of agroforestry system may include silvipasture systems, woodlots, and protective systems. The advantages of such systems are manifold which include improvement in soil moisture retention, less evaporation of soil moisture, better soil health from litter fall and root biomass. In addition, they provide shade to crops and also act as shelterbelts against strong winds. When groundnut and maize were grown under shade in an alley cropping system, they outperformed the control plots significantly in terms of crop yield, due to microclimate modification in the alleys (Adlan et al. 2019). Under the changing climate scenario, crop productions may also be hampered due to changing pest and disease dynamics. Integration of trees into cropping systems often results in decreased day time temperatures, variable relative humidity conditions, and soil moisture (Jacobs et al. 2022). Lower temperatures and humidity fluctuations under shade may result in pest and disease suppression (Sharma et al. 2020). Overall agroforestry systems make a more resilient system against climate change variables. However, increased evapotranspiration losses in agroforestry systems may result in competition with companion crops for water and nutrient sources which can result in decreasing yields. On the other hand, trees also have the potential to tap into deeper layers of soil, into different water reservoirs where conventional crops cannot reach, thereby making the water available to them in the later stages. Thus, any agroforestry system planning should be backed by proper planning regarding the species of the trees to be grown, the topography and diversity of landscape, and the climate of the place.

4.10 Modification of Weather

Good plant growth occurs when all the climatic factors are favorable and best growth occurs under optimum atmospheric conditions. Any deviation from the favorable climate results in stress situations for the plant, resulting in decline in plant growth, yield, and quality of the produce. Deviation from favorable creates extreme weather conditions, which lead to weather hazards, for example, heavy rainfall leads to flood while scanty rainfall leads to drought situations. Similarly, extremes of temperatures lead to heat and cold waves. Modification of precipitation, cyclone, fog, frost, and evaporation are attempted to create favorable conditions for crop growth and thereby minimize losses. Modification of precipitation is done by artificial rain making with cloud seeding (Abshaey et al. 2022). The main principle in artificial rain making involves introduction of artificial condensation nuclei into the clouds as they may not be present in the atmosphere in sufficient amount which is required for growth of rain drops. Based on the thermal energy, clouds may be classified as warm or cold clouds. In cold cloud seeding, an artificial hygroscopic nucleus of silver iodide or dry ice is introduced to increase the number of ice crystals and thus initiate rain. In warm cloud seeding, coalescence process in presence of large water droplets results in precipitation and this is achieved by introduction of large hygroscopic nuclei such as sodium chloride which accelerate the coalescence process. However, artificial rain making has some drawbacks. Some of the chemicals used for cloud seeding are potentially harmful and it can put plants as well as the environment at risk. Moreover, wind is an important factor in cloud seeding which may push the seeded cloud to a location where it is not required. In cyclone modification, the outer clouds around the eye of the cyclone are seeded using silver iodide to induce precipitation before the cyclone reaches its mature stage. The huge amount of latent heat of condensation released in the process tends to spread the storm over a larger area, thus reducing the magnitude of the violent force and this result in minimizing the magnitude of losses. Fog creates humid conditions around plants, which promotes plant diseases and, thus, should be dissipated. Frost occurs when temperature near ground surface decreases below 0 °C, resulting in lethal damage to plant. The harmful effects of frost on plants can be minimized by procedures that aim to increase the night time temperatures, such as using small heaters or irrigating the field (Mahi and Kingra 2007).

5 Conclusion

The effects of changing climate are more and more prominent every year with increasing incidents of extreme weather events. These result in various stresses in crops, ultimately threatening food security. This calls for drastic measures where microclimate modification techniques have a crucial role. However, careful planning is important in any attempt at microclimate modification. When the climate is made favorable for a certain species of crop, it may be detrimental for other crops or even the neighboring crops as the requirement for atmospheric optima is different for each species. Even the climatic needs for a crop may vary throughout the growing stages, for example, conditions favoring a crop from planting to emergence may be different from the needs during its growth stages. Thus, microclimate modification techniques may be specific, intermittent, or continuous depending on the situation. Proper implementation of the right techniques at the right time will be essential to combat the changing climate thereby sustaining the productive potential of different field crops.

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Chapter 30
Bioremediation: A Substantive Potential for Clean Earth

Bhupinder Dhir

Abstract Bioremediation technique involves use of living organisms in removal, degradation or immobilization of pollutants present in various components of the environment. Bioremediation is carried out by living organisms which include microorganisms and plants. Bioremediation can be done at the site of contamination or contaminants can be carried away from the site for treatment. Techniques such as biostimulation, bioaugmentation, bioventing, biopiles, and bioattenuation help in the removal of contaminants from the environment by microbes. Processes such as phytoextraction, phytostimulation, phytovolatilization, phytodegradation, and rhizofiltration involve use of plants for removal of contaminants. The rate of bioremediation depends upon the type of pollutant, its concentration and physicochemical factors. Bioremediation is an affordable environment friendly technique that can be used for treating various types of environmental contaminants, including inorganic, organic waste, radionuclides, and many more. Biotechnology techniques have proved effective in improving efficiency of bioremediation. Bioremediation, thus, can prove as an asset as it possesses great potential in cleaning various components of environment.

Keywords Algae · Biotechnology · Fungi · Heavy metals · Microbes · Plants · Pesticides · Radionuclides

1 Introduction

Environment has shown rapid deterioration all over the globe. Tremendous increase in urbanization, industrialization has led to continuous addition of various contaminants in the environment. According to an estimate about ten million tons of toxic

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substances get added to environment every year. Most of these pollutants are carcinogenic. They persist in environment and cause great harm to ecosystems and human health. Improper disposal and lack of suitable treatment of domestic, industrial, and agricultural wastes severely affect the environment and people. A clean and healthy environment is required for maintenance of public and ecological health.

Environmental remediation includes methods and practices that remove or degrade contaminants/pollutants. Techniques such as incineration and excavation have been followed since years to remove environmental contamination (Gomes et al. 2013; DalCorso et al. 2019). Use of such technologies gets restricted because of issues such as high cost, inefficiency, alteration in physicochemical and biological properties of various components of environment and secondary pollution (DalCorso et al. 2019). Since these technologies showed a lot of disadvantages, the need for cheap, highly efficient, environment friendly, and sustainable technologies for treatment of environmental pollution was realized.

Bioremediation has emerged as one of the most promising techniques that can be used for cleaning up the environment and ecological restoration (Arora 2018; Salilh and Tarekegn 2020; Bala et al. 2022). Microorganisms and plants assist in treatment, degradation, and removal of contaminants present in the surroundings (Rayu et al. 2012). The process of bioremediation involves the role of use of living organisms in conversion of contaminants into nontoxic forms. The natural process of bioremediation is based on biological agents that treat/convert harmful contaminants into less or nontoxic forms (Abatenh et al. 2017). Living organisms such as bacteria, fungi, algae, and higher plants play an important role in this technique and assist in degradation and detoxification of hazardous substances. The metabolic activities of living organisms help in the degradation of contaminants. Plants play an important role in removal of contaminants and, hence, cleaning of environment (Ashraf et al. 2019). Plants prove useful in remediating large areas. In addition, they also improve fertility of soil fertility by releasing organic matter (Aken et al. 2009; Wuana and Okieimen 2011).

Bioremediation technology got wider acceptance because it helped in achieving clean environment at a very economical rate and with minimum spread of contaminants to other media. Cost-effectiveness, high competence, minimal generation of secondary pollutants or residues such as sludge, and no complex requirements are some of the features that make the technology widely acceptable (Vidali 2001).

This chapter provides updated information about various processes, recent updates, new approaches, challenges and future considerations of the technique. The role of the technology in environmental cleanup and restoration has also been discussed.

2 Bioremediation

Bioremediation can be carried out at or away from the site/source of generation (Hussain et al. 2022). The degradation of the pollutant occurs at the polluted site; hence, spread of pollution is prevented without harming the ecosystem. This results in less disturbance to environment/ecosystem as the contaminant is treated at its place avoiding excavation and transport. In-situ bioremediation can be done via intrinsic (natural) approach in which remediation is carried out under natural conditions or engineered approach that involves environmental modifications (such as aeration, nutrient application, and addition of microbes). Bioventing, biosparging, bioaugmentation, biostimulation, biosorption, bioleaching, etc. are some of the bioremediation techniques that occur at or away from the site/source of generation.

In bioventing technique, air and nutrients are supplied to a contaminated soil through wells. This results in stimulation of the indigenous aerobic bacteria. The flow of air at low rate provides oxygen required for biodegradation. Microorganisms present naturally in the soil or subsurface soil provide aerobic conditions.

In biosparging technique, air is put under pressure in the water table. This results in increase in oxygen concentration in groundwater which promotes the breakdown of contaminants by bacteria (Adams and Reddy 2003). Biosparging helps in treating/reducing the level of petroleum compounds present in groundwater or soil present below the water table. This technique helps in successful treatment of petroleum hydrocarbons contamination of soil and groundwater (USEPA 2004; Machackova et al. 2012). During 1997–2000, biosparging technique has been applied to remove/treat arsenic-hydrocarbon at oilfields in Odessa, Texas, USA (Cooley et al. 2009; Machackova et al. 2012). In bioaugmentation, high rate of degradation of contaminants is achieved at sites of contamination (Tyagi et al. 2011; Kumar et al. 2011b). Microbes found in soils degrade waste effectively. The process of in-situ treatment is slow and cannot be applied to the sites.

In ex-situ bioremediation, pollutants are treated after removal from the site. This type of remediation saves time and is successful in treating wide range of contaminants. This process is more effective than in situ treatment. The technique is expensive because contaminants need to be transported to the treatment site. This type of treatment system requires more space and is time consuming. Composting, land farming, biopile system, and bioreactors are different ex situ bioremediation methods. In solid-phase bioremediation technology, soil is removed from the polluted soil and converted into heaps. Microbes present in the piles help in removal of pollutants. Components such as water, nutrients, and oxygen present in the bioreactor help in the degradation of contaminants by microbes.

Irrespective of remediation at the site or away from it, rate of remediation is regulated by factors such as category of pollutant, concentration of pollutant, physic-chemical features such as level of oxygen and nutrients and physical factors. Remediation type depends on the pollutant and its concentration.

3 Agents of Bioremediation

Natural agents such as microorganisms and plants help in carrying out bioremediation. Bacteria (aerobic and anaerobic), algae, fungi, and plants (both terrestrial and aquatic) present at the site of bioremediation or added exogenously assist in bioremediation (Tarekegn et al. 2020). The indigenous microorganisms or those isolated from other resources can be used at the polluted site. Microorganisms have shown capacity to remove various pollutants including organic compounds such as pesticides, agrochemicals, chlorinated compounds, organic halogens, hydrocarbons, inorganic contaminants such as heavy metals, nuclear waste, greenhouse gases, dyes plastics, and many xenobiotic compounds.

The rate of removal/treatment varies for each pollutant/contaminant. It also depends on the nature of toxicants and contaminants. Microbes biotransform the contaminants mainly by bringing change in the structure via by enzymes (Smitha et al. 2017).

3.1 Remediation Through Bacteria

Bacteria show capacity to accumulate and degrade metals, radionuclides, organic compounds such as pesticides, hydrocarbons, alkanes, and polyaromatic compounds (Tarekegn et al. 2020) (Table 30.1). Contaminants provide carbon to microbes. Aerobic bacteria in particular have shown capacity for remediation of chemical compounds such as chlorinated aromatic compounds, polychlorinated biphenyls, trichloroethylene, and chloroform. They degrade compounds and convert them into less toxic forms. *Pseudomonas, Acinetobacter, Actinobactera, Arthrobacter, Sphingomonas, Beijerinckia, Nocardia, Flavobacterium, Rhodococcus*, *Alcaligenes, Nitrosomonas, Xanthobacter, Mycobacterium, Rhizoctonia, Trametes,* and *Serratia* are some of the bacterial species that show immense capacity to remove complex organic compounds. Methane serves as a source of carbon and energy for methylotrophs (aerobic bacteria). Degradation of compounds such as chlorinated aliphatic compounds such as trichloroethylene and 1,2-dichloroethane is carried out by enzyme methane monooxygenase. Anaerobic bacteria have also shown capacity to degrade biphenyls and chloroform. Microbial genera also degrade petroleum compounds.

Pseudomonas aeruginosa, Bacillus, *Sphingomonas, Gallionella, Staphylococcus aureus*, S*tenotrophomonas* sp. Br8 are some bacterial species that biomineralize radionuclides including uranium (Dushenkov 2003; Choudhary and Sar 2011; Merroun et al. 2011; Lopez-Fernandez et al. 2014; Krawczyk-Bärsch et al. 2020; Shukla et al. 2020; Sánchez-Castro et al. 2020). Microbial reduction of selenium, neptunium, plutonium, and technetium has been noted (Lloyd 2003). Bacteria show capacity to biosorb uranium, plutonium, americium, strontium, and cerium (Nakajima and Tsuruta 2004; Merroun et al. 2005; Chandwadkar et al. 2018; Ilyas et al. 2020). Biosorption of cesium and strontium was noted in *Pseudomonas fluorescens* and *Bacillus cereus* (Ma et al. 2011; Kim et al. 2016; Long et al. 2017). Extracellular polymeric substances present in *Pseudomonas* sp. help in sorption and reduction of plutonium (Boggs et al. 2016). *Desulfovibrio äspöensis, Sporomusa* sp. possess capacity to remove plutonium via binding of polymers (Moll et al. 2006, 2017). *Pseudomonas aeruginosa* J007 strain isolated from uranium mine at Uranium

Table 30.1 Major bacterial species showing potential to remove/treat contaminants

Contaminants removed/treated	Bacterial species
Radionuclides (^{137}Cs, ^{60}Co)	*Serratia* *Arthrobacter* *Microbacterium* *Desulfomicrobium* *Desulfotomaculum* *Desulfovibrio* *Acidovorax* *Shewanella* *Geobacter* spp. *Cellulomonas*
Heavy metals (Cr, Cd, Pb, Cu, Zn)	*Desulfovibrio desulfuricans* *Flavobacterium* sp. *Methylobacterium organophilum* *Staphylococcus* sp. *Streptomyces* sp. *Acinetobacter* sp. *Arthrobacter* sp. *Pseudomonas aeruginosa* *Bacillus subtilis* *Bacillus cereeus* *Staphylococcus* *Pseudomonas fluorescens* *Aeromonas* sp. *Aerococcus* sp. *Rhodopseudomonas palustris* *Saccharomyces cerevisiae* *Lysinibacillus sphaericus* CBAM5

(continued)

Table 30.1 (continued)

Contaminants removed/treated	Bacterial species
Organic compounds (hydrocarbons, aromatic compounds, halogenated compounds, organic solvent, petrol, diesel, lindane, DDT, phenol, endosulfan, chlorpyrifos, methyl parathion, azo dyes)	*Dietzia* *Pseudomonas putida* *Pseudomonas halodurans* *Pseudomonas alcaligenes* *Pseudomonas mendocina* *Pseudomonas veronii* *Pseudomonas aeruginosa* *Halomonas* *Halobacterium* *Haloharcula* *Haloferax* *Methylobacter alcaliphilus* *Acinetobacter baumanii* *Ralstonia* sp. *Microbacterium* sp. *Achromobacter* *Flavobacterium* *Arthobacter sp* *Alcaligenes odorans* *Bacillus subtilis* *Bacillus cereus* *Corynebacterium propinquum* *Staphylococcus* *Enterobacter* sp. *Photobacterium* sp. *Micrococcus luteus* *Listeria denitrificans* *Nocardia atlantica* *Exiguobacterium indicum* *Exiguobacterium aurantiacums*

Corporation of India Ltd., Jaduguda, India showed capacity to resist and accumulate uranium.

Inorganic contaminants such as heavy metal ions are removed by bacteria via mechanisms such as biosorption, entrapment, efflux, reduction, precipitation, and complexation (Vullo et al. 2008; Eswayah et al. 2017). They convert ions into minerals as the result of cellular activities via process of biomineralization (Simkiss and Wilbur 2012). Many microbial species showed capacity to biosorb contaminants. *Biosorption* is the attachment of compounds to biomass without any involvement of metabolic activity (Das 2012; Newsome et al. 2014). Metal ions show accumulation or adsorption at the cell surface of living cells. Besides this, ion exchange followed by penetration in the cell membrane was another strategy reported in microbes (Tong et al. 2004). Carboxyl, amine, hydroxyl, phosphate, and sulfhydryl groups help in the attachment of ions at the surface (Lloyd and Macaskie 2000; Newsome et al. 2014).

3.2 Remediation Through Cyanobacteria

Cyanobacteria also show good potential to degrade organic pollutants. They help in detection, transformation or degradation of xenobiotics/pollutants (Table 30.2). Each species shows variation in capacity to degrade pollutants. Lipids, polysaccharides and carbohydrates present on the cell wall of *Cyanobacteria* possess negatively charged functional groups. These negatively charged groups bind metals and hence help in removal of metals from water. Metal gets adsorbed to the surface of the cell. After uptake, metals get localized in vacuoles and precipitated on the cell surface in *Cyanobacteria*.

Cyanobacterial species has shown capacity for bioremediation (Al-Amin et al. 2021). *Oscillatoria, Synechococcus, Nodularia, Nostoc,* and *Cyanothece* are some of the cyanobacterial species that show capacity to degrade and biosorb variety of

Table 30.2 *Cyanobacteria* species showing capacity for removal of contaminants

Contaminants removed/treated	Species
Radionuclides (^{226}Ra, ^{90}Sr, ^{239}Pu, ^{241}Am, ^{134}Cs, ^{85}Sr, ^{226}Ra)	*Gloeomargarita lithophora* *Arthrospira platensis* *Laminaria*
Heavy metals (Cu, Fe, Cr, Ni, Zn, Cd, Hg, Pb)	*Anabaena doliolum* *Nostoc linckia* *Oscillatoria limosa*
Inorganic ions (ammonium, nitrate, nitrite, phosphate)	*Synechocystis salina* *Phormidium foveolarum* *Chlorella sorokiniana* *Aphanocapsa* *Anabaena* *Microcoleus* *Nostoc* *Oscillatoria* *Phormidium*
Organic contaminants (salicylate, phenanthrene-38, hydrocarbons)	*Synechocystis salina* *Phormidium foveolarum* *Chlorella sorokiniana* *Aphanocapsa* *Anabaena* *Microcoleus* *Nostoc* *Oscillatoria* *Phormidium*

contaminants present alone or along with other contaminants. The contaminant removal efficiency ranged from 69% to 99.6%.

Cyanobacteria also showed capacity to accumulate high concentration of insecticides. *Cyanobacteria* showed capacity to transform fenamiphos, a pesticide (Gupta et al. 2018). Degradation of organophosphorus and organochlorine insecticides has been noted in *Synechococcus elongates, Anacystics nidulans,* and *Microcystes aeruginosa*. Several microalgal species such as *Oscillatoria*, *Phormidium, Aphanocapsa,* and *Westiellopsis* are some algal species that show potential to treat industrial effluents (Vijayakumar 2012).

3.3 Remediation Through Fungi

Fungi exhibit great potential to remediate various inorganic and organic contaminants present in the environment (Table 30.3). *Phanaerochaete chrysosporium* (white rot fungus) show high potential to remove/degrade various environmental pollutants. Fungal species viz., *Aspergillus niger, A. fumigates, Aureobasidium pullulans, Cladosporium resinae, Funalia trogii, Ganoderma lucidum, Penicillium* spp.*, Rhizopus arrhizus,* and *Trametes versicolor* show high capacity to remove heavy metals (Loukidou et al. 2003; Say et al. 2003; Pinedo-Rivilla et al. 2009; Tastan et al. 2010; Ramasamy et al. 2011; Espinosa-Ortiz et al. 2022).

Removal of radionuclides such as uranium via biomineralization has been noted in *Aspergillus niger, Paecilomyces javanicus,* and *Saccharomyces cerevisiae* (Khani et al. 2005; Mumtaz et al. 2013, Rummel et al. 2014; Liang et al. 2015; Stevenson et al. 2017; Narendrula-Kotha and Nkongolo 2017; Lopez-Fernandez et al. 2018; Zheng et al. 2018; Chen et al. 2020). Fungi have also shown potential to mineralize other radionuclides, including cesium, strontium, technetium, plutonium, or neptunium (Fomina et al. 2007; Pan et al. 2009; Sivaperumal et al. 2018; Thorpe et al. 2016). Yeast *Rhodotorula mucilaginosa* showed capacity for biosorption of curium (Lopez-Fernandez et al. 2019). Lichens also showed capacity to biosorb uranium (Purvis et al. 2004).

3.4 Remediation Through Plants

Use of plants in removal/treatment contaminants from the various components of environment (water, soil, and air) is referred as phytoremediation or green technology. Microorganisms associated with plants in the root zone (rhizosphere) play an important role in remediation of pollutants. Pesticides, chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), petroleum hydrocarbons, radioactive elements, explosives, and heavy metals are some of the contaminants that have been successfully treated/removed via green technology.

Table 30.3 Fungal species with potential for removing/treating contaminates

Contaminants removed/treated	Species
Heavy metals (Cr, Cu, Ni, Pb, Hg, Cd)	*Saccharomyces cerevisiae* *Trichoderma viride* *Aspergillus niger* *Aspergillus flavus* *Aspergillus versicolor* *Aspergillus fumigatus* *Penicillium janthinellum* *Aspergillus versicolor* *Neurospora crassa* *Phanerochaete chrysosporium* *Hymenoscyphus ericae* *Neocosmospora vasinfecta* *Verticillium terrestre* *Paecilomyces* sp. *Terichoderma* sp. *Microsporum* sp. *Cladosporium* sp.
Organic compounds [Polyaromatic hydrocarbons, polychlorinated biphenyls, aliphatic hydrocarbons, phenol, catechol, lindane, 2,4-dichlorophenol, 2,6-dimethoxyphenol, pentachlorophenol, tetrachloroethylene, 2-chlorophenol, trichloroacetic acid, hexachlorocyclohexane, endosulfan, tribromophenol, benzene, toluene, ethyl benzene, xylene, dyes (crystal violet, malachite green, bromophenol blue, orange G orange I, remazol brilliant blue R, crystal violet)]	*Aspergillus awamori NRRL 3112* *Aspergillus terricola* *Aspergillus terreus* *Aspergillus niger* *Aspergillus fumigatus* *Penicillium camemberti* *Penicillium chrysogenum Paecilomyces* *Coriolus* *Pycnoporus* *Pleurotus* *Fomitopsis* *Daedalea* *Phlebia brevispora* *Trichoderma* sp. *S019* *Trametes versicolor* *Trametes hirsutus* *Trametes villosa* *Bjerkandera adusta Chaetosartorya stromatoides* *Agaricus augustus* *Phanerochaete chrysosporium* *Pycnoporus sanguineus* *Trogia buccinalis* *Fusarium solani* *Tyromyces palustris Gloeophyllum trabeum*
Crude oil	*Aspergillus niger* *Candida glabrata* *Candida krusei* *Saccharomyces cerevisiae*

3.4.1 Algae

Algae have shown tremendous potential to treat organic contaminants from the environment (Chekroun et al. 2014) (Table 30.4). Removal/degradation of hydrocarbon has been reported in microalga. Adsorption of radionuclides such as cesium has been reported in marine algal species such as *Sargassum glaucescens* and *Cystoseira indica* (Jalali-Rad et al. 2004; Dabbagh et al. 2008). Cell wall and extracellular polymeric substances of *Shewanella* algae helped in biosorption of neptunium (Singhal et al. 2004; Deo et al. 2010). Algal species viz., *Spirogyra and Cladophora* showed capacity to biosorb various heavy metals such as Cr, Cu, Fe, and Mn (Lee and Chang 2011; Yin et al. 2012).

3.4.2 Higher Plants

Higher plants show capacity to extract, immobilize, or transform pollutants. Plants and associated rhizospheric microorganisms show high organic and inorganic pollutant removal capacity (Berti and Cunningham 2000; Cheng et al. 2017). The contaminants are taken up from the soil matrix via roots and degraded with the help of the activity of microbes present in the rhizosphere (Jacob et al. 2018; DalCorso et al. 2019). Aquatic and terrestrial plants show equally good potential to treat various contaminants from the environment (Table 30.5).

Table 30.4 Algal species showing contaminant removal capacity

Species	Contaminants removed/treated
Vacuoliviride crystalliferum *Polysiphonia fucoides* *Graesiella emersonii*	Radionuclides (^{51}Cr, ^{54}Mn, ^{57}Co, ^{60}Co, ^{65}Zn, ^{85}Sr, ^{109}Cd, ^{110m}Ag, ^{113}Sn, ^{137}Cs, ^{241}Am)
Spirogyra *Spirulina* *Nostoc*	Heavy metals (Cr, Cu, Pb, Cd)
Skeletonema costatum *Nitzschia* sp. *Chlorella sorokiniana* *Portieria hornemannii* *Porphyra yezoensis* *Chlamydomonas reinhardtii* *Chlorococcum* sp. *Scenedesmus obliquus* GH2 *Coprinellus radians* *Candida viswanathii* *Gleophyllum striatum*	Organic compounds (polycyclic aromatic hydrocarbons, phenanthrene, fluoranthene, TNT prometryne, α-endosulfan, methylnaphthalenes, dibenzofurans, benzopyrene, pyrene, anthracene, dibenzothiophene, crude oil)

Table 30.5 Terrestrial and aquatic plant species with potential for remediation of contaminants

Plant species	Contaminant removed/treated
Terrestrial species	
Pteris vittata *Sedum alfredii* *Phytolacca americana* *Thlaspi caerulescens* *Silene vulgaris* *Schima superba* *Alyssum* sp. *Medicago sativa* *Helianthus annuus* *Astragalus racemosus*	Heavy metals (As, Cr, Cd, Zn, Hg, Mn, Ni, Pb, Se)
Helianthus annuus *Lactuca sativa* *Silybum marianum* *Centaurea cyanus* *Carthamus tinctorius*	Radionuclides
Hybrid poplar *Cucurbita*	Organic compounds (polychlorinated biphenyls, polychlorinated dibenzodioxins)
Spincea oleracea *Dacus carota* *Lactuca sativa* *Allium cepa* *Solanum tuberosum*	Antibiotics (tetracyclines, polyether, semisynthetic and macrolides, aminoglycosides, sulfa and β-lactams antibiotics)
Datura innoxia *Citrus citrus*	TNT, other explosives
Aquatic species	
Salvinia sp.	Heavy metals (Cr, Cd, Zn, Ni, Pb, Co)
Lemna minor *Elodea canadensis* *Cabomba aquatica* *Schoeplectus lacustris* *Typha latifolia* *Iris pseudacorus* *Phragmites australis* *Chrysopogon zizanioides*	Organic compounds Copper sulfate Flazasulfuron Dimethomorph Atrazine
Myriophyllum spicatum *Chrysopogon zizanioides*	TNT

Removal of pollutants from the environment occurs via mechanisms such as phytostabilization, rhizofiltration, phytoaccumulation, and phytovolatilization. Pollutants present in the soil get removed via phytostimulation and rhizodegradation processes. The degradation of pollutants is supported by rhizospheric microbial communities (Ernst 2005; Marques et al. 2009). The success of the phytoremediation depends on the plants and microbes and their interactive association. The pollutants get removed via degradation, detoxification or sequestration. Microbes present in the rhizospheric zone play a major role in phytostabilization (Rufyikiri et al. 2002). Contaminants irrespective of being organic, such as insecticides, chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), petroleum hydrocarbons, surfactants, and explosives, or inorganic, such as radionuclides and heavy metals, can be treated by phytoremediation. Nitroreductase, dehalogenase, laccase and peroxidase are the major enzymes that assist in the breakdown of contaminants into simpler forms.

In phytoextraction technology, contaminants are removed from soil or water by plants. They get translocated from roots to other plant plants and get accumulated in the harvestable plant parts such as stem, leaves and fruits (Brunner et al. 2008; Ali et al. 2013; Jacob et al. 2018). Phytostabilization method helps in immobilization of contaminants in the belowground parts thereby prevent their migration into the ecosystem (Marques et al. 2009). Addition of organic or inorganic amendments in the soil improves the efficiency of phytostabilization technique (Alvarenga et al. 2009; Gerhardt et al. 2017). The contaminants are broken down into simpler forms with the help of enzymes such as peroxidases and laccases released by plant roots. The contaminants taken up by the plants get converted into volatile forms and are released into the atmosphere. This process of remediation is known as phytovolatilization.

The removal of heavy metals and radionuclides by plants involves processes such as extraction, transformation, and sequestration (Dalvi and Bhalerao 2013; Javed et al. 2019). Organic pollutants such as hydrocarbons, chlorinated compounds get converted into simpler forms followed by their stabilization in the root zone.

Plants show high metal accumulation capacity (Clemens 2006). These plants are called as hyperaccumulators (Kramer 2010; Sarma 2011). Hyperaccumulators show Hg accumulation above levels of 10 mg/kg, Cd and Se show accumulation above levels of 100 mg/kg, Cd, Co, Cu, Cr, Ni and Pb show accumulation above the levels of 1000 mg/kg and Zn and Mn show accumulation to the levels above 10,000 mg/kg (Baker and Brooks 1989). The plants showing metal hyperaccumulation depict shoot to root heavy metal accumulation ratio greater than 1. These plants show high rate of metal transportation (Marques et al. 2009; Rascio and Navari-Izzo 2011).

The microbial communities present in the root zone help treatment/removal of air pollutants (Gawronski et al. 2017; Wei et al. 2017). The phenomenon is termed as phylloremediation. Studies have demonstrated that leaves of plants help in reducing the level of air pollutants and volatile organic compounds (VOCs). Stomata adsorb or absorb particulate matter, and leaves assimilate SO_2, NO_2, CH_2O (formaldehyde) further convert them into simple organic compound such as amino acids, proteins. Stomata via flow of gases also adsorb or absorb other chemicals. The bacteria present on the leaf surface degrade or convert volatile organic compounds to less nontoxic forms. Plant-supported microbes biodegrade or biotransform air pollutants by converting them into organic compounds.

Nitrogen is absorbed in the form of nitrate (NO_3) by plants. It is used by plants in the synthesis of nitrogenous compounds such as amino acids and proteins. *Eucalyptus viminalis, Populus nigra, Robinia pseudoacacia*, *Erechtites hieracifolia, Crassocephalum crepidioides*, *Magnolia kobu,* and *Nicotiana tabacum* are some of the plant species assimilate nitrogen (Morikawa et al. 1998). Polyaromatic hydrocarbons (PAHs) get adsorbed by leaves of plants. A study conducted in early spring in Southern Ontario, Canada showed that levels of the compounds such as phenanthrene, anthracene, and pyrene got reduced by the canopy of deciduous forest trees (Choi et al. 2008). The rate of removal of PAHs differs among species. The variation in removal capacity could be due to presence of plant's morphological features, chemical constitutions and leaf-associated microbes. The plant's ability to adsorb, assimilate and tolerate air pollutants varies for each species.

4 Factors Affecting Bioremediation

Chemical nature of pollutants, their concentration, duration of exposure and physicochemical properties of the medium (water and soil) affect the rate of bioremediation to a great extent. Biodegradation also get affected by environmental factors such as temperature, pH, availability of oxygen, and nutrients. Degradation of the pollutant also depends upon enzymatic metabolic pathways of microorganisms.

4.1 Biotic or Biological Factors

Biotic factors play an important role in degradation of organic contaminants. It includes microbial diversity and type of plants. Interaction among microorganisms/protozoa/bacteriophages (competition, succession, and predation) affects bioremediation. Microorganisms secrete enzymes that assist in chelation of contaminants in the root zone (Sheoran et al. 2011). The degradation of contaminant depends upon the level of the contaminant, enzyme activity and catalyst.

Chelating agents lead to formation of water-soluble heavy metal–chelate complexes in the soil. These complexes are portable, therefore are easily taken up by the plant (Wuana and Okieimen 2011). Phytosiderophores, carboxylates, and organic acids secreted by the plants in the rhizosphere bind metals and form compounds. These compounds alter physical and chemical characteristics of the soil, help in chelation of compounds, and increase mobility, solubility, and bioavailability of metal ions (Lone et al. 2008; Gerhardt et al. 2009; Robinson et al. 2009).

4.2 Abiotic or Environmental Factors

Temperature, pH, moisture, availability of water, nutrients, oxygen, and redox potential affect the growth and activity of microbes. The remediation process depends majorly on availability of pollutants, their concentration, chemical nature, and type of pollutant and solubility. Optimum range of these parameters is required as they influence microbial growth, rate of biodegradation and hence the removal of the contaminants. A pH range of 6.5–8.5 has been found to be most suitable for degradation of pollutant in aquatic and terrestrial environment (Vidali 2001). Water availability is another factor that is very important for efficient bioremediation. Oxygen is required for the initial breakdown of the contaminants. Temperature affects rate of biochemical reactions. Environmental conditions affect the interaction between the microbes and pollutant.

Nitrogen, phosphate, sulfur, iron, and potassium are the nutrients present in the polluted environment that support microbial growth and metabolism. These nutrients provide basic requirements to microbes and provide necessary enzymes for breakdown of contaminants. The nature of pollutants, i.e., solid, semisolid, liquid, volatile, organic, or inorganic, affects degradation of pollutants.

5 Other Strategies for Improving Performance of Microbes and Plants

Microbial communities present in the rhizosphere help in improving performance of plants involved in remediation of contaminants. Microbial species, particularly plant growth-promoting rhizobacteria (PGPR), have shown to increase the efficiency of plants for remediation. These bacteria promote growth of plants, safeguard plants from pathogens, enhance tolerance capacity of plants against various stresses, and promote uptake of nutrients (Ma et al. 2011; Ruiz et al. 2011). The growth regulators (such as indole acetic acid), produced by bacteria help in formation of lateral roots and root hair which promote growth of plants (Glick 2010; DalCorso et al. 2019). Plant growth-promoting rhizobacteria secrete compounds such as biosurfactants and siderophores, which assist in mobilization of contaminants (Sheoran et al. 2009).

Microbes associated with arbuscular mycorrhizal fungi (AMF) also play a role in treating the contaminants present in the soil (Chen et al. 2008). Arbuscular mycorrhizal fungi increase the surface area of plant roots thereby increasing the efficiency for absorption of pollutants. Absorption of water, uptake of nutrients and heavy metal bioavailability increase due to AMF (Göhre and Paszkowski 2006). Mycorrhizal fungi alter the physical and chemical characteristics of the soil and chemical composition of plant root exudates, which affect the availability of contaminants for bioremediation (Sarwar et al. 2017). The phytohormones produced by AMF promote growth of plants and assist in removal of contaminants.

6 Role of Biotechnology in Improving Bioremediation Capacity of Organisms

Biotechnology techniques have proved useful in improving the bioremediation potential of living organisms (Eapen and D'souza 2005; Dhankher et al. 2011; Fasani et al. 2018). Genetic engineering approaches improve efficiency of organisms (both microbes and plants) for remediation (Marques et al. 2009). The genome of living organisms can be modified via biotechnology to enhance tolerance and breakdown capacity of pollutants (Singh et al. 2011). Overexpression of genes responsible for increase in uptake, metabolism and transport of pollutants increases the remediation potential of living organisms (microbes and plants). Transgenic plants and microbes with higher efficiency for treatment/removal of contaminants such as organic pollutants, metals, metalloids, and explosives have been developed (Khan and Mir 2021) (Table 30.6).

Genetic engineering approach has been followed to develop microorganisms with enhanced potential of degrading contaminants and, hence, high bioremediation capacity. Genetic engineering has been used to develop microorganisms with high intrinsic pollutant sequestering ability and high tolerance to environmental

Table 30.6 Transgenic plants developed for enhanced metal tolerance/phytoremediation

Gene transferred for accumulation/tolerance of	Target plant species
Cd	
MT1 gene γ-Glutamylcysteine synthetase Glutathione synthetase Cysteine synthetase	Tobacco Mustard Mustard Tobacco
Cu	
MTA gene	*Arabidopsis*
Al	
Citrate synthase	*Arabidopsis*
Al, Cu	
Glutathione *S*-transferase	*Arabidopsis*
Se	
Selenocysteine Methyl transferase ATP sulfurylase CAPS	*Arabidopsis* Mustard
Cd, Pb	
Znt A-heavy metal Transporters YCF1	*Arabidopsis*
As	
Arsenate reductase γ- glutamylcysteine Synthetase	Mustard

contaminants (Bae et al. 2001; Majare and Bulow 2001). Genetic modification increases the efficiency of organisms for bioremediation by increasing tolerance capacity and pollutant accumulation capacity (de Mello-Farias et al. 2011; Dhanwal et al. 2017; Gong et al. 2018). Expression of metallothioneins (MTs) in bacterial cells enhances metal accumulation. *Staphylococcus xylosus* and *Staphylococcus carnosus* strains that show high expression of chimeric proteins on the cell surface have been developed (Samuelson et al. 2000). Both strains showed improved nickel-binding capacities.

Phytoremediation efficiency depends upon high uptake of pollutant followed by its detoxification. Fast-growing and high biomass producing plants accumulate high level of toxicants. Genetic engineering has been used to develop high biomass and fast-growing species. The genes coding for resistance to pollutants have also been identified, isolated from living organisms and expressed in plants (Seth 2012). Genes involved in inducing resistance against inorganic and organic pollutants in plants have been expressed in plants by the use of biotechnology (James and Strand 2009; Kumar et al. 2011a). Plant- and bacterial-origin genes are isolated and transferred into genome of the target plant. Genetic engineering techniques have proved useful in improving growth and promoting biomass production in hyperaccumulator. Traits such as hyperaccumulation of contaminants (such as metals) have been introduced in plants (DalCorso et al. 2019). Genes responsible for uptake, translocation, and sequestration of heavy metals have been successfully introduced in plants (Mani and Kumar 2014; Das et al. 2016). The plants overexpressing these genes show enhanced tolerance capacity against various contaminants including heavy metals. These plants also possess high heavy metal-accumulation ability. Genes encoding metal/metalloid transporters have also been introduced and overexpressed in target plants (Wu et al., 2010). Overexpression of genes coding for enzyme glutamylcysteine synthetase that assist in high heavy metal accumulation capacity has been introduced in plant species such as *Populus angustifolia*, *Nicotiana tabacum* and *Silene cucubalis* via genetic engineering technique (Fulekar et al. 2009). The gene *gshl* coding for enzyme gamma-glutamylcysteine synthetase isolated from *Escherichia coli* has been introduced into *Brassica juncea*. The transgenic plants developed by this approach show high tolerance to cadmium and synthesized phytochelatins, glutathione and total nonprotein thiols at high levels. Genes like *AtNramps*, *AtPcrs*, and *CAD1* responsible for increased heavy metal uptake and resistance have been introduced into plants.

Nicotiana tabacum plants that show high expression of yeast metallothionein gene have been developed. These plants showed high tolerance to Cd. Overexpression of Hg reductase gene responsible has been expressed in *Arabidopsis thaliana*. The transgenic plants developed by this approach show high tolerance to Hg. Two genes, namely, *arsC* and gECS1 that code for arsenate reductase and glutamylcysteine has been isolated from microbes and overexpressed in plants. The plants showed enhanced capacity for capturing arsenate and degrading it. Microbial genes such as *ArsC isolated* from *E. coli* have been expressed along with gene coding for enzyme α-glutamylcysteine synthetase. The plants developed by this approach showed enhanced potential for As elimination and high As tolerance potential. The enzyme α-glutamylcysteine synthetase responsible for synthesis of glutathione (GSH) increases As conjugation. Incorporation of the gene *ArsB* promotes translocation of As to leaves through efflux, while gene *ArsM* assists in the volatilization of As by supporting methylation to trimethylarsine (Berken et al. 2002). Genetically modified plants that express enzymes that help in methylation of Se derivatives and convert Se into volatile forms have been developed. Genes *merA* and *merB* encoding for enzymes mercuric reductase and organomercurial lyase have been introduced in plants. The transformed plants show high Hg removal capacity. Tobacco, yellow poplar, cottonwood, and rice plants with *merA* gene inserted into them showed high resistance to Hg and high Hg(0) volatilization efficiency (Bizily et al. 2000). Transgenic tobacco plants show high level of Hg accumulation in shoots and high tolerance to organomercurial compounds such as phenylmercuric acetate (PMA).

Exposure to pollutants results in oxidative stress. The production of reactive oxygen species during oxidative stress can be overcome by protective machinery such as antioxidants (Koźmińska et al. 2018). Overexpression of genes of antioxidant machinery induced protection to oxidative stress. Transgenic plants showing enhanced capacity for elimination of explosives such as 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and glyceryl trinitrate (GTN) have also been developed. Expression of bacterial genes coding for nitroreductases (*pnrA*) and cytochrome p450 in plants increased their uptake, tolerance, and detoxification capacity for explosives.

Herbicide-resistant plants and plants with high capacity for herbicide remediation have been developed using biotechnology approaches. Enhanced resistance to herbicide and increased detoxification capacity in plants can be increased by overexpressing the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS).

Microbial genes encoding enzymes atrazine chlorohydrolase (*atz*Z) and 1-amino cyclopropane-1-carboxylate deaminase have been introduced in plants. The plants show increase in remediation capacity for atrazine. Plants that express cytochrome p450 show good capacity for removal/degradation of organic chemicals. This approach has been followed to transform tobacco and poplar. Genetic engineering technology has been used to successfully develop plants with potential for metabolism of chemical compounds such as vinyl chloride, benzene, toluene and chloroform. Transgenic plants with good rhizodegradation capacity for polychlorinated biphenyls (PCBs) and polyaromatic hydrocarbons (PAHs) have been developed.

Plants with high capacity for remediation of air pollutants have been developed via genetic engineering (Abhilash et al. 2009). Cysteine is synthesized via enzyme cysteine synthase involving use of H_2S and SO_2 as a source of sulfur. Rice overexpressing genes responsible for synthesis of cysteine synthase has been developed via genetic engineering approach. Exposure to high level of H_2S results in enhanced capacity for sulfur assimilation (Yamaguchi et al. 2006). Transgenic *Arabidopsis* plants expressing gene that code for enzyme nitrite reductase that catalyzes conversion of nitrite to ammonium have been developed (Takahashi et al. 2001). Overexpression of *CYP2E1* gene that codes for cytochrome P450 2E1 has been transferred to tobacco plants. Transgenic plants show good decomposition potential for chlorinated solvents and aromatic hydrocarbons. Poplar plants expressing mammalian gene, *CYP2E1*, show enhanced capacity for degradation and removal of organic pollutants from the air (Doty et al. 2007). Genes encoding for enzyme chlorocatechol 1,2-dioxygenase (*tfdC*) from bacteria *Plesiomonas* have been inserted into *Arabidopsis thaliana* (Liao et al. 2006). The transgenic plants show enhanced tolerance to catechol. The plants also showed capacity to convert catechol to cis, cis-muconic acid. Transgenic plants with high bioremediation potential for removal of aromatic pollutants have been developed by introducing genes derived from microbes (Liao et al. 2006).

7 Applications of Bioremediation

Bioremediation technique targets at removal of contaminants from the environment (Balba et al. 1998; Vangronsveld et al. 2009). The contaminated environment can successfully be remediated or restored using bioremediation (Balba et al. 1998; Conesa et al. 2012; Mani and Kumar 2014). Many success stories about the bioremediation technology have been known.

An area (about 11,000 m^3) contaminated with organic pollutants such as pharmaceutical compounds, polyaromatic hydrocarbons, heterocyclic organic compounds, phenols, and chloroform was successfully remediated by an organization named TERI (Tata Energy Research Institute, New Delhi) using oilzapper-mediated bioremediation technique. The contaminated soil of the area was removed and spread over a high-density polyethylene geomembrane (HDPE liner). This liner prevented percolation of contaminants into the ground. Oilzapper is a microbial consortium developed by assembling four bacterial species. The microbes assisted in breakdown of fractions of complex mixture of petroleum hydrocarbons. The hydrocarbons present in soil got transformed to nontoxic compounds. Application of oilzapper to soil, followed by a treatment of nutrient mix in water, promotes microbial growth. The bioremediation was carried out in two batches for time duration of about 80 days, and 87–93% degradation was achieved at various sites.

A study conducted at the Aleutian Island showed that an area of about 1900 m^3 having petroleum-contaminated soil was subjected to bioremediation pile. The bioremediation process got stimulated after addition of nutrients and oxygen due to increase in microbial activity. The system showed a significant (80%) reduction in diesel concentrations of soil within 6 months.

Fuel oil spill of Prestige located in coastal areas of Spain was remediated in 2002 by bioremediation. Addition of exogenous microbial populations accelerated biodegradation by stimulated indigenous populations for induced natural attenuation.

Successful removal of petroleum hydrocarbons found in the subsurface soil and groundwater has been done. Heavy oils present in the soil of a locomotive maintenance yard in California have been remediated successfully. A multistep laboratory treatment was done followed by a field demonstration to get about 94% removal of TPH in less than 16 weeks. Oils in soil of an oil refinery in Germany have been remediated (84% reduction) following excavation and in-situ treatment within 24 weeks (Maitra 2018). Oil-contaminated desert soil in Kuwait has been remediated involving land farming, composting piles, and bioventing soil piles. About 80% reduction was noted in 12 months.

Inoculation of *Bradyrhizobium, Azotobacter,* and vesicular arbuscular mycorrhizal species, *Glomus* and *Gigaspora* sp. enhanced capacity of plants for restoring productivity, fertility, and stability at a zinc-mined site (Juwarkar and Singh 2010).

8 Conclusions and Future Prospects

Biodegradation is natural and environment friendly process of cleaning environment by removing pollution. Microbes and plants show capacity to effectively degrade various toxic environmental pollutants. Advantages such as cost effectiveness, no further generation of pollution make the bioremediation technology a viable option for cleaning the environment. Bioremediation helps in transforming the harmful chemicals into chemicals which do not prove toxic and hence causes less harm. Bioremediation has been successfully implemented at various sites around the world. Improvement in microbes and plants has been achieved by biotechnology. Genetic engineering technology alters microbes and plants in a way that desired traits such as fast growth, high biomass production and high tolerance capacity can be achieved. Genes involved in uptake, movement, sequestration, and tolerance of pollutants have been successfully inserted in microbes and plants. Biotechnology has proved useful in getting transgenic plants with high capacity for environmental cleanup. Research studies need to be conducted to find out the mechanism involved in the degradation of pollutants in genetically transformed plants and microbes. Phytoremediation technologies are currently practiced at a small scale and only for few pollutants. Therefore, plants with multiple genes inserted can prove beneficial for meeting requirements need to be developed. Biotechnological approaches can prove as asset for improving ability of plants for tolerance for pollutants and achieve high phytoremediation efficiency.

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Chapter 31
Consolidating the Knowledge of Black Soldier Fly Larva Compost: A Resilience Response to Climatic Variations, Resource Conservation, and Food Security Challenges

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Abstract The increase in the population has led to numerous environmental issues like the higher production of solid waste. Moreover, this increased solid waste generation is also due to industrial progress and commercialization. Poor waste management threatens the health of both the environment and humans. For the last several years, the use of the black soldier fly (SBF), *Hermetia illucens*, as an organic waste recycler has achieved great popularity. Black soldier fly larvae (SBFL) consume a variety of organic wastes, such as by-products of agriculture, dairy manure, as well as food waste, and hence lower the original volume of the waste by approximately 50% in a short time as compared to other methods of composting. Using SBFL to convert municipal solid waste into nutrient-rich compost for vegetable production might help the cities to reduce their dependency on food imports and waste output. Moreover, SBFL comprise 42% crude protein and 29% fat, with a more amazing saturated fat content than other insects. Other lucrative benefits of SBFL in comparison with the other common insects are its potential of turning waste into food, providing economic benefits and recycling nutrients while reducing pollution and expenses. They can be used as feed for poultry, animal husbandry, and pets. Moreover, SBFL might theoretically be processed and transformed into protein with a strong taste for its commercial usage in human diets. However, the

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benefits of SBFL are also their biggest drawbacks since social stigmas and legislative bans against consuming creatures that consume waste are added to the existing taboos against eating insects.

Keywords Waste management · Food waste · Compost · Black soldier fly · Pets

Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
GHG	Greenhouse gas
N_2O	Nitrous oxide
OM	Organic matter
PBac	Pathogenic bacteria
SBF	Black solider fly
SBFL	Black soldier fly larvae
SBFLC	Black soldier fly larva compost

1 Introduction

Population growth is directly or indirectly connected to the production of solid waste. The commercial, agricultural, construction, and food industries contribute to solid waste generation (Shitu et al. 2005). The continuous rise in the world population is expected to increase the amount of solid waste. Due to the rise of consumerist modes of living, economic development, and metropolitan area networks, the last several decades have witnessed considerable shifts in mass consumption, production, and waste disposal (Weng and Fujiwara 2011; Ioannou et al. 2022). All of these causes lead to the continuous range of vast amounts of waste. Researchers urgently need to create technologies and techniques to address the issues related to waste production. The fundamental goal of waste management is to decrease the waste generated, lowering disposal costs and the impact on the environment and human health (Amrul et al. 2022; Periathamby et al. 2009). Poor waste management will result in environmental problems that several low- and middle-income countries confront due to reckless landfilling and unregulated incineration, which pollute the air and water (Kaza et al. 2018). Organic materials account for 50–70% of solid waste disposed of in landfills, with the remainder consisting of a combination of plastics, metals, paper, and glass. Garbage pickers gather a big proportion of metallic waste for the purpose of recycling while leaving a substantial amount of nonmetallic waste for decaying in landfills (Komakech et al. 2015). The by-products of organic waste decomposition are methane (CH_4) and carbon dioxide (CO_2), resulting in the emission of greenhouse gases (GHGs) that cause global warming (Isibika et al. 2019). Furthermore, inadequate sanitation in landfills promotes the proliferation of flies, rodents, and rodent vectors which are responsible for the spread of diseases in the vicinity like malaria and cholera (Chowdhury et al. 2017). Composting is one strategy for reducing the quantity of organic waste disposed of in landfills. Composting is a tried-and-true method of managing organic waste that may drastically reduce the quantity of waste generated (Diener et al. 2009). Composting organic waste from landfills has several environmental advantages, including lower GHG emissions (Wei et al. 2017). Compost is an organic substance that may be added to soil to help plants thrive and minimize trash transported to landfills (Amrul et al. 2022). There are various composting methods (onsite composting, window composting, in-vessel composting, and vermicomposting) (Palaniveloo et al. 2020; Bidlingmaier et al. 2004). However, these methods have their limitation, such as being expensive, requiring a large space to operate, GHGs emissions, attracting various types of insects, and being easily affected by the change in weather (Cheng et al. 2022; Aziz et al. 2018; Lim et al. 2017; Ramnarain et al. 2019).

Treating organic waste with SBFL is an innovative approach that has recently gained popularity (Čičková et al. 2015; De Smet et al. 2018; Makkar et al. 2014). The SBFL devour organic-rich waste such as agro-industrial by-products (Meneguz et al. 2018), dairy manure (ur Rehman et al. 2017), and food waste (Nguyen et al. 2015). As a result, the nutrients in SBFL are transformed into proteins and lipids for animal feed (Liu et al. 2017; Xiao et al. 2018) that can alleviate the scarcity of feed for animals, which is facing the continuous rise in the prices during the last couple of decades (Stocker et al. 2014). Furthermore, the frass of SBFL can be utilized as a fertilizer (Ma et al. 2018; Xiao et al. 2018). Another advantage of the method is that SBF adults don't bite so the disease can't be transmitted to others. The scientists discovered that SBFL release antibacterial chemicals that cause trouble during egg laying in flies and reduce the diseases related to food like *Salmonella enterica* and *Escherichia coli*. As a result, there is no chance of transmission of disease when SBF farming is done on commercial scale. Various aspects determine the economic feasibility of treatment of waste, for example, the kind of organic source, nutritional content, and ratio of conversion of waste to biomass (Lalander et al. 2019).

2 Composting Methods

Composting is a waste recycling technique that relies on the biological breakdown of organic materials present in the waste under aerobic conditions to produce sterilized and stabilized compost. Composting organic municipal solid waste from landfills provides several environmental benefits, including reduced GHGs emissions (Wei et al. 2017). Compost can be added to soil for increasing the growth of plants and can decrease the waste thrown into the landfills (Amrul et al. 2022). More than 30% of waste (yard and food waste) dumped openly can be composted (Pastorfide and Pastorfide 2021). Composting the waste will reduce the landfills and emission of GHGs as well as encourage sustainable solid waste management (Sekito et al.

2019; Yang et al. 2019). Compost is an amendment for soil that helps in carbon sequestration, water retention, and erosion prevention (Hasling 2012). There are various composting methods, which are as follows (Palaniveloo et al. 2020; Bidlingmaier et al. 2004):

- Onsite composting
- Aerated static pile composting
- Aerated (turned) windrow composting
- In-vessel composting
- Vermicomposting

Each type has its advantages and shortcomings, as described in Table 31.1.

Table 31.1 Different composting methods with their advantages and shortcomings

Types	Advantages	Drawbacks	Duration	Compost capacity	References
Onsite composting	Requires less space. Less expensive	It is affected by the change in weather. It can attract unwanted insects and animals	Long	–	Cheng et al. (2022)
Aerated static pile composting	In conjunction with positive pressure, it is beneficial	The operation is difficult (e.g., duct blockage). Leachate generation. Indoors, excessive off-gas must be addressed. More expensive. Slow decomposition	Long	More than 10 tons of waste	Lim et al. (2017) and Bidlingmaier et al. (2004)
Aerated (turned) windrow composting	Cost-effective. It is simple to operate. Compost of acceptable grade	Process control at the lowest level. Extensive land is needed	Long	More than 10 tons of waste	Aziz et al. (2018)
In-vessel composting	Degrades quickly. Cost of waste transportation is low	The vast land is needed. Expensive	Short	1–5 tons of wastes	Lim et al. (2017) and Bidlingmaier et al. (2004)
Vermicomposting	Requires less space. Cost-effective. Rich in nutrients	Difficult to handle. Produces unpleasant smell	Short	2–3 tons of wastes	Ramnarain et al. (2019)

3 Black Soldier Fly Larva Compost

The utilization of SBFL for composting organic waste is an innovative as well as environmentally beneficial strategy with huge potential, thus capturing people's attention worldwide. Composting with SBFL is a self-sustaining and economical approach that promotes higher resource recovery and the generation of advanced products, consequently creating new economic niches for the entrepreneurs as well as industrial sector in the developing nations (Singh and Kumari 2019). The SBFL treatment technique is one such method that incorporates three key terms in its application: revenue production, nutrient recovery, and waste composting (Attiogbe et al. 2019; McConville et al. 2020). It is a considerably superior option to conventional composting systems because of its low cost, low maintenance, fewer complications, land needs, minimal ecological footprints, and favorable economic possibilities (Singh and Kumari 2019).

3.1 Black Soldier Fly Larvae Life Cycle

The SBF belongs to Stratiomyidae family and has the potential to recycle organic waste (da Silva and Hesselberg 2020). Although the SBF originated in the Americas' tropical, subtropical, and northern climates, it is now found in tropical and temperate locations across the world (Čičková et al. 2015). Adults of SBF are weak flyers who spend most of their time sleeping on plants and can only survive for about 2 weeks on the water. These adults do not bite contrary to other common flies, as they lack a mouthpart, stinger, and digestive tracts. The male SBF has golden while female has a reddish-brown abdomen, and their average length is 15–20 mm (Kumar et al. 2018). The mature female SBF only mates and lays eggs once in her life. The SBF mates while flying and requires large spaces for nuptial flight (Surendra et al. 2020). The male SBF hatches 2 days before the females. The eggs are deposited in dry cracks by female in close proximity to the substrate, and eggs hatch into newborn larvae in approximately 4 days (Hoc et al. 2019). Larvae feed on organic waste such as food leftovers, manure, rotten plants, and municipal garbage (Diener et al. 2011). The larvae can grow up to 27 mm long and 6 mm wide and weigh up to 220 mg (Makkar et al. 2014). The mature larvae unload digestive tracts and leave the substrate to pupate in a safe and dry place. It is known as "self-harvesting" because it gets rid of the labor-intensive farming stage (Wang and Shelomi 2017). When the larvae have got their maximum, they contain 33% fats and a protein level of 36–48% (St-Hilaire et al. 2007a) and mature into adults in around 14 days (Pathak and Rajendra 2015). Figure 31.1 depicts the SBF's life cycle, from the egg to maturity, as it takes approximately 40–43 days because the phases may lengthen by virtue of food availability and other variables. The cycle might take up to 4 months. SBFL consume as much organic garbage as possible before pupating and transforming into adults (Purkayastha and Sarkar 2021; Lopes et al. 2022; Amrul et al. 2022).

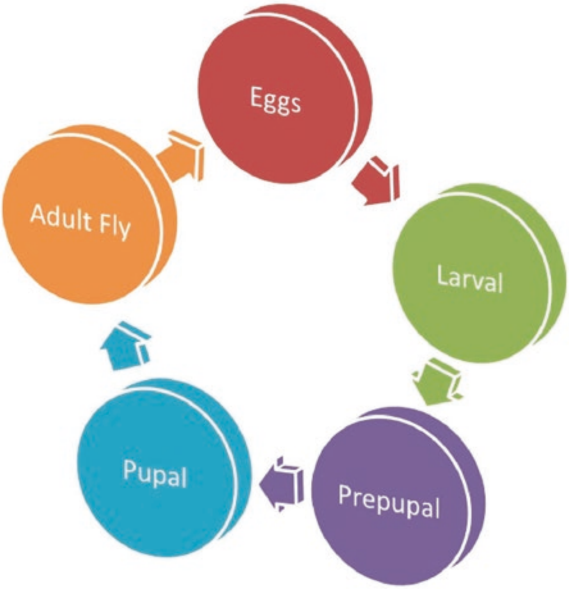

Fig. 31.1 Life cycle of black soldier fly

3.2 Environmental Conditions

3.2.1 Temperature

The collected SBFL frass has a temperature range of 24–27 °C (Attiogbe et al. 2019; Sarpong et al. 2019). The mesophilic phase of SBFL composting occurs; SBFL carry on altering the organic matter (OM), but greater aeration throughout the SBFL composting process regulates a reasonably consistent temperature (approximately 30 °C) for optimum waste consumption by SBFL (Pang et al. 2020a). Raising SBFL at the optimal temperature increases their capacity to decrease *E. coli* (Liu et al. 2008).

3.2.2 Moisture Content

The SBFL frass generated from brewery spent grain is the driest, with 30% moisture content, while frass derived from sawdust combination, chicken feces, and food waste (1:2:3: ratio) is the wettest, with 72% moisture. The frass with high moisture content has a clayey texture, creating difficulty in harvesting the SBFL biomass beneath the moist frass. Rinsing the wet frass beneath running water is one method for extracting the SBFL biomass (Dortmans et al. 2017). Unfortunately, this procedure washes off frass, and it is a loss because frass may be converted to useful agricultural by-products. Dry frass can be produced using appropriate waste in the treatment of SBFL. It is important to note that the dry frass is near to the compost which is not yet matured considering the organic waste should be composted quickly for around 14 days and may include phytotoxins that affect plant development. Several studies propose that dry frass should be post-treated to guarantee maturity and stability (Lopes et al. 2022).

3.2.3 pH

The lowest value of pH (5.6) of SBFL frass from food waste (vegetables and fruit) and the maximum value of pH with the combination of sawdust, feces of chicken, and food waste (1:2:3 ratio) were observed. The SBFL frass pH normally ranged from 7.0 to 8.0, and it is favorable for boosting health of plants (Surendra et al. 2020) and creating a conducive habitat for favorable bacteria in SBFL frass (Choi and Hassanzadeh 2019).

3.3 Processing

The SBF is found in many regions with hot, tropical, or subtropical conditions all year (Dortmans et al. 2017; Gold et al. 2018). The SBFL eat human excreta, animal manure, carrion, fruits, and vegetable wastes (da Silva and Hesselberg 2020). The organic waste is consumed by SBFL, which converts it into larval biomass, thus leaving back a compost-like substance that has properties comparable to immature compost (Zurbrügg et al. 2018; Xiao et al. 2018). The basic SBF organic waste processing plant includes waste processing (e.g., inorganic removal, dewatering, particle size reduction), SBFL treatment of waste, separation of SBFL from the residue, and isolating larvae and leftover material to market. Furthermore, a nursery that keeps healthy adults and larval SBF offers a continuous and stable supply of descendants for organic waste treatment (Dortmans et al. 2017).

3.3.1 Challenges for Processing

The SBF organic waste processing is a newer treatment method (Lohri et al. 2017). The following are the current problems for the efficient, long-term deployment and operation of this technology:

- Precision, dependability, and efficient management of SBF nursery for maximum production.
- Low levels of technological readiness of the scale in infrastructures and technologies. This affects the financial viability and items' ability to penetrate markets. New agreements are being formed between insect firms and technology suppliers to develop large-scale SBF organic waste processing facilities.

- Missing product benchmarks: While research and firms demonstrate the advantages of SBFL products, these advantages are waiting to permeate the related sectors and result in high product needs. It is also connected to previously mentioned modest size of facilities.
- Inadequate or restricted regulations: Several countries (e.g., the United States, the EU, Canada, Australia, Mexico, China, South Africa, Uganda, and Kenya) have begun to authorize the use of SBFL to generate feed under confident conditions (e.g., animal-specific, registration, processing) (Gold et al. 2018).

3.4 Characteristics

There are several methods to measure the activity and stability of organic fertilizers in the soil, but we can get important information about any soil from its C/N ratio. Municipal food waste has a C/N ratio ranging from 8:1 to 9:1, kitchen garbage has a C/N ratio ranging from 8:1 to 17:1, okara and wheat bran have a C/N ratio of 8:1, brewery wasted grain has a C/N ratio of 17:1, and fruit and vegetables have a C/N ratio of 27:1. The C/N ratio will continually drop in a well-managed composting process. It is because of the biological mineralization of carbon molecules and CO_2 loss (Diaz and De Bertoldi 2007: Basri et al. 2022).

4 Benefits of Black Soldier Fly Larva Compost

Compost-like qualities exist in SBFL frass. The frass is rich in macronutrients (NPK), micronutrients, and OM contents, making it favorable for agricultural application (Attiogbe et al. 2019; Bortolini et al. 2020; Gao et al. 2019). The SBFL frass offers several advantages, including the presence of chitin, which supports soil microbiota, and high P and N contents for plant nutrition (Schmitt and de Vries 2020; Klammsteiner et al. 2020). Furthermore, the addition of SBFL frass benefits the microbial community (Gold et al. 2020), thus making N accessible for plant absorption (Choi and Hassanzadeh 2019). The SBFL frass may recover N and P from the food chain and reuse it as fertilizer, thus minimizing the dependency on artificial fertilizers. Chitin in SBFL frass also promotes the growth of plants and activates the defense systems (Surendra et al. 2020). The SBFL frass (also a type of chitin) can be digested by the plants, but when stressed, other chitin releases antimicrobial peptides which produce hindrance in defense (Choi and Hassanzadeh 2019). It is due to the peculiarity of SBFL, which finally creates an antimicrobial peptide that lowers harmful microorganisms throughout the treatment process, like *Salmonella enterica* and *E. coli*. One of their potentially positive effects is the capacity of chitin and its metabolites to boost the processes by lowering the number of plant pests. A small quantity of chitin of SBFL frass applied to plants improves growth, produces more blooms and seeds, and attracts more pollinators (Basri et al. 2022).

4.1 Food Security

4.1.1 Black Soldier Fly Larvae as a Feed Source

4.1.1.1 Fish

The high lipid and protein contents of SBFL meal and oil make it a viable alternative to fish oil and meal, a good animal feed (Kroeckel et al. 2012). The significance of fish oil and meal in aquaculture is widely established. However, due to human consumption and limited fisheries, supplies have been reduced, and costs have grown, pushing fisheries to explore alternatives such as vegetable oils (Li et al. 2016). If fed on a lipid-rich diet, SBFL can collect lipids in their body which is thus typically much more appealing for the fish as compared to vegetable oils. The omega-3 fatty acid-rich prepupae are formed when we supplement fish offal in the diet of larvae (St-Hilaire et al. 2007b). Such "enhanced" prepupae are appropriate fish feeds, with no remarkable variations in fish growth and visual development than a regular fish meal when fed to rainbow trout (Sealey et al. 2011). Another study on rainbow trout found that up to 40% defatted SBFL supplementation in the diet had no detrimental impact on the physiology of fish or the physical quality of fillet. However, there was a decrease in beneficial unsaturated fats (Renna et al. 2017). Research on juvenile Jian carp demonstrated no variation in growth performance between soybean and SBFL oil yet increased lipid deposition when SBFL oil quantity in the diet rose (Li et al. 2016). Thus, several researchers have concluded that SBFL can play a vital role in sustainable aquaculture as a fraction or entirely by replacing the meal (Diener et al. 2009; Wang and Shelomi 2017).

4.1.1.2 Animals

The SBFL are thought to be a possible soy-based or maize feed substitute for chickens in the poultry industry. Since the SBFL species naturally colonizes and degrades chicken manure, poultry farms frequently maintain their colonies for waste management and pollution reduction (Bradley et al. 1984; Wang and Shelomi 2017). Cullere et al. (2016) found no difference in productive performance, weight, yield, and breast meat of broiler quails (*Coturnix coturnix japonica*) compared to control and two amounts of SBFL diet. The SBFL treatment showed no influence on taste perception, the composition of cholesterol, oxidative status, as well as meat quality. Nevertheless, it boosted the contents of amino acids in meat, resulting in higher nutritional status. However, it raised levels of undesirable monounsaturated and saturated fatty acids. The same findings were seen with SBFL addition in the feed of *Gallus gallus domesticus* broiler hens, except that defatted SBFL minimized the harmful influence on fatty acid profiles. In both circumstances, scientists discovered SBFL to be a suitable protein source for chicken feed (Schiavone et al. 2017a). The authors came to the conclusion that the inclusion of SBFL assured good productive performances, carcass characteristics, and overall quality of meat (Schiavone et al. 2017b). The SBFL augmentation to 50% or completely replacing soybean cake in laying hen feed showed no influence on the health of the hen and had no or very minute effect on egg quality (Maurer et al. 2016). The SBFL are also appealing to poultry, with reports of laying hens seeking out SBFL from feeders rather than continuing to consume wheat-soy diets. Thus, SBFL are a potential partial substitute for chicken feed, giving additional protein while having the advantage of being raised on the manure of same birds which consume it, thus valorizing as well as reusing waste (Wang and Shelomi 2017).

4.1.1.3 Humans

It is very tough to find the evidence of ingestion of *Hermetia illucens* by humans (Mitsuhashi 2017). One aspect of the challenge is that ethnographers are not often entomologists, and local people are unlikely to mention an insect's scientific name, making exact identification of what species one is eating impossible (Ramos-Elorduy 1997; Mitsuhashi 2017). There are various species of insects consumed by humans, such as termites (Kinyuru et al. 2013), houseflies (Jiao et al. 2019), caterpillars (Mba et al. 2019), grasshoppers (Kim et al. 2019), beetles (Yang et al. 2014), and other insect species rich in protein. Furthermore, insects contain 21–65% crude protein, similar to meat and fish (Braide et al. 2010). We have only discovered one clear incident of people eating SBFL. More than 60 kinds of insects are consumed in Malaysia's Sabah province on the island of Borneo, mostly by the people of tribes of the indigenous Kadazan-Dusun, a group contributing to about one-third of Sabah's population. One of these are SBFL, which are eaten raw with tapai, a locally produced fermented beverage (Chung et al. 2002).

4.1.2 Effect of Black Soldier Fly Larva Compost on Growth and Nutrient Quality of Plants

Choi et al. (2009) compared commercial fertilizer to insect-derived compost regarding OM and N, P, K, contents. Furthermore, this research involved analysis of the leaves and nutrient availability of the Chinese cabbage plant. It was discovered that the plants had the same values except for the P availability to plant, which was higher in the group that used insect-derived compost. In the field, black soldier fly larva compost (SBFLC) generated from the brewery, green market, and poultry waste was evaluated as a fertilizer for shallots, pepper, and maize. The authors did multiple field studies by employing 2.5–10 t ha^{-1} of each frass alone and with chemical fertilizers. In general, it was discovered that fertilizing with chicken dung, the popular local fertilizer, produced similar growth responses in plants (Quilliam et al. 2020). Furthermore, it was discovered that using a mixture of SBFLC and the chemical NPK fertilizer improved plant response. Similarly, in another study, the soil was conditioned with okara-derived SBFLC at 10%, 20%, and 30% rates. Applying frass in the soil increased the concentrations of N, P, and K. However, between 20% and 30% frass, lettuce growth was poor, but 10% frass positively promoted lettuce growth. The authors suggested that the undesirable growth at a high level of frass may be attributable to the fertilizer's low C/N ratio (7.27), which caused rapid mineralization of nutrients in the soil (Chiam et al. 2021). Differing from this, Menino et al. (2021) witnessed that ryegrass growth was improved after applying six dosages of SBFL frass to the soil as a fertilizer. Furthermore, enhanced soil fertility treated with frass was identified in connection to greater soil OM, P_2O_5, and K_2O concentrations, typically regarded as good when avoiding the chemical fertilizer and adding the organic one. Aside from having greater OM concentrations in frass-amended soils, another advantage of employing frass as a biofertilizer is the concentrations of plant-accessible nutrients. Beesigamukama et al. (2021) used 5-week composted frass in Acric Ferralsols soils and measured nutrient mineralization for 125 days. They found net immobilization of N in the frass-treated soil for 30–60 days. Repeated application of frass resulted in a higher N release in the soil. Moreover, the release of Mg, N, and P in the soil was much greater than in non-treated soil. These findings suggested that the mineralization of nutrients of frass has occurred. From the organic fertilizers, the mineralization/immobilization of nutrients strongly relies on parameters such as the C/N ratio and biological stableness (Chen et al. 2014). Due to the significant variations in frass compositions and their related structural matrices, behavior of these products in soil may differ as well (Lopes et al. 2022). Likewise, Rummel et al. (2021) treated silty loam soil with SBFL frass equivalent to 170 and 510 kg N ha^{-1}. According to the authors, the frass with the minimum ratio of C/N leads to N accumulation and mineralization. They also discovered that mineralization kinetics regarding C and N were affected by the substrate quality utilized as larval feed.

4.1.3 Suppression of Soil Pathogen

The SBFLC has immense potential for disease suppression in plants (Anyega et al. 2021). Previously, it has been suggested that using SBFLC can reduce the use of pesticides to control disease in plants (Schmitt and De Vries 2020). The ability of SBFLC to suppress diseases in plants is associated with the existence of several biostimulants (bioactive compounds and microorganisms) and compounds rich in chitin (Lopes et al. 2022). While passing through the larval instars, the molting of larva occurs, which enriches the frass with exuvia containing chitin. Chitin is well known for its ability to suppress various diseases, i.e., via controlling fungal and nematode attacks (Postma and Schilder 2015; Oka 2010). Many mechanisms associated with such control appear to be connected with the existence of chitin in the nematode's egg shells (Wharton and Jenkins 1978) and the cell wall of the fungus (Lopes et al. 2022). Moreover, the addition of SBFLC, a chitin-rich product, can enrich the soil with chitinolytic microorganisms, which reduces the activities of fungi and nematodes (Klammsteiner et al. 2020; Oka 2010). Besides, SBFL also influence reducing the pathogenic bacteria in different types of manures. In a study, chicken manure, cow manure, pig manure, and sewage sludge compost were inoculated with SBFL. Results revealed that adding SBFL reduced the abundance of pathogenic bacteria (PBac) by 90–93% in chicken manure and cow manure while 86–88% in sewage sludge compost and pig manure. Thus, it can be concluded that SBFL can potentially destroy the PBac in organic manures (Awasthi et al. 2020).

4.2 Environmental Benefits

4.2.1 Management of Heavy Metals Polluted Soils

Several anthropogenic activities, industrial development, and agricultural practices are responsible for soil contamination with heavy metals. Unfortunately, soil contaminated with heavy metals poses adverse effects on the health of humans and the ecosystem (Naeem et al. 2021; Shahbaz et al. 2019). Several functional groups in the insect feces can efficiently bind heavy metals in the soil and reduce their availability to plants (Wang et al. 2022). Furthermore, applying insect frass under soil flooding can reduce soil Eh values, thus reducing the bioavailability of heavy metals (Kashem and Singh 2004; Tack et al. 2006; Wang et al. 2016). In a 2-year pot experiment, soil polluted with Pb and Cd was amended with 2%, 4%, 6%, and 8% of SBFLC (Wang et al. 2022). The effects of these variable doses of SBFLC on the uptake of Pb and Cd in rice plants were observed. Results revealed that adding SBFLC increased the values of soil pH, OM, and P. Furthermore, reductions (by 8.3–56.8%) in the weak acid-soluble state and the increase in the oxidizable (by 22.4–165.7%) and residual (by 1.8–225.6%) states of Cd and Pb were observed in soil. Interestingly, in rice plants, SBFLC reduced Cd (up to 66.7%) and Pb (up to 61.8%). It was noted that Cd and Pb contents in rice plants were lower in the second year compared to the first.

4.2.2 Mitigation of Drought Stress in Soil

The by-product of the decomposition of organic waste with SBFL is frass (Chiam et al. 2021) which is used as a biofertilizer (Poveda et al. 2019). This frass can potentially increase soil fertility due to its high contents of labile carbon and nutrient richness; thus, it can overcome drought stress (Kagata and Ohgushi 2012; Houben et al. 2020). Other benefits of insect frass are resistance to drought and salinity, disease suppression, and improving the quality and yield of plants (Beesigamukama et al. 2020). In an experiment, three different types of frasses were prepared by feeding three types of diet (A, B, and C) to insects (*Tenebrio molitor*). Later, the effects of the three types of frasses were used to mitigate the effects of drought, saline, and flooding stress on the chard plant (*Beta vulgaris* var. cicla) and bean plant (*Phaseolus vulgaris*) (Poveda et al. 2019). The results highlighted that the frass from diet A (low in fat and starch content) had a larger amount of P, K, Mg, and Mn. The larger amount of P, K, Mg, and Mn was the main reason for the increased tolerance of plants under abiotic stresses and increase in dry weight, root length, and length of aerial part of the plants.

4.3 Resource Conservation

4.3.1 Waste Reduction

The worldwide production of organic waste is not only a threat to human health but also to the ecosystem's biodiversity (Siddiqui et al. 2022). Wowrzeczka (2021) found that the global waste generation will reach about 3.4 billion tons by 2050. The crucial step for sustainable solid waste management is reducing organic waste volume (Salam et al. 2022). The SBFL composting has an immense potential to reduce the volume of waste in 2–3 weeks (Gold et al. 2018; Chiam et al. 2021). The SBFL eagerly eat organic waste (slaughterhouse waste, animal organs, rotting plants, animal manure, food waste, sludge, distiller grains, etc.), on account of which a huge reduction in the volume and weight of waste is observed in a comparatively short period (Salam et al. 2022). However, the physicochemical properties of organic waste greatly affect the degree of reduction. For instance, waste containing different types of waste has more reduction than waste having only a single type of waste (Nyakeri et al. 2017; Lopes et al. 2022). According to different studies, the feeding rate will be 95–100 mg/larvae/day if the waste contains only food waste (Parra Paz et al. 2015; Purkayastha and Sarkar 2021). The feeding rate can elevate to 200 mg/larvae/day if the fecal sludge is mixed with food waste (Nyakeri et al. 2019; Purkayastha and Sarkar 2021). Interestingly, SBFL reduce the volume of organic waste and convert it into protein-rich products, which can bring sustainability into agribusiness (Diener et al. 2009). Approximately 30 tons of waste per day is bioconverted by the SBFL. It results in 33.3% production of residue used as fertilizers and 7.7% prepupal biomass, a source for animal feed (Singh and Kumari 2019).

4.3.2 Production of Biofuels

The worldwide energy demand will reach 820 quadrillion of Btu (Q Btu) by 2040 (EIA 2013). The term "biodiesel" got popularized worldwide in the last three decades. Food crops are not used to prepare biodiesel because they are consumed as food sources (Zheng et al. 2012). The SBFL have an immense potential to convert raw materials into biodiesel, thus reducing the direct utilization of edible crops for biodiesel production (Singh and Kumari 2019). In a study, the rice straw and restaurant solid waste digested by SBFL and microbes produced SBFL grease that was used for the production of biodiesel. Zheng et al. (2012) showed that 1000 g of the waste consumed by 2000 larvae produced almost 43.8 g of the biodiesel. Likewise, CH_4 production is directly related to the moisture content of the organic waste, and as the organic waste is wetter,

CH_4 production is higher (Pang et al. 2020a, b). In an experiment, organic household waste was treated with 5-day-old SBFL. The results revealed that the average CH_4 and nitrous oxide (N_2O) production per ton of waste was 0.4 g CH_4 and 8.6 g N_2O (Mertenat et al. 2019). Similarly, Pang et al. (2020b) calculated CH_4 production in which waste containing pig manure and corncob was used in five treatments, each containing 1 kg waste under C/N ratios of 15, 20, 25, 30, and 35, respectively. The production of CH_4 in these C/N ratios was 0.76, 0.77, 0.49, 0.15, and 0.08 g/kg.

4.3.3 Nutrient Recycling

The SBFL can potentially convert a large amount of organic waste into protein and animal feed (Yang and Liu 2014; Purkayastha and Sarkar 2021). The SBFL take up nutrients present in the organic waste. Later, the larvae containing fats and protein are used as feed of animals, pets, poultry, and fish (Amrul et al. 2022). Moreover, SBFL frass is used as an organic fertilizer or soil amendment (Amrul et al. 2022; Siddiqui et al. 2022). In an experiment, the SBFL converted 4.17–6.61% of C and 17.45–23.73% of N from organic waste to rapidly harvestable biomass (Pang et al. 2020b). The SBFL also have the potential to recycle P and N by 85% and 75% of the organic waste (Salam et al. 2022).

5 Conclusions

The SBFLC has shown its efficacy as a biofertilizer by enhancing the growth of plants via the provision of essential nutrients. Furthermore, the SBFL have multiple advantages, such as it is used as feed for poultry and fish and, to some extent, can be the future food for humans. The SBFL are proven to be the best solution for converting solid waste into a nutrient-dense by-product. The SBFL composting is 50 times faster than the traditional composting methods. Moreover, the GHGs emissions from SBFL composting are far less than the other composting methods. The SBFLC can be used as the soil amendment, which helps the plants to resist various pests and insects. The application of SBFLC in soil supports to cope with drought stress. Moreover, biogas and biodiesel can be recovered from the composting process, reducing our reliance on existing natural resources.

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Chapter 32
Roles of Organic Acids in Plant Stress Tolerance, Food Security, and Soil Remediation

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Abstract Nowadays, the world's most important concerns are environmental degradation and food safety. The rise in environmental pollution is attributed to the significant increase in population over the previous few decades. The key concerns include soil remediation and meeting the growing population's dietary needs. However, the role of organic acids (OAs) in cleaning heavy metals (HMs) polluted soils, plant growth and yield, and food safety remains unclear. Several OAs (succinic, citric, malic, oxalic, maleic, malonic, fulvic, and humic acids) play important roles in food security, soil remediation, and plant growth. In this chapter, we have compiled existing literature regarding the sources of OAs, their interaction with plant growth, food preservation, and remediation of HMs polluted soils. Organic acids have been shown to be effective in agricultural applications. The use of OAs aids the plant in overcoming several harsh conditions like salinity, drought, temperature variations, and HMs stress. Additionally, OAs improve plant yield, growth, and nutrition via solubilizing nutrients from the soil. Apart from it, OAs are known to enhance the bioavailability of HMs in polluted soils and favor their removal through several plants. Likewise, OAs also play a critical part in preserving food against bacteria, mold, yeast, and other food-degrading microorganisms.

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Abbreviations

ATP	Adenosine triphosphate
DA	Dalton
EDDS	Ethylenediamine disuccinic acid
GSH	Glutathione
H_2O_2	Hydrogen peroxide
HMs	Heavy metals
HMWOAs	High molecular weight organic acids
LMWOAs	Low molecular weight organic acids
MDA	Malondialdehyde
MW	Molecular weight
OAs	Organic acids
OM	Organic matter
ROS	Reactive oxygen species

1 Introduction

The OAs present in the soil are associated with the carbon (C) cycle and are an integral part of the soil organic matter (OM) (Adeleke et al. 2017; Hubova et al. 2017). The OAs are derived from several processes comprising OM breakdown, plant root exudates, and microbial secretions (Sindhu et al. 2022). Many soil processes are thought to be mediated by OAs. To date, data suggests that OAs have an impact on soil characteristics linked with the OAs and the solid collides of the soil (Dinh et al. 2017).

In recent times, abiotic stresses such as temperature fluctuations, deficient or excessive water, high salinity, and HMs affect plant development and growth, thereby reducing agricultural productivity and yield (Yadav et al. 2020). Moreover, environmental degradation has become another serious challenge to food security because of climatic variations, which are more intense and less predictable in recent years (Najim et al. 2022; Wang and Frei 2011). Approximately, 90% of farmlands are susceptible to the individual or many environmental stresses. However, abiotic stresses are responsible for the 50% yield reduction of several main crops (Reis et al. 2012; Yadav et al. 2020). Abiotic stresses adversely affect seed emergence, plant development and growth, and several essential metabolic pathways in higher plants, which further leads to their death (Tahjib-Ul-Arif et al. 2021; Gill and Tuteja 2010). Food safety is critical for global economy, health, and social concerns since millions of people die yearly from foodborne infections (Scallan et al. 2011). Innovation in food manufacturing techniques and increased worldwide distribution and supply of food are all contributing factors to the risk of food contamination (Theron and Lues 2007; Coban 2020). Microorganisms are the main culprit of food-related diseases. Microbial genera that cause foodborne diseases include *Listeria*, *Bacillus*, *Aspergillus*, *Clostridium*, *Staphylococcus*, and *Escherichi*a (Lee and Paik 2016). Among numerous microbial-based products, OAs are largely produced globally and are extensively utilized as antimicrobial materials in several food industries (Liu et al. 2020). The OAs often prevent cells from the active transit of excessive inner protons, which consume cellular adenosine triphosphate (ATP) and wipe out cells (Bangar et al. 2022). They also prevent from the development of harmful microorganisms. The primary targets of these OAs are bacterial cell walls, cytoplasmic membranes, and particular bacterial metabolism that cause the annihilation and destruction of microorganisms (Nair et al. 2017). For instance, lactic acid secreted by bacteria provides a local microenvironment, unfavorable to infections (Dittoe et al. 2018).

In recent years, HMs pollution has gained the worldwide attention because of their harmful impacts on humans, animals, and plants. In plants, the exposure to the higher HMs concentrations impacts plant development, growth, and yield as well as various biochemical and physiological processes such as water relation, photosynthesis, nutrition, and respiration (Osmolovskaya et al. 2018). Several OAs, such as aconitate, citrate, malonate, oxalate, tartrate, and malate acid, are known to reduce HMs toxicity to the plants through their chelation and form strong bonds with them (Anjum et al. 2015). The desorption of HMs from soil particles varies due to changes in the complex formation strength of OAs and HMs (Ghasemi-Fasaei et al. 2021; Geng et al. 2020). By creating water-soluble compounds with HMs, low molecular weight organic acids (LMWOAs) can enhance their phytoavailability (Agnello et al. 2014) and increase their capacity to be uptaken by the plants (Yu et al. 2020; Huang et al. 2020a). Figure 32.1 shows an overview of the benefits of OAs to plants and the environment.

2 Classification of Organic Acids

The classification of soil OAs is mainly based on their molecular weight (MW), referred to as LMWOAs and high molecular weight organic acids (HMWOAs) (Potysz et al. 2017). Dalton (DA) unit is used to weigh OAs (Perminova et al. 2003). For example, the MW of HMWOAs ranges from a few hundred to millions of DA, which is why they are referred to as HMWOAs, while the MW of LMWOAs is relatively low, ranging between 46 and 100 DA. The HMWOAs are comparatively less soluble in water than LMWOAs. Besides MW, carboxylic groups in LMWOAs range from one to three, whereas in HMWOAs, they exceed more than three. Some examples of LMWOAs are succinic, citric, malic, oxalic, maleic, and malonic acids, while fulvic and humic acids are included in HMWOAs (Sindhu et al. 2022).

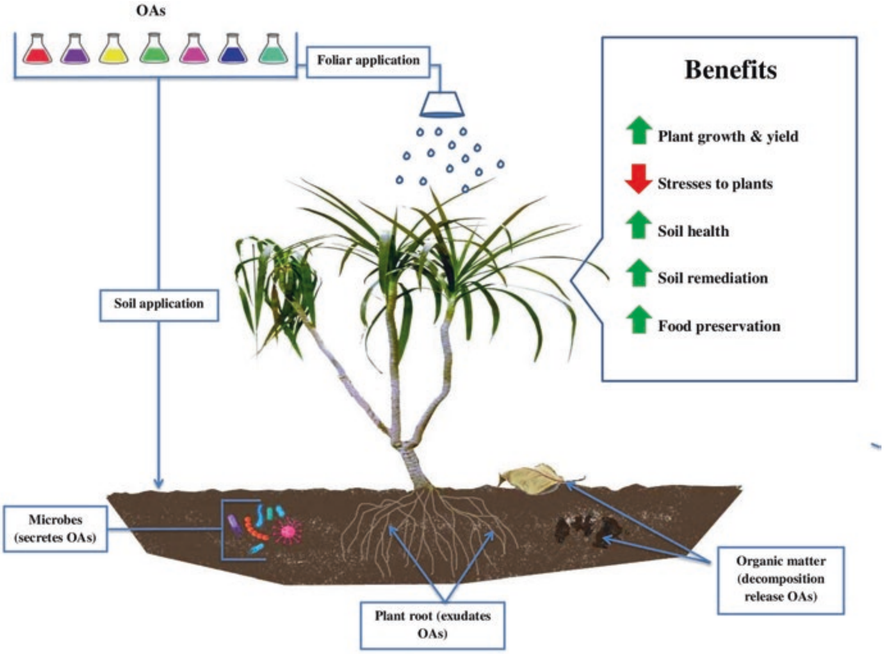

Fig. 32.1 An overview of the benefits of organic acids to plants and the environment

3 Sources of Organic Acids

3.1 Plant Root Exudates

According to recent research, the principal source of OAs in the rhizosphere soil is the plant roots, which secrete OAs (Virk et al. 2022). Among the prominent OAs excreted by plant roots are tartaric, oxalic, formic, acetic, succinic, malonic, citric, fumaric, and malic acids (Dinh et al. 2017). Almeida et al. (2020) observed that under the P deficiency, three different species of grass (ruzi, palisade, and guinea) secreted OAs (citric, isocitric, oxalic, tartaric, succinic, and lactic acids) in the soil through their roots. Likewise, Louw-Gaume et al. (2017) observed that the ruzi grass and signal grass released oxalic, lactic, acetic, glycolic, and formic acids under the P deficiency. Various biotic and abiotic factors, like physiological stress, nutritional deficiency, and soil physical changes, have a major impact on plant root exudates (Jiang et al. 2017; Hartman and Tringe 2019). Additionally, the magnitude of OAs synthesis and secretion in the root zone of plants has been observed to differ between plant varieties and significantly impact the growth and maturity of the plant (Panchal et al. 2021; Dinh et al. 2017).

3.2 Microorganisms

The OAs (formic, citric, succinic, lactic, malonic, acetic, and oxalic acids) are synthesized and released by several soil microorganisms (bacteria and fungi) (Magdziak et al. 2017). For instance, a study revealed the excessive secretion of different OAs after the addition of six different bacterial strains (*Pantoea* FF1, *Agrobacterium* A18, *Staphylococcus* MFDCa1, *Alcaligenes* 637Ca, MFDCa2, and *Bacillus* M3) in Braeburn on MM106 and Braeburn on M9 (Aras et al. 2018). Similarly, it was also found in another study that the inoculation of *Pantoea* sp. S32 significantly affected the concentrations of malic, citric, and oxalic acid in the experimental soil (Chen and Liu 2019). Additionally, two bacteria (*Pseudomonas* sp. strain AZ5 and *Bacillus* sp. strain AZ17) were also observed to produce lactic, citric, malic, oxalic, succinic, and gluconic acids in reasonable amounts (Zaheer et al. 2019). Interestingly, both bacterial strains produced a significant amount of acetic acid compared to the other OAs.

3.3 Decomposition of Organic Matter

The OAs are produced by the mineralization of OM and organic amendments in the topsoil (Xu et al. 2012). Microorganisms aid in producing different OAs, such as HMWOAs and LMWOAs, during the degradation of organic materials (Aytenew and Bore 2020; Ghosh et al. 2012). Some prominent LMWOAs are produced during the degradation of OM, such as aconitic, formic, acetic, citric, malonic, lactic, fumaric, oxalic, tartaric, succinic, and maleic acids (Dinh et al. 2017). For instance, it was found that oxalic, lactic, citric, formic, and acetic acids concentrations were enhanced in the first 3 days of composting, possibly due to the fast breakdown of organic constituents present in the compost (Wei et al. 2018). Likewise, Tran et al. (2019) reported that the production of lactic acid was observed prominently in the early days of food waste compost, whereas acetic acid was observed in the last stage of the composting.

4 Roles of Organic Acids Under Stressed Conditions

4.1 Abiotic Stresses

More food production with minimal agricultural damage to fulfill the needs of the ever-growing human population has taken on an extraordinary significance in recent years. Nonetheless, a considerable part of arable land is subjected to abiotic stresses (salinity, drought, HMs, alkalinity, temperature, etc.) that are projected to worsen owing to variable climatic conditions. These abiotic stresses change different plant physiological and biochemical characteristics, thereby reducing the yield and biomass of the plant (Tahjib-Ul-Arif et al. 2021; Wani and Sah 2014).

4.1.1 Salinity

The ability of a plant to endure salt stress can be enhanced by applying citric acid in the soil, resulting in increased plant growth and development (Tahjib-Ul-Arif et al. 2021). For example, the foliar application of potassium citrate and salicylic acid improved the yield by enhancing the activities of several essential antioxidants in cotton plants under salt stress (El-Beltagi et al. 2017). Similarly, ascorbic, salicylic, and citric acids, as a sole treatment or combination, have shown an enhancement in the growth, yield, and antioxidants activities in two different years of maize production under saline stress (El-Hawary and Nashed 2019). Moreover, the aerial spraying of humic acid and fulvic acid, as a solo and combined with arginine and glutamine, positively influenced the three olive species (Miri Nargesi et al. 2022). In another study, the application of citric and malic acids alone, as well as their combination with tomato peels and banana peels, had been shown to enhance the root development and sugar yield of sugar beet grown under salinity stress (Ahmed et al. 2017).

4.1.2 Drought

Pretreatment with citric acid affects the transcription of stress-responsive genes, leading to increased tolerance in tobacco plants under drought conditions (Xie et al. 2022). In an experiment, humic acid positively affected the yield and nutrient availability of *Nigella sativa* under water deficiency (Hayati et al. 2022). In another investigation, it was found that the citric acid application positively influences the growth, water status, photosynthesis, and yield of *Phaseolus vulgaris* (El-Tohamy et al. 2013). Likewise, humic acid was observed to enhance the growth of durum wheat under drought conditions (Pazoki 2016). The foliar spray of OAs, solely and with potassium citrate on cotton plants, has been shown to increase the plant height, number of fruiting branches, number of open bolls, boll weight, chlorophyll content, carotenoids, and the activity of peroxidase (Gebaly et al. 2013). Additionally, citric acid application promoted the development of *Brassica oleracea* seedlings by alleviating oxidative damage under drought stress. Furthermore, citric acid also improves P absorption and reduces hydrogen peroxide (H_2O_2) content in cabbage (Miyazawa 2014).

4.1.3 Temperature

In recent years, many crops suffered from yield loss due to temperature stress. The application of citric acid is known to reduce heat stress in various plants (Tahjib-Ul-Arif et al. 2021). The citric acid (20 mM) spray on *Lolium arundinaceous* leaves enhanced chlorophyll content and photosynthetic efficiency and improved the activities of antioxidants while reducing malondialdehyde (MDA) content, cell membrane damage (via reducing electrolyte leakage), reactive oxygen species (ROS), and leaf senescence (Hu et al. 2016). Furthermore, aerial spraying of citric acid at the rate of 2.5 g L^{-1} and 5 g L^{-1} enhanced the quality of tomato fruit plus yield at high temperature (El-Desouky et al. 2011). Reportedly, citric acid application has also been known to alleviate cold stress in *Hibiscus rosa-sinensis* by delayed defoliation and producing maximum number of leaves (Zhang et al. 2009).

4.1.4 Alkalinity

According to the literature, alkalinity can be tolerated with citric acid. The application of citric acid (50 mg L^{-1}) in *Leymus chinensis* improved the growth, photosynthesis, activities of antioxidants, and alkalinity stress mitigation in plants treated with 100 mM Na_2CO_3 (Sun and Hong 2011). Furthermore, soil application of citric acid at dose of 40, 80, and 120 mg kg^{-1} considerably amplified root development, root surface zone, plant biomass, and nutrients in chestnut planted on high pH soil (Gong and Fan 2018).

4.1.5 Heavy Metals

Plant exposure to HMs results in lowering plant biomass, stunted growth, and poor yield (Zaheer et al. 2015). The application of OAs has been found to alleviate HMs stress in various studies (Table 32.1). For example, OAs treatment promoted plant development and biomass; improved the contents of chlorophyll, water status attributes, and antioxidants enzymatic activities; and reduced ROS contents (Al Mahmud et al. 2018; Amir et al. 2020). In Cu-polluted soil, the addition of 2.5 mM citric acid in nutrient medium enhanced *B. napus* growth, photosynthetic pigment, antioxidants enzymatic activities, and Cu accumulation in plant tissues. The findings suggested that citric acid application alleviated HM stress in *B. napus* via suppressing electrolyte leakage, MDA, and H_2O_2 contents (Zaheer et al. 2015).

5 Food Security

5.1 Effects of Organic Acids on Plant Growth and Yield

A study reported that the sole treatment of Cd significantly reduced the fresh plant biomass and shoot height of *B. juncea* by 33.7% and 31.1%, respectively. Interestingly, the treatment of citric acid (0.6 mmol kg^{-1}) combined with castasterone (at 100 mM) boosted the fresh plant weight of *Brassica juncea* L. by 38.5% and shoot height by 38.3% (Kaur et al. 2017). Citric acid also supported the biomass of *Pelargonium hortorum* by 25% in Pb-polluted soil (Gul et al. 2020). Sebastian and Prasad (2018) reported that the rice biomass was enhanced

Table 32.1 Alleviation of heavy metals stresses to different plants by applying different organic acids

Heavy metals	Type of organic acid	Plant species	Findings	Citations
Cadmium	Malic, tartaric, and citric acids	Willow	The provisions of malic, tartaric, and citric acids increased the photosynthesis apparatus in the leaves of *S. variegate* grown in Cd-contaminated soil. Interestingly, tartaric and malic acids improved the total and shoot biomass compared to citric acid. This enhancement in biomass and plant growth could be due to the mitigation of Cd-induced toxicity to the photosynthetic pigments by enhancing chlorophyll contents after adding malic acid. Similarly, tartaric acid prevents *S. variegate* leaves from ultrastructural impairment due to Cd. Meanwhile, citric acid improved carotenoids and the chloroplast volume in mesophyll cells	Chen et al. (2020)
	Citric acid in combination with salicylic acid (SA) as a plant growth stimulator	*Brassica juncea*	The alone dose of Cd reduced the growth and photosynthesis and increased H_2O_2, consequently declining cellular viability. Moreover, Cd toxicity also disturbed the stomatal pore size which influenced internal CO_2 levels and the activity of carbonic anhydrase. The conjointly citric acid and SA seem more effective and mitigated Cd-induced toxicity in *B. juncea* and improved the activities of antioxidants via membrane stabilization and photosynthesis by accelerating the stomatal activity and pore size.	Faraz et al. (2020)
	Citric acid	*Brassica juncea*	Citric acid was applied (0.5 mM and 1.0 mM) under Cd toxicity for 3 days. Both citric acid levels increased *B. juncea* growth, photosynthesis, residual water status, the activities of antioxidants, the efficiency of the glyoxalase system, and phytochelatin content. In a similar context, citric acid also enhanced the Cd contents of roots and shoots and its aerial transport in a dose-dependent manner.	Al Mahmud et al. (2018)
	Citric and malic acids	*Oryza sativa*	The exogenous provision of malic and citric acids reduced Cd accumulation in leaf owing to upregulation of tonoplast-restricted HM ATPase ($OsHMA_3$), which permits vacuolar Cd sequestration in roots. Additionally, both acids increased biomass, glutathione (GSH), anthocyanin, and photosynthesis	Sebastian and Prasad (2018)
	Citric acid	*Brassica juncea*	The presence of phytosterols (castasterone, citric acid) increased the secretion of indigenous LMWOAs, thereby reducing Cd toxicity. Furthermore, the binary treatment of citric acid and castasterone improved numerous physiological and biochemical attributes of *B. juncea*	Kaur et al. (2018)
			The seeds of *B. juncea* were treated with castasterone before sowing in Cd spiked soil. The sole or combined treatment of citric acid reduced Cd toxicity and improved the growth, photosynthetic pigments, and activities of antioxidants	Kaur et al. (2017)
		Corchorus olitorius	The provision of citric acid in nutrient solution mitigated Cd toxicity via eliminating oxidative injuries and improved the enzymatic activities. The Cd concentrations in roots and shoots were reduced in the presence of citric acid. Therefore, citric acid has no advantage on Cd phytoextraction by *C. olitorius*	Hassan et al. (2016)

Copper	Oxalic, citric, and tartaric acids	*Ricinus communis*	The applications of LMWOAs in Cu-contaminated soils significantly increased Cu accumulation in *R. communis* compared to control. Similarly, the values of bioconcentration and translocation factors were also enhanced by the provision of LMWOAs, thereby increasing Cu extraction by castor bean. Interestingly, LMWOAs also increased soil enzymatic activities without altering soil pH	Huang et al. (2020b)
	Citric acid	*Pisum sativum*	The exogenous citric acid applications significantly boosted plant growth by minimizing the oxidative stress due to Cu	Massoud et al. (2018)
Lead and mercury	Citric acid	*Typha latifolia*	The sole doses of Hg and Pb (1, 2.5, and 5 mM) reduced numerous agronomic parameters of *T. latifolia*. However, citric acid (5 mM) provision in nutrient solution enhanced physiological traits, antioxidant enzymes, and Hg and Pb accumulations in different plant tissues while eliminating oxidative stress due to Hg and Pb	Amir et al. (2020)
Lead and arsenic	Citric acid and GSH	Two varieties of *Solanum lycopersicum*, Pusa ruby and Arka Vikas, were selected	The sole doses of As and Pb reduced germination rate, growth attributes, and photosynthesis and damaged DNA and structural stability. The citric acid and GSH treatments potentially relieved As and Pb toxicity from both cultivars	Kumar et al. (2017)
Chromium	Citric acid	*Helianthus annuus*	The *H. annuus* plants were grown in soil spiked with various levels of Cr (0, 5, 10, and 20 mg kg^{-1}). The findings suggested that Cr presence in the soil adversely affected various morphophysiological features and photosynthesis machinery. Citric acid application in the soil (2.5 and 5 mM) mitigated Cr toxicity via improving growth, biomass, soluble protein content, and gas exchange attributes. Moreover, citric acid also increased Cr mobility in the soil and its accumulation and aerial transport in *H. annuus*	Farid et al. (2017)
		Brassica napus	Soil application of citric acid mitigated Cr toxicity in *B. napus* through increasing the activities of antioxidants enzymes in the leaves and roots. Moreover, Cr accumulation in *B. napus* tissues and its uptake were increased by citric acid applications in the soil	Afshan et al. (2015)
Aluminum	Citric, succinic, oxalic, and tartaric acids	*Medicago sativa*	The influences of aerial provisions of citric, succinic, oxalic, and tartaric acids were examined on *M. sativa* grown in nutrient solution containing 100 μM Al at acidic pH (pH = 4.5). The presence of Al in nutrient solution results in the significant inhibition of biomass and nutrient uptake. The aerial applications of succinic acid improved plant growth and root development compared to other OAs. Similarly, succinic acid also enhanced mineral nutrients acquisition and accumulation of other OAs in roots, thereby enhancing the gene transcription of phosphoenolpyruvate carboxylase and malate dehydrogenase in *M. sativa* roots. Moreover, malic and oxalic acids promoted oxalate secretion and reduced Al accumulation in the roots of *M. sativa*	An et al. (2014)

by the exogenous applications of malic acid and citric acid (50.0 μM) in the Cd-contaminated soil. Likewise, another study concluded that treating the soil with citric acid at 2.5 mM and 5 mM positively affected biomass of sunflower (*Helianthus annuus*) under Cr stress (at 5, 10, and 20 mg kg^{-1}). Furthermore, it was observed that applying citric acid (2.5 and 5 mM) alone and combined with Cr increased the plant biomass and growth. The combined treatment of Cr (20 mg kg^{-1}) and citric acid (5 mM) showed significant amplification in the plant and root length by 29% and 20%, correspondingly. Additionally, the citric acid enhanced the biomass, width, and count of leaves, number of flowers $plant^{-1}$, and dry biomass (Farid et al. 2017). Similarly, Chen et al. (2020) reported in a study that the addition of citric acid, tartaric acid, and malic acid enhanced the total biomass of willow by 52%, 75%, and 108%, respectively. Furthermore, the application of malic, citric, and tartaric acids upgraded the root biomass by 102%, 61%, and 55%, correspondingly, under Cd stress. The OAs (citric, malic, and tartaric acids) boosted the leaf biomass of willow. In another experiment, citric acid under different HMs (Hg and Pb) stresses assisted the plant in coping with stress and enhancing the agronomic traits of *Typha latifolia.* It was found that the addition of citric acid in nutrient medium containing Hg and Pb boosted the plant growth, count of leaves per plant, and length of root. Furthermore, the citric acid treatment enhanced the biomass over control treatment (Amir et al. 2020). A similar finding was observed where the treatment of citric acid (0.6 mM) and salicylic acid (0.01 mM) showed an enhancement in plant growth by 14.9% and 11.9%, respectively. In addition, the treatment of citric and salicylic acids boosted the biomass of *B. juncea* (Faraz et al. 2020).

5.2 Role of Organic Acids as Preservatives

5.2.1 Animal Feeds

Organic acids have been utilized to sustain complex feed or other components for decades (Khan and Iqbal 2016). It is done to retain feed attributes at their peak. Such precautions are necessary because the feed contains mold, germs, and yeasts that may swiftly spread even under ideal storage circumstances. Some OAs, such as lactic, propionic, formic, and acetic acids, have specific mold-inhibiting or antibacterial qualities and are used as food preservatives (Guimarães et al. 2018). Preservative efficacy is often studied in vitro. The minimum inhibitory concentration is employed as an assessment criterion for antibacterial effectiveness. *Staphylococcus aureus* and *Escherichia coli*, for example, need high minimum inhibitory concentrations than other bacteria (Bangar et al. 2022). Antibiotics were once widely employed in increasing the quality of animal feed. However, preventive usage of antibiotics at minimum effective dosages is accused of producing resistance against various antibiotics (neomycin, apramycin, spectinomycin, and trimethoprim-sulfonamide) (Fairbrother et al. 2017; Amezcua et al. 2002). For the prevention of *E. coli* associated diseases that are present in the piglet feed, an appropriate feed for piglets according to their age, combined with additives, is being well explored nowadays. According to recent research, ruminants fed with forage treated with lactic acid bacteria, which ferment dissolved carbohydrates into several OAs, are thought to elicit probiotic benefits (Markowiak-Kopeć and Śliżewska 2020).

Nonetheless, formic acid, propionic acid, fumaric acid, citric acid, benzoic acid, and their derivatives have favorable impacts on pig growth. When a blend of OAs was employed, the gain during the fattening phase was enhanced (Bangar et al. 2022). The OAs as additives in the feed are believed to boost microbial activity in the gastrointestinal tract via different actions (Li et al. 2018). The OAs used in animal meals necessitate a better comprehension of their effect on the gastrointestinal tract of animals (Dittoe et al. 2018).

5.2.2 Human Food

The fermentation of lactic acid has been used in food items for ages and is considered the trademark of fermentation owing to its availability in many ferments. It is formed through fermentation and allows us to manufacture specific ferments. It is vegan because it is not of animal origin as an acid secreted by bacteria. Acetic acid's preservation action is most commonly utilized in sliced bread, sour vegetables, jams, and fruit juice drinks (Theron and Lues 2010). The concentration, application length, temperature, microorganism adsorption to the surface, and technique, such as spraying or immersion, all play a role in successful lactic acid based decontamination (Bangar et al. 2022). It is frequently utilized in meat, fruits, vegetable preservatives, and dairy and alcoholic products, as do many other OAs. The annual usage of fumaric acid in the United States was predicted to be 18,000 tons (Fu et al. 2010). Recent research revealed that nisin-loaded chitosan monomethyl fumaric acid is being used in orange juice as a preservative (Khan et al. 2018). Furthermore, the literature showed the effectiveness of formic acid (1%) as well as combinations of sodium formic, propionic, and formic acids against different *Salmonella* bacteria which are present in food products (Koyuncu et al. 2013).

6 Soil Remediation

To date, the efficacy of OAs for the removal of toxic HMs from the polluted soils has been widely narrated. In a study, the soil was spiked with Pb at various doses (0, 250, 500, 100, and 1500 mg kg^{-1} soil) for enhanced phytoextraction using garden geranium (*Pelargonium hortorum*). It was observed that the application of citric acid in the soil as an acidifier enhanced Pb phytoavailability in soil (Gul et al. 2020). Likewise, Huang et al. (2020b) used three different LMWOAs (citric, oxalic, and tartaric acids) in the Cu-polluted soil by using castor bean (*Ricinus communis*). The Cu concentrations in the shoots and roots of castor bean were enhanced by 5–148% and 6–106%, respectively, over control. The total Cu uptake by the plant was increased by 21–189% in all the LMWOA treatments. Moreover, the application of citric and lactic acids at various doses (0.05, 0.1, and 1 mM) positively influenced uranium uptake by *Brassica juncea* (Wu et al. 2020). Similarly, Sidhu et al. (2018) reported in a study that the Ni as alone treatment has drastic effect on the plants. However, Ni application combined with ethylenediamine disuccinic acid (EDDS) not only has a positive effect on plant growth and biomass but also enhances its bioavailability. Similarly, a study by Eren (2019) revealed that the phytoextraction efficiency of rosemary was improved with citric and humic acids. Likewise, the combined treatment of NH_4NO_3 and citric acid increased the Cu content in the roots of common wormwood (*Artemisia absinthium*) by 5.39%, in contrast to control. Additionally, the application of malic acid combined with NH_4NO_3 also positively affected the Cu concentration in the roots (Ghazaryan et al. 2022).

In a pot experiment, Lu et al. (2021a) applied five different LMWOAs (glacial acetic acid, citric acid monohydrate, DL-malic acid, oxalic acid, and DL-tartaric acid) at the rate of 0, 1, 2, 3, 4, 5, and 6 mmol kg^{-1} in the soil. The glacial acetic acid (4 mmol kg^{-1}) enhanced carbonate Cd content by 54.65%, whereas citric acid monohydrate (3 mmol kg^{-1}) positively affected the carbonate Cd. Furthermore, the DL-tartaric acid (3 mmol kg^{-1}) amplified the carbonate and exchangeable Cd contents. The DL-malic acid also increased the carbonate-bound Cd in the soil by 45.27–72.95%. In another study, the spray of five LMWOAs (citric, malic, oxalic, acetic, and tartaric acids) at 2, 4, and 6 mmol kg^{-1} rates was added in the soil after 20, 30, and 40 days' old seedlings of sunflower. It was observed that oxalic acid augmented Cd accumulation in the plants by 51%, 38%, and 42% on 20, 30, and 40 days at 2, 4, and 6 mmol kg^{-1}, respectively. Furthermore, applying other LMWOAs also enhanced Cd uptake by the plants (Lu et al. 2021b).

7 Conclusions

The LMWOAs and HMWOAs are proven to be effective in the field of agriculture. Furthermore, OAs help plants in overcoming numerous stresses (drought, salinity, and HMs) and increasing production. As a result, OAs may be described as environmentally friendly compounds suggested for sustainable agriculture. Moreover, OAs offer several benefits, including being employed as food preservatives and increasing biomass, carotenoid, soluble protein, and antioxidants enzymatic activities of the plants. The application OAs has been proven to enhance the bioavailability of HMs, resulting in enhanced phytoextraction, which can greatly help decontaminate HMs polluted soils.

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Chapter 33
Role of Microbial Ecology to Manage Remediation and Degradation Processes in the Environment

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Abstract Bioremediation of polluted sites is the main consideration in environmental biotechnology. Many different environmental issues have confronted the world in the past few decades, and microorganisms have played a significant role in providing an innovative method to control environmental threats. Microorganisms can survive in all parts of the biosphere due to their metabolic activity. Their diverse nutritional capabilities allow them to be used as bioremediation agents for environmental contaminants. Bioremediation removes waste and other hazardous substances from our environment by degrading, immobilizing, or detoxifying microorganisms. The foremost objective is to transform and degrade pollutants like heavy metals, hydrocarbons, pesticides, oil, dyes, and other toxic contaminants. It is carried out enzymatically by metabolizing, so it plays an essential role in resolving a wide range of environmental issues. The degradation rate is determined by two factors, which are abiotic and biotic conditions. Many different techniques have recently been used to improve microbial degradation. Genetically engineered microorganisms (GEMs) play a pertinent function in biodegradation applications in groundwater, activated sludge environments, and soil. Because of their high degradative abilities, these products can degrade chemical pollutants.

Keywords Microbial ecology · Bioremediation · Genetically modified microbes
Toxicants · Microbes

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1 Introduction

Bioremediation is a natural strategy for converting raw materials into forms that other organisms can use and reprocess. The world is confronted with varieties of environmental pollution. Microbes are required for a crucial substitute approach to solving issues. Because of their incredible metabolic activity, microorganisms can thrive in any place in the biosphere and continue living in a wide range of environments. Even though microbial nutritional capacity is so diversified, it is used in the bioremediation of contaminants (Tang et al. 2007). Microorganisms eradicate chemical wastes, degrade them, immobilize them, or detoxify them through bioremediation. The basic idea is to degrade and transform pollutants like hydrocarbons, oil, heavy metals, pesticides, and dyes. Microbes are distributed widely throughout the biome due to their exceptional metabolic capacity and potential to expand a diverse range of environments (Strong and Burgess 2008; Salemdeeb et al. 2017). Metabolism plays a significant role in fixing numerous environmental issues. Microorganisms can also degrade pollution through their nutritional adaptability. Due to various advantages over conventional cleanup techniques, microscopic organisms are the main pollution removal components in soil, water, and sediments. Microbes repair natural environments and prevent much more contamination. It is carried out using specific microbes' capacity to convert, modify, and absorb toxic materials to produce energy and biomass (Sufficiency et al. 2022).

Bioremediation aims to break down or incorporate contaminants into less harmful or nontoxic compounds instead of removing and storing them. The use of biological weapons to clean up contamination is referred to as bioremediation. Bacteria, archaea, and fungi are frequently used in first-generation bioremediation. This biotechnological technique removes the risks of pollutants from the environment via biodegradation. The terminologies bioremediation and biodegradation are increasingly being used synonymously. Two types of factors influence the deterioration rate of biotic and abiotic surroundings. Globally, multiple approaches and practices are used in this domain (Demnerova et al. 2005; Zhou et al. 2021). The chapter summarizes current trends in microorganisms' use in bioremediation and provides essential background information recognized as a gap in the research. It is presently a well-known area of research because microbes are eco-friendly and provide beneficial genetic material for addressing environmental problems (Fig. 33.1).

2 Environmental Factors Associated with Bioremediation

Bioremediation is the activity of using bacteria, fungi, and plants to degrade, eliminate, modify, immobilize, or detoxify toxins and contaminants in the environment. Microorganisms act as biocatalysts via their enzymatic pathways, fostering the advancement of biochemical processes that destroy the intended toxic substance (Madhavi and Mohini 2012; Adams et al. 2015). A wide range of substances and compounds may be useful to microorganisms in the fight against pollution if they

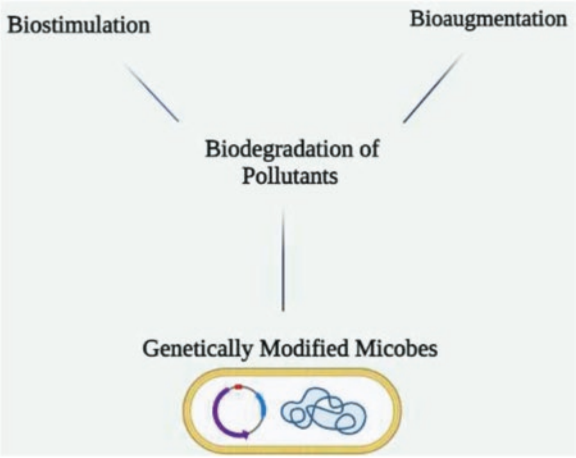

Fig. 33.1 Pollutant bioremediation can be amplified by engineered approaches

can be used to develop energy and nutrition for their new cells. The chemical type, presence, and physicochemical properties are all factors that enhance the efficiency of bioremediation. The degradation process is slowed because bacteria and contaminants do not come into contact with each other. In addition, microbes and toxicants are not distributed throughout the environment (Boopathy 2000). Bioremediation mechanisms face many challenges due to the numerous factors involved. Several environmental factors are involved in pollutant degradation, including microbes that degrade pollutants, access to pollution by microbes, the type of soil, temperature, pH, and nutrients, as well as oxygen and other electron acceptors (Couto et al. 2014).

3 Environmental Factors Influence the Biodegradation of Pollutants

Depending on the microbial population's metabolism and the chemical properties of the toxin, this pathway may be involved in various ways. However, the actual effective contact between the two is ascertained by the atmospheric parameters of the interaction location. pH, temperature, moisture, soil structure, water solubility, nutrients, location, redox potential, and oxygen content can imply microorganism growth and activity (Arumugam et al. 2017). There are different pH levels at which biodegradation occurs; however, most aquatic and terrestrial systems require pH levels between 6.5 and 8.5 to be the most effective. The moisture affects the nature of the soluble element and the amount of the constituents, the pressure, and the pH of both aquatic and terrestrial systems, regulating the metabolism of contaminants (Vidali 2001).

The following are the majority of environmental parameters.

3.1 Availability of Nutrients

The critical nutritious stability for microbe proliferation and reproduction and the level and efficiency of biodegradation are all amended by nutrient-combined application. By adjusting the microbial C:N:P ratio, nutritional stabilities, specifically the distribution of necessary nutrients such as N and P, can optimize biodegradation efficiencies (Sangkharak et al. 2020). Microorganisms necessitate a variety of nutrients, including C, N, and P, to thrive and continue their microbial activity. In low concentrations, the level of hydrocarbon breakdown is minimal. Increasing microbe metabolic activity leads to improved biodegradation (Thavasi et al. 2011). Nutrient availability limits biodegradation in aquatic environments. Microbes, like all other organisms, necessitate resources to grow and develop. These nutrients can be identified in the natural environment, although in small quantities (Macaulay 2014; Keener et al. 2000).

3.2 Temperature

Temperature is the foremost physiological factor influencing microbial survival and hydrocarbon composition. Temperatures below freezing inhibit oleophilic cell thermal transport, ultimately making them metabolically inactive. Degradation pathway enzymes have an ideal metabolic turnover temperature and will differ at different temperatures (Romera et al. 2007). Moreover, the thermal decomposition for a specific part requires a necessitated temperature. Temperature also influences microorganisms' physiological indicators, accelerating or slowing the bioremediation process. The proportion of microbes' behavior rises with temperature and maxima at the recommended range. It precipitously reduced with each additional temperature increase or decrease and eventually stopped when it reached a predetermined temperature (Giriyan et al. 2021).

3.3 Concentration of Oxygen

The requirement for oxygen varies from species to species. According to their necessities, the biodegradation efficiency can be accelerated. Because most life forms require gaseous oxygen, biological degradation occurs in both aerobic and anaerobic conditions. Most of the time, the presence of oxygen enhances hydrocarbon metabolism (Abatenh et al. 2017).

3.4 Moisture Content

Microbes require moisture to grow. This content in the soil is counterproductive to biodegradation agents (Patel et al. 2022).

3.5 pH

Microbes and their metabolic reactions are regulated by the pH of contaminants, which represents acidic, basic, and alkaline states. The pH of the soil can be used to predict microbial development (Si-Zhong et al. 2009). pH values were altered, impoverishing results, because metabolic processes are sensitive to pH changes (Wang et al. 2011).

4 Analysis of Bioremediation Contamination

An appropriate remedial study must be conducted before formulating a bioremediation treatment. Furthermore, along with determining the extent of contamination horizontally and vertically, the parameters and locations to be sampled, and selection, were discussed, as well as the methods for collecting and analyzing the samples. The metals are essential for bacteria and fungi in minuscule amounts, but the excessive amount of metals hinders cellular metabolism. Metal substances have an indirect and direct effect on the speed of deterioration. The presence of pollutants can harm microbes and slow the decontamination process when they are abundant. The toxicant, its concentration, and the microbes affected all influence the degree and mode of toxicity. Different organic and inorganic substances are toxic to certain living organisms (Patel et al. 2022).

5 Enzymatic Metabolites of Contaminants

Biologic factors involve microbial competition for a limited carbon source, microbiome antagonism, and protozoa and bacteria predation of microorganisms. The presence of toxicants and the quantities of “catalyst” are readily used to estimate the rate of contamination degradation. A catalyst refers to the number of organisms and enzymes that can metabolize the contaminants (Poursat et al. 2019)**.** The contaminant breakdown can be increased or decreased by the production of particular enzymes by the cells. Furthermore, contaminant metabolism requires specific enzymes, their “affinity” for pollutants, and their accessibility. The mutated gene, gene transfer, enzyme activity, competition interaction, succession, and demographic change until imperative biomass is reached (Hug et al. 2013).

5.1 Enzyme Degradation in Bioremediation

Bioremediation is the approach of biological pollutant degradation to a harmless state below regulatory concentration limits under controlled circumstances. Microorganisms are optimal for removing contaminants because they have enzyme inhibitors that allow them to absorb toxins (Tratnyek et al. 2020). The essence of bioremediation is to induce microscopic organisms to function efficiently by supplying them with the nutrients and other substances they require to demean pollutants that are hazardous to the environment and living creatures. Every metabolic reaction requires enzymes. Ligases, transferases, lyases, isomerases, hydrolases, and oxidoreductases are instances of these enzymes (Lueders 2017).

Many enzymes have a very broad deterioration capability due to their inadequate and specific substrate affinity. For remediation to be efficacious, microbes enzymatically target and convert impurities into nontoxic substances. Bioremediation performs effectively when the ambiance facilitates microbes' production and expansion. Environmental factors are frequently influenced to hasten microbial growth and degradation (Hollender et al. 2017). Bioremediation happens spontaneously and is aided by the introduction of living organisms and nutrients. Biodegradation is the foundation of the bioremediation technique. It refers to the transformation of organic harmful pollutants into innocuous or naturally present materials such as water, inorganic substances, and carbon dioxide which are secure for people, animals, plants, and aquatic species. Many mechanisms and routes for the biological degradation of a wide range of natural substances have been found; for instance, it occurs in the absence and presence of oxygen (Helbling et al. 2010).

6 Benefits of Microbial Remediation

(i) This is an instinctual technique that necessitates less time, but it is an effective waste treatment method for toxicant materials. The pollutant becomes available, and microbes can decompose it and multiply it. As the pollutant decays, the biodegradative population reduces. Treatment residues are frequently innocuous products like cell biomass, H_2O, and CO_2.

(ii) The process usually involves minimal effort and does not disrupt normal dominant characteristics. Aside from avoiding hazardous conditions associated with transferring massive amounts of waste off-site, this also eliminates the need to transport waste off-site.

(iii) It is an applied technique as considered cheap than other approaches for toxic waste cleanup. It is a pivotal method for treating oil-contaminated zones.

(iv) It aids in the complete removal of toxins; several harmful materials can be converted into nontoxic substances, lowering the possibility of future problems associated with the handling and decommissioning of contaminants.

(v) It is a comparatively green methodology which does less damage to ecosystems because it simply uses natural processes.

(vi) There are no potential hazardous compounds in this. Phosphorus and other essential minerals are used to generate effective and rapid microbial activity.

Bioremediation, which converts odorous compounds into liquid and nontoxic gases, also decimated them.

(vii) Due to its primary role in the surroundings, this method is simple, labor-intensive, and inexpensive.
(viii) It is an environment beneficial and long-lasting technique.
(ix) Instead of moving toxins from one ecological means to another, such as from land to atmosphere or into water, the contaminants are completely destroyed.
(x) Its implementation is comparatively uncomplicated.
(xi) An efficient way to clean up ecosystems from a wide range of contaminants while remaining environmentally friendly.

7 Drawbacks

(i) It only pertains to biodegradable materials. Not all toxins can be degraded entirely in a brief amount of time.
(ii) There is concern that biodegradation components are more deleterious or last longer than their parent substances.
(iii) Most biological mechanisms are specialized. The availability of metabolically resourceful microbiota, sustainable environmental growth conditions, and ideal quantities of nutrients and contaminants are all essential selection factors.
(iv) Extrapolating from lab and small-scale investigations to large field activities is tough.
(v) Bioremediation strategies which are suited for sites with complex combinations of pollutants which are not evenly distributed in the ecosystem require more research. Contaminants can exist in the form of solid, liquid, or gas.
(vi) Biodegradation product's bioavailability and toxicity are not usually described.
(vii) This takes considerably more time than unconventional treatment methods such as digging and removing soil or burning.
(viii) Bioremediation performance standards continue to be a source of regulatory uncertainty. As there is no universally accepted definition of "clean," determining the efficacy of bioremediation is challenging.

8 Types of Bioremediation

Bioremediation methods employ a variety of treatment technologies and methodologies. Bio-stimulation, bio-augmentation, bio-piles, bio-attenuation, and bioventing are the most common bioremediation techniques.

8.1 Bio-Stimulation

Bio-stimulation is the most extensively used bioremediation technique, which involves adjusting conditions like nutrient addition, aeration, temperature, and pH to encourage the proliferation of indigenous microorganisms on the site (Shan et al. 2010). Bio-stimulation procedures can be used in both open systems (including vast bodies of water like oceans) and closed systems (like storage tanks).It has the advantage of requiring remediation by native microbes that are well adapted to the subterranean ecosystems and ubiquitously distributed. The challenging issue is that the transport of chemicals in such a way that they are easily accessible to subterranean microbes is dependent on the subsurface geology (Bond and Lovely 2002). It's challenging to disseminate additives over the affected region due to tight, impermeable subterranean soil type (rigid clay minerals and other finely grained materials). Cracks in the subsurface provide alternative paths for additives to follow, preventing additives from being distributed evenly. The provision of nutrients may also increase the development of heterotrophic microbes that are not intrinsic degraders of totally crude oil, resulting in a conflict between the indigenous microfloras (Chen et al. 2012).

8.2 Bio-Attenuation

Bio-attenuation, even referred to as organic attenuation, is the expulsion of contaminants from the ecosystem. This method makes use of biological procedures (animal and plant uptake, anaerobic and aerobic biodegradation), physical processes (dispersion, volatilization, diffusion, sorption or desorption, advection, dilution), and chemical reactions (complexation, abiotic transformation, and ion exchange) (Lebeau et al. 2008). The more general notion of natural attenuation includes terms like biotransformation and intrinsic environmental cleanup. Once particles affect the environment, nature has four categories for cleaning it up.

(i) Compounds are consumed by microscopic bugs or microbes that live in soil and groundwater. The residues are digested, eventually converting to harmless gases.
(ii) Toxins can cling to soil and bind to it, keeping them there. That does not eliminate the chemicals from the site; however, it prevents these chemicals from degrading aquifers and departing the area.
(iii) Contamination could combine with fresh water when it flows with soil and groundwater. It lowers or dilutes pollutant levels.
(iv) Some synthetics such as oil and solvents could vaporize in the soil, changing from liquid form to gaseous form. If such gases escape into the air near the Earth's surface, they might be destroyed by sunlight. Bioremediation would be aided by bio-augmentation or bio-stimulation if bio-attenuation is not fast enough or complete sufficiently (Mrozik and Piotrowska-Seget 2006).

8.3 *Bio-Augmentation*

This is an exemplification of biodegradation. The introduction of pollutant-degrading microbes (natural or foreign) to enhance the biodegradative capability of native microbial communities in a contaminated environment is known as bio-augmentation. To accelerate the growth of natural microbe populations and improve the degradation of contaminants in affected areas, specific biostimulation techniques can be employed (Li et al. 2010). Microbes are taken from the remedial area, cultivated one by one, genetically changed, and then reintroduced. For example, when soil and aquifers are polluted by chlorinated ethenes, like trichloroethylene tetrachloroethylene, all important microbes are discovered in their surroundings. Its purpose is to show that organisms in situ can eliminate and turn these pollutants into nontoxic ethylene and chloride (Bond and Lovely 2002). When screening for microorganisms to be used for bio-augmentation, parameters influencing proliferation such as pollutant fraction and compound composition, particulate distribution to microbes, the character and proportions of the microbial community, and the physical factors should all be presumed (Garima and Singh 2014).

Bio-augmentation is the technique of introducing designed microbes into a system that act as a bioremediate, allowing complex contaminants to be removed swiftly and completely. Furthermore, genetically engineered microorganisms have demonstrated and proven that they could improve the degradative effectiveness of a wide spectrum of pollutants in the ecosystem (Barkay and Wagner-Dobler 2005). Due to the broad metabolic profile, the end products are less complicated and innocuous. Because native species are unable to break down specific substances quickly enough, they should be genetically altered by DNA modification. Genetically modified microorganisms decompose contaminants quicker than natural species, competing with native species, hunters, and abiotic forces. Genetically modified microorganisms show potential in the cleanup of soil, activated sludge, and groundwater with the improved decomposing ability for diverse range of physical and chemical contaminants (Bernstein et al. 2008).

9 Genetically Engineered Microbes

The genetic information of these microfloras has been modified using genetic engineering. Microbes, both artificial and natural, transmit genetic material. This scientific mechanism is known colloquially as DNA recombinant technology. Through this technique, in which microorganisms are genetically modified, it is possible to eliminate and utilize unwanted hazardous wastes (Davidson et al. 2013; Ramos et al. 1994). Recombinant organizers are produced using natural and DNA recombinant techniques, which involve the exchange of genetic material between living organisms. Recent techniques help to insert a specific gene for particular enzyme production that can degrade different pollutants (Frische 2002).

Genetically engineered microorganisms (GEMs) play a significant role in biodegradation implementations in groundwater, activated sludge environments, and soil. These have high metabolizing abilities and can breakdown a broad variety of chemical toxins (Huang et al. 2004). There are presently many ways to enhance degradative capabilities by using various genetic engineering techniques, including rate-limiting steps in recognized metabolism pathways being genetically operated to increase yield degradation rates and other new metabolic pathways being assimilated into bacterial strains for already recalcitrant compound degradation (Sriprang et al. 2003; García and Díaz 2014). There are four strategies done in genetically engineered microorganisms:

- Pathway regulation and construction
- Bioprocess monitoring, control, and development
- Modification of enzyme affinity and specificity
- Bio-reporter bio-affinity sensor application for toxicity reduction, endpoint analysis, and chemical sensing

Bacteria's essential gene carried single chromosome, and gene identifying enzymes used for catabolism of some unusual substrate can be carried on plasmids. It is involved in energy metabolism so that genetically engineered microorganisms can be effectively used for biodegradation (Wackett 2004).

9.1 Biodegradation of Polluted Sites by Recombinant DNA Technology

Bio-stimulation and bio-augmentation are methods used for the recovery of the contaminated sites. In the seventies, the genetic encoding of catabolic enzymes was studied for their characterization and continued until the point when they began to be cloned. Many microbiologists have known the impact of genetic engineering for knowing microbial degradation (Bakersmans and Madsen 2002). In genetically modified microorganisms (GMM), this technique has been used to alter the exchange of genetic materials between microorganisms. These GEMs have got a special potential source for the groundwater, soil, and activated sludge indicating the specific wide range of chemical contamination present in it (Min et al. 2016). As time passes, access to the biodegradation of microorganisms becomes reality, and much of the fieldwork got started and points to risk assessment and biosafety of it (Izmalkova et al. 2013).

The following are the principles for the bioremediation of genetic engineering by the GEM:

1. Modification of enzyme specificity and affinity
2. Bio-reporter sensor applications
3. Biological process for monitoring and control

9.2 Molecular Pathways for the Optimization of Biodegradative Capabilities

Tools that are used in molecular biology offer the optimization of biodegradative capacities to find new pathways for the assembling of cataloged segments for the different microbes. Meanwhile, genes that regulate the breakdown of contaminants, such as toluene, halogenated pesticides, and some toxicants, have been observed. Each substance necessitated an independent plasmid to diminish all the toxic compounds separately (Sriprang et al. 2003). They are divided into four main different categories: OCT plasmid, XYL plasmid, CAM plasmid, and NAH plasmid. Genetic modification and bacterial strains which got the capability of degrading the different hydrocarbons after the process successfully cause the production of multi-plasmid *Pseudomonas* with the ability to oxidize aromatic and poly-aromatic hydrocarbons. *Pseudomonas putida* contains the NAH and XYL plasmids, which are created by recombining the CAM and OCT through conjugation. This allows it to grow repeatedly on crude oil, and the metabolism of hydrocarbons becomes more specific compared to a single plasmid (Gong et al. 2016). The photosynthetic bacterium is utilized in genetic engineering to facilitate the transport and metabolism of mercury for the purpose of expelling HM wastewater.

Among the most advanced techniques in environmental sites for bioremediation is the endophytic and rhizosphere used in plants to decay harmful complexes in the soil. For gene recombination, first, select suitable strains for cloning; the inserted gene should have a significant upregulation and oversensitivity to rhizospheres. This is because they can facilitate the degradation of organic pollutants, thereby transforming rhizobacteria into rhizo-remediation constructs for gene-guided contamination management (Zhao et al. 2021). The genetic engineering in strains contains the whole problem related to the mixed culture of strains because of the field testing of the different organisms and microorganisms in the environment for the considerable action toward it, due to the biosafety of ecological damage (Popat and Deshusses 2009).

9.3 Bioremediation of Pollutants and Strains Using Molecular Method

The number of strains produced in pollutants of many bioreactors it involves into the situ bioremediation is quite limited. Another issue related to bacterial and strain species is that the traditional enrichment procedures often fail due to the high degradability present in the ecological system. As a result, these strains cannot be effectively utilized as bio-monitoring facilitators (Wackett 2004). The process of stable isotope probing (SIP) and other mechanisms in environment is equivalent because of the aerobic fast growers, by doing the favor to the biodegradation due to the relation of the recombinant gene as far as it goes under natural conditions. It develops the unwelcoming biomass which disturbs the cell mass because of the maximum catalytic capacity (Pandey et al. 2005). The microbiological biomass existing in the niche may prevent it by protozoa that stop the growth of the bacterial population up to an optimum capability (Foster et al. 2002).

The other main problem in bioremediation is unfriendly ground conditions for the microbes because of molecular implementations for categorized pathogens like *Escherichia coli* (*E. coli*), and the bacterial microbes have the characteristic for open biotechnology for the development and to meet new challenges (Nordin et al. 2005). In many cases, the design structure of bioremediation for the specific bacteria results in laboratory conditions by ignoring all the complex situations. In any case, there is yet no proof of genetically engineered (GE) bacteria causing the bioremediation because of adverse chemical effect and their influence on the microbial community (Kallscheuer et al. 2016). As a result of extensive research efforts, significant advancements have been made in the field of environmental microbiology. But yet, the GE bacteria in many environmental situations still need to get the latest finding of it (Jõesaar et al. 2017).

9.4 Benefits of Genetically Engineered Microorganisms

There are many advantages of GEMs in bioremediation. The main advantages include increased substrate utilization, recovery of waste-polluted areas, high catalytic capacity with a small quantity of cell mass, neutralization or decontamination of hazardous substances, and purification leading to environmental preservation. These microorganisms are resistant to environmental problems (Prakash et al. 2011).

9.5 Drawback of Genetically Engineered Microorganisms

There are various drawbacks of GEMs that are not encountered in traditional strategies. Their discharge in the surrounding environment can lead to cell death, and abiotic factors, as well as seasonal variations, can have both direct and indirect effects on microbial activities. Sometimes, GEMs may exhibit slowed growth and substrate degradation. Introducing a new foreign functionalized strain into the system can result in its inactivation, and there may be unpredictable effects on the occurrence and composition of natural functional and structural microbe communities (Labra et al. 2001).

10 Microbial Degradation and Its Role in Organic Pollutants

Degradation is the conversion of material from one form to another, and microbial degradation is the conversion of organic compounds by microbes. Many pollutants dangerously impacted our environment and public health. Renovation and remediation of hazardous material have received much attention. There are many microorganisms capable of degrading different contaminants (Cregut et al. 2013). Microbial degradation is biodegradation, and it is known as biologically catalyzed reduction of chemical compound's complexity. It is the process of breaking down organic substances into smaller compounds; this is done by microbial organisms' completion of the biodegradation process called mineralization, so mostly biodegradation word is used to represent a biologically mediated change in the substrate (Engel and Moran 2013). Microbes transfer substances through enzymatic or metabolic processes that are based on two processes: co-metabolism and growth. Co-metabolism is the process of organic compound metabolism in the presence of a growth substrate and a growing medium, which serves as the primary energy and carbon source. In growth organic pollutant used for energy and carbon sources, this leads to mineralization of organic pollutants (Gautam et al. 2007). There are many microorganisms involved in the biodegradable processes such as bacteria, yeast, and fungi. Protozoa and algae are considered as scanty regarding their contribution to the biodegradation process. Aerobic degradation occurred in the presence of oxygen, but an aerobic degradation occurred without oxygen. The end product of degradation processes is carbon dioxide. Organic matter is generally biodegradable material such as animals and plants and other artificial matter similar to them. Biodegradation is used for waste management associated with bioremediation (Guillet et al. 1974).

10.1 Degradation Dimension of Protozoa

Protozoa are the most important members of the microflora in both terrestrial and aquatic; however, their contribution to hydrocarbon biological degradation is limited (Madoni 2011). There are several speculations about how protozoa continue the degradation of organic residues, which encompass six main components:

(i) Nutrient biosorption increased nutrient turnover.
(ii) Bacterial induction regulates the number of grown cells and releases active components.
(iii) Selective farming can reduce the challenge of resources and space and is beneficial for degrading bacteria.
(iv) The physical disturbances increase the content of oxygen and surface for the decomposed matter.
(v) The degradation can release the important enzymes taking part in degradation.
(vi) Sym-metabolism generates energy and carbon sources for pathogens during the degradation reaction (Martin-Gonzales et al. 2006).

11 Implications of Microbes in Pollutant Biodegradation

Microorganisms are required in the degradation process and play a significant role in biodegradability; they regulate the degradation mechanism and decompose organic material into nutrients that can be recycled and used by other biological entities. It can also help in waste recycling. Fungi, bacteria, and yeast help in the decay of organic matter (Griffths 2020). Strategies of biotransformation and bioremediation attempt to address the astonishing microbial degradative divergence to deform, naturally occur, accumulate, or transfer a huge range of compounds, for example, poly-aromatic hydrocarbons, polychlorinated biphenyls, metals, and radionuclide (Gul et al. 2022). Over the last few decades, high-toxicity secondary metabolites have been released and produced into surroundings for indirect or direct implementation for more than a lengthy period, severely contaminating the environment. Other types of compounds include polychlorinated biphenyl, fuels, dyes, pesticides, polycyclic aromatic hydrocarbons, and others. In contrast, naturally occurring organic compounds are rapidly degraded by flora, unlike other synthetic chemicals such as metals and radionuclide (Ru et al. 2020).

11.1 Hydrocarbons

These are carbon- and hydrogen-containing biomolecules. Cyclic molecules, linked or branched, can be referred to as aliphatic or aromatic hydrocarbons (Dias et al. 2015)

11.2 Polycyclic Aromatic Hydrocarbons

They are an essential contaminant category of hydrophobic organic pollutants. They are broadly found in soil, air, and sediments. Industrial production is a major source of this pollutant. In recent decades, there has been increasing interest in studying it due to the discovery of its prevalence, environmental persistence, and toxic characteristics (Kim et al. 2004). Biological sediments and soil can accumulate these contaminants, aquatic organisms can deposit them, and humans can absorb them through seafood. Their biodegradation can be regarded on one hand to be a factor of natural carbon cycle processes. Bioremediation of polycyclic aromatic hydrocarbon-polluted environment required microorganisms, and it is an attractive technology for polluted site restoration (Wang et al. 2009).

11.3 Polychlorinated Biphenyls

They're a mixture of synthetic organic substances. They have been used in a variety of commercial applications, including heat transfer, electrical tools, and hydraulic tools, due to their chemical stability, nonflammability, electrical insulating properties, and high boiling points. Carbonless copy paper, dyes, pigments, and rubbers, as well as plastics, rubbers, and paints, contain them as the plasticizer. They are toxic compounds, and they disrupt the endocrine and cause cancer in living beings, so their concern is environmental pollution (Aken et al. 2009).

11.4 Dyes

Dye is the substance which is used to color textile, leather, paper, and other materials, and this material of coloring can alter the product by washing, heating and light, and those factors which degrade the quality of life. Dyes are different from pigments because they are finely ground solid dispersed in solids and liquids and with the elements that can blend with other materials (Elisangela et al. 2009).

Some compounds contain carbon, while others do not, particularly those derived from pharmaceuticals, cosmetics, and many aromatic compounds (-N=N-) found in various synthetic dyes (El-Sheekh et al. 2009). These dyes can be biodegradable due to their complex structures and can undergo physical and chemical treatments, including oxidation, filtration, coagulation, and electrochemical mechanisms. The utilization of microorganisms that effectively decolorize the complex structures of synthetic dyes has proven to be beneficial in various applications (El-Rahim et al. 2008).

11.5 Radionuclides

These atoms, known as radionuclides, have an unstable nucleus capable of producing radiation particles but not converting that energy into more radiation particles. Subatomic particles like alpha and beta are emitted as gamma rays during the radioactive decay of the radionuclide (Koul and Adlakha 2021).

11.6 Heavy Metals

Aside from other emerging pollutants, metals can be disrupted, converted, or removed. Metal bioremediation can be accomplished through the biotransformation system. Microorganisms act on HMs via biosorption (HMs are absorbed by cell surfaces via physicochemical mechanisms), bioleaching (HMs are mobilized by excreting organic acid), biomineralization (HMs are immobilized by insoluble sulfides and polymeric complexes), intracellular accumulations, and enzyme-catalyzed transformation (Kim et al. 2015; Al-Khafaji et al. 2018).

12 Conclusion

Microbial activities are crucially significant in the ecosystem due to organic toxicants and the preservation of the organic carbon cycle. Degradation processes transform heavy metals and hydrocarbons into a wide variety of synthetic compounds that have toxicological effects. Several factors affect biodegradation, such as aeration, pH, temperature, moisture, and low bioavailability. Environmental biotechnology strives to address problems by using microorganisms through bio-stimulation and bio-augmentation. Furthermore, genetic engineering contributes to reducing waste and making the environment more sustainable.

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Chapter 34
Principles and Applications of Environmental Biotechnology for Sustainable Future

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Abstract This chapter reviews the state of art and potential of environmental biotechnology, as well as the challenges and considerations that go along with it. Given the wide range of issues that the industry and country face in the discipline of environmental biotechnology, the functions of some biological processes as well as biosystems to control environmental safety and health based on the use of living organisms have been investigated. The success as well as the possibilities in the advancement of technology is considered while evaluating environmental remediation pollution control monitoring and detection. To demonstrate each of the major areas of environmental biotechnology, such as wastewater treatment, many related topics have been chosen. Dealing with both process engineering and microbiological elements of waste gas treatment, soiltreatment, and solid waste treatment. The specific significance of environmental biotechnology in the time ahead is stressed due to the possibility to offer up-to-date solutions and directions in the repair of damaged environments while avoiding future waste discharge and creating pollution control alternatives. To capitalize on these opportunities, creative and new techniques advancing the use of genetic engineering technology and molecular

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biochemical processes are being investigated. This strategy would improve knowledge of present biological processes to boost their productivity, adaptability, and efficiency. There is an example of the implementation and development of such strategies. The contribution of environmental biotechnology to the creation of a truly sustainable future is indeed made clear. By fusing biotechnology alongside related technologies and making sure that safety procedures are an essential part for the project, environmental biotechnology has served as one of the opportunities for avoiding, stopping, and restoring environmental damage. Biotechnological methods and commodities could be employed with the aim of long-term ecological safety to protect environmental safety.

Keywords Biosystems · Environmental safety · Adaptability · Environmental degradation

1 Introduction

Biotechnology is the purest, most rational, and most significant technology of the century; it encompasses any act of human intellect in the production, marketing, and presentation of different animal products, mostly through molecular manipulation (Fahmideh et al. 2014). Environmental biotechnology is the use of microorganisms to improve the quality of the environment. For decades, the main instruments for defining characteristics and directing environmental biotechnology activities have been available (Daugulis and Boudreau 2003). Traditional biomass measurements, such as volatile suspended solids, have not lost their versatility. Nonetheless, molecular biology tools have made it possible to investigate the variability of microbial communities (Dietz and Schnoor 2001). Environmental biotechnology has the potential to revolutionize the possibilities for pollution control, wastewater and solid waste treatment, production with less pollution discharge or fewer raw materials consumption, and assure health of environment by genetic engineering and biomonitoring. Environmental biotechnology is a sustainable way of developing clean procedures and goods that are less harmful and have a lower impact on the environment than their originators, as it has a big ability to contribute to a detection, prevention, and cleanup of environment pollution and waste degradation. It plays an essential part in the industrial, food, agroforestry, mineral sectors, and raw material when it comes to clean technology solutions.

The bulk of environmental issues are caused by disturbances in the interactions among both humans and the environment. Such perturbations can have a wide range of repercussions, including water, air, and soil pollution. Human civilization will be impacted in a number of ways as a result of these environmental repercussions, including human safety and health, wealth, and the value of nature. Pollution, or contamination of the earth's environment, negatively affects not only human health but also the standard of living and ecosystems (IPCC 2014). It is being stated unequivocally that blaming the effects of human-brought rises in heat retaining gases for the ongoing rise of global warming is not an option. There is no longer any doubt about climate science's credibility or maturity. Climate change is terrible because it has the tendency to reshape the human world in such a way that life has become extremely difficult. Industrial activities may cause water contamination as a result of heavy metal disposal, such as lead mercury, selenium, and copper; this contaminated water may have health concerns for humans, such as after swallowing or coming into contact with contaminated soil (Shayler et al. 2009). Environmental issues can be evaluated on a continental, local, or global scales (WHO 1982). Environmental issues created by contaminants that linger in the environment for extensive period and are transferred over great areas are examples of global issues. People pay more attention to air pollution because they have large-term and long-scale consequences. It makes no difference where the emissions occur on the planet because the toxins quickly spread throughout the atmosphere, with effects lasting decades or centuries (GISS 2017). As a result, global issues such as climate change and ozone layer depletion are worldwide issues that require immediate global answers. The increasing speed of industrialization and urbanization, combined with technological innovation, has resulted in massive amounts of municipal solid waste (MSW) being generated all over the world (Singh and Sarkar 2015; Srivastava et al. 2015, 2016; Singh et al. 2017). Moreover, 52% of the world's population already lives in cities and suburban, with that number predicted to rise to 64–69% by 2050 (World Bank 2013). Several types of air pollutants are discharged into the atmosphere during the MSW management process. Furthermore, when wastes are piled high in open landfills/dumps, particular organic matters decompose and emit toxic gases. In utmost developing nations, inadequate waste disposal and treatment methods are utilized to manage MSW, resulting in the manufacturing of a variety of air pollutants, such as polychlorinated dibenzo-p-dioxins or dibenzofurans (PCDD/Fs), greenhouse gases (GHGs), odorous particulate, and matter gases (Vaish et al. 2019).

Mitigation and adaptation are two options for dealing with climate change. The use of heat trapping gases could be minimized by reducing their sources or increasing their sinks. It is also a good opportunity to consider how we can lessen our vulnerability to climate change's negative consequences. The competition for energy in commodity production, transportations, and other vital necessities is the primary source of all chemical pollution. As a result, it is critical and opportune to increase the use of alternative energy sources such as hydroelectric, solar, and wind power. Contamination risks to soil and water can be reduced if agricultural chemicals are used properly and efficiently, and home and industrial effluents are recycled (Senusi et al. 2018). Biotechnology's application to environmental issues is not a strange idea. Waste treatment plants (WTP) and composting, while not often recognized as instances of biotechnology, undoubtedly satisfy the criterion of integrating biological and technology. Engineers have spent a lot of time studying WTPs and have come up with a number of designs for dealing with both home and industrial waste. In fact, the DuPont Company does have a commercial facility that handles 35 million of gallons of hazardous materials every day from around the country. Because of the process's complication and only limited microbiological understanding, it is possible that it has not been recognized as a biotechnology example.

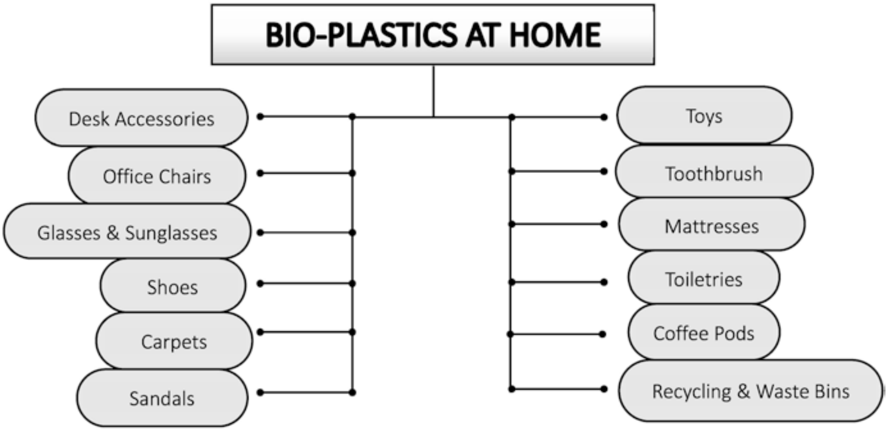

Fig. 34.1 Bioplastics at home

The information gathered from such plants, on the other hand, is being immediately applied to addressing many of today's environmental crises, and such systems must be contemplating prototypes for today's modern biotechnology applications to environmental issues (Litchfield 1991) (Figs. 34.1 and 34.2).

2 Application of Environmental Biotechnology

2.1 Bioremediation

The fast growth of agriculture and industry over the last several decades had caused pollution of the environment through a variety of pollutants, containing heavy metals, plastics, polychlorinated biphenyls, and numerous agrochemicals. Because of their toxicity and nonbiodegradability, their existence within the environment is the major point to be focused. Their interaction and cohabitation in the environment have a significant impact on and threaten the natural environment and human health. Additionally, the existence of these contaminants has an impact on soil quality and fertility. To repair such situations, physicochemical approaches are applied, although they are less successful and have large operating costs (Kour et al. 2021). Bioremediation is an effective, broad, low-cost, and environmentally acceptable cleaning method. Bioremediation technique is an efficient option for the elimination of environmental toxins since it is both cost-effective and environmentally friendly and is a practical solution (Kour et al. 2019; Yadav et al. 2017; Ite and Ibok 2019).

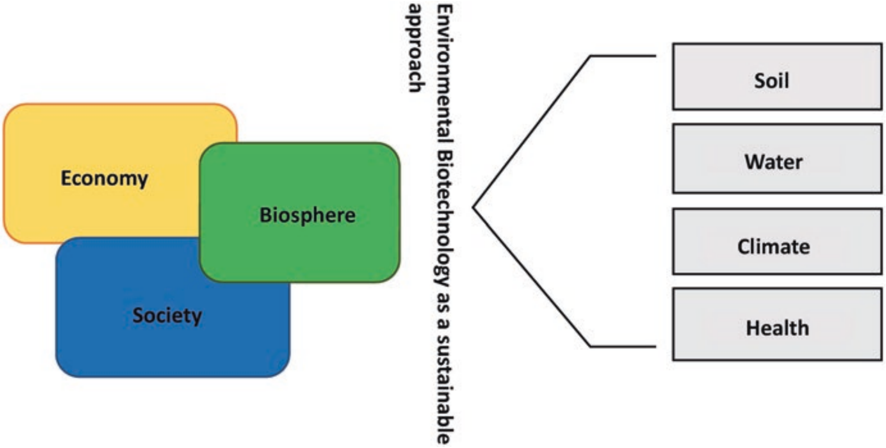

Fig. 34.2 Environmental biotechnology as a sustainable approach

2.1.1 Ex Situ Bioremediation Methods

The contaminants are retrieved from the contaminated site and carried to a new place for treatment using this procedure. The choice of ex situ bioremediation method is determined by the cost of treatment, the extent of pollution, the nature of contaminant, the gradation of pollutant, the geology of the site, and the geographical location of the polluted site (Philp and Atlas 2005). This procedure is difficult where plants remove pollutants without harming the top soil and help to maintain soil fertility. Generally, this procedure is used for soil remediation owing to its safe use in the environment with the approval of governmental standards. This system also has drawbacks, for example, health hazards associated with the interchange of polluted area (Kumar 2019).

2.1.1.1 Windrows

This ex situ approach includes rotating disturbed soil on a regular basis along with view of intensifying bioremediation by increasing the degradation actions of soil bacteria. The intervallic transforming of soil by combining water improves aeration, equivalent dispersal of contaminants, microbial and nutrient degradation, and therefore the rate of bioremediation, which can be accomplished by mineralization, absorption, and biotransformation. Because of the soil type, windrows had a greater rate of hydrocarbon removal. Recurring shifting of soil is ineffective and cannot be used to remove harmful volatile chemicals. This windrow treatment comprises the emission of CH_4 gas as a result of the anaerobic zone, resulting in less aeration (Azubuike et al. 2016; Hobson et al. 2005).

2.1.1.2 Biopile

This method of bioremediation comprises the exclusion of toxic soil layers above ground, tailed by increased microbial activity, degrading, nutrient modification, and aeration. The soil contaminants are degraded in this technique over a period of weeks to months. The pH, oxygen, temperature, nutrition, and moisture content are all important factors in this operation. Hydration, air circulation, leachate, a nutrient collection system, and a treatment bed are among the components of these approaches. The biopiling technique includes many systems that aid in the cleanup of polluted soil, including an air circulation system, a nutrient system, and a leachate collecting system. Biopiles are frequently employed due to their advantageous properties such as cost efficiency and sustainability (Lors et al. 2012; Yadav 2021), which promote biodegradation if air circulation, hydration, and nutrients are properly maintained. Because of their excellent flexibility and high breakdown rate, as well as an integrated heating system that boosts microbial activity, this technology reduces the time required for cleanup. The use of wood bark, sawdust, and straw speeds up the cleaning process. Ex situ remediation can successfully remove contaminants in challenging conditions, such as extremely cold climates, and can assist prevent vaporization (Dias et al. 2015; Gomez and Sartaj 2014; Whelan et al. 2015).

2.1.1.3 Bioreactor

Bioreactors are utilized in the sustainable and rapid bioremediation method (Pino-Herrera et al. 2017). Raw materials are turned into products in a bioreactor by a chemical reaction in a vessel. Using a bioreactor, a sequence of biological processes converts the pollutants into the desired products. Continuous bioremediation of contaminants or toxins may be achieved in a bioreactor by controlling aspects such as moisture, temperature, pH, nutrients, and oxygen level (Hussian et al. 2020). There are numerous bioreactor operating phases accessible, fed batch, comprising batch, multistage, continuous, and sequencing batch. Sanitization by bioreactors is an efficient technology that may readily provide yields of more than 90% due to the regulated and enhanced biological response within the bioreactor, allowing for quicker and more effective biodegradation or treatment (Cristorean et al. 2016).

2.1.2 In Situ Bioremediation Methods

The in situ method removes contaminated elements at their source without the need for excavation. It does not affect the structure of the soil and is less costly than ex situ bioremediation approaches because there is no extra expense for excavation activities in this method. In addition to this benefit, this strategy prevents the spread of contaminants from one location to another. In situ bioremediation also enhances microbial breakdown in hazardous contaminated soil by bringing out the activities between contaminants and biomass (Sharaff et al. 2020; Singh et al. 2020a, b). Biosparging and bioventing can be improved. This bioremediation technology has effectively cleaned polluted sites polluted with dyes, hydrocarbons, heavy metals, and chlorinated solvents (Folch et al. 2013; Frascari et al. 2015; Kim et al. 2014; Roy et al. 2015).

3 Bioventing

By supplying unsaturated zones with oxygen, this technique encourages the activity of local bacteria for better bioremediation. Bioventing provides nutrients and moisture to promote bioremediation (Philp and Atlas 2005). Bioventing is being considered for places affected by petroleum products (Sharma et al. 2019). Because of its interoperability, it is widely used. This approach works in tandem with the physical venting process to accelerate the breakdown of pollutants.

4 Bioslurping

Bioslurping combines the vacuum and bioventing technologies to improve free product recovery to handle two distinct pollutant mediums. This technology efficiently cures petroleum hydrocarbon pollution while also being cost-effective. The vadose zone, or unsaturated zone, is cleaned up, and LNAPLs are eliminated. Due to the sluggish rate of oxygen exchanges, this method has the drawback of slow microbial mass mobility. The humidity, which reduces permeability into the soil, has a significant impact on microbial activity (Kim et al. 2014).

5 Biosparging

Biosparging is same as bioventing in the air and is introduced into soil surfaces to boost microbial activity and hence improves pollutant removal from polluted sites. The efficiency of biosparging is recognized by two critical factors: soil absorption and contaminant biodegradability (Philp and Atlas 2005). The amount of groundwater oxygen is raised in this procedure by increasing the pressure of the air supply, which promotes the process of biodegradation through bacteria found naturally in the soil (Singh and Yadav 2020). It only improves the collaboration between soil and water. The use of tiny air injectors has the advantages of being cost-effective and simple to operate (Kumar et al. 2018).

5.1 Biomining

Biomining is the technique of removing specific metals by their ores by utilizing biological methods, frequently involving microbes. Two procedures, known as bioleaching and biooxidation, are used to carry out biomining. While the term "bioleaching" is frequently used to describe the biomining of base metals, "biooxidation" is primarily utilized to treat sulfidic-refractory gold ores and concentrates. The techniques used in biomining are inexpensive, nontoxic, efficient, and environmentally benign (Brierley 2008).

6 Techniques of Biomining

The following processes are used to extract various metals in accordance with the requirement (Siddiqui et al. 2009):

7 In Situ Leaching

Instead of gathering ore and transporting it to an extracting plant remote from the mine, the mineral is extracted straight from the mine. In situ biomining is often used to recover trace quantities of minerals contained in ores after a traditional extraction procedure has been finished. The mine is bombarded to decrease ore mass and boost permeability before being treated with water and the solutions based on acidic nature containing bacterial inoculums. Pipes or shafts are used to deliver air supply. Biooxidation occurs in situ as a consequence of growing bacteria and results in the extraction of the mineral from the ore (Haque and Norgate 2014).

8 Dump Leaching

The earliest method is dump leaching. Dump leaching is simply the accumulation of uncrushed waste rock in dumps (Siddiqui et al. 2009). It is employed in the extraction of relatively low-quality ores from minerals. The larger rocks are fractured in the pit by blasting and transported as large shards to landfills. These dumps contain millions of tons of run-of-mine ore. Acidified water is sprayed on the uppermost floor, where it percolates and produces the necessary conditions for the growth of microorganisms in order to oxidize the mineral and extract the metal. Dump leaching was a common method for extracting copper sulfide ores (Brierley 2008).

9 Heap Leaching

Base metal extraction through sulfide rocks using heap bioleaching is a process that is expanding quickly. Massive quantities of relatively low-quality ores and pollutants via mineral extracting procedures make up bioheaps. In heap leaching, the overloaded secondary sulfidic ores are piled on leach pads which can be aerated through a bottom of the heap and then agglomerated with sulfuric acid. After being given time to settle for 1–6 weeks, the ore then is leached for 400–600 days using acidic leach liquor. Copper recoveries during this time range from 75% to 95%. Biopiles, biomounds, and biocells are other names for bioheaps. Additionally, they are used in the biodegradation of chemical and petroleum waste (Rawlings 2013).

10 Vat Leaching

Vat leaching is a technique of extracting minerals from oxide ores that includes keeping ore slurry and solvent in huge tanks with agitators for several hours. It is used to perform cyanidation on ores with high gold concentration and to recover precious metals from ores. The procedures used in biomining might be effective only if there is adequate adhesion of microorganisms to the surface, which is achieved through good biofilm growth (Siddiqui et al. 2009).

10.1 Wastewater Treatment

In response to the growing water issue in the green twenty-first century, particularly prosperous materials and technology for wastewater treatment are desperately required (Yi et al. 2017, 2019). Tremendous strides had been achieved in this direction up till now. The three primary classes of wastewater treatment techniques are physical technology, chemical technology, and biotechnology. Biotechnology uses microorganisms' resources to remove pollutants from wastewater while scarcely altering the environment. Biotechnology is less expensive for genuine wastewater treatment than physical and chemical technologies and is more suited for contemporary environmentally favorable development (Yang et al. 2018; Huang et al. 2018). Standard biotechnologies are frequently used in today's wastewater treatment facilities to produce pretty persuasive treatment outcomes, but they come with a number of drawbacks, including the need for a sizable amount of land, the release of a lot of sludge, and the inefficiency of many wastewater toxic substances (e.g., personal care products, pharmaceuticals, azo dyes, and endocrine disrupting compounds). New enhanced biological techniques as well as a number of integrative biotherapies have been suggested as solutions to these problems. The three main biotechnologies employed in wastewater treatment are denitrifying anaerobic methane oxidation (DAMO), anammox systems, and biofilm techniques. To support biotreatment procedures, physical or chemical treatments, such as Fenton's oxidation, ozonation, photocatalysis, and adsorption of activated carbon, are frequently utilized as pretreatments or post treatments. In comparison to a single biotreatment procedure, the combined process often has a better treatment efficiency. Numerous researchers have attempted to use the best biological technology available for wastewater treatment up to the present time. The pilot plant employed microbial electrolysis cells for real wastewater treatment. High-strength actual wastewater may be treated compactly and inexpensively by using aerobic granular sludge technology. The biological wastewater treatment procedures' use of sorption and biotransformation has a significant influence on how effectively organic microcontaminants are removed. Depending on the application industries, each biotechnology offers different advantages and disadvantages for the real treatment of wastewater. Finding the best solutions to satisfy certain needs in real-world circumstances is crucial. It is necessary to provide a thorough overview of the best biotechnological procedures for handling wastewater under various circumstances (Yi et al. 2020).

10.1.1 Moving Bed Biofilm Reactor

The fundamental method for treating wastewater is considered as activated sludge method, where microorganisms are essential (El-Taliawy et al. 2018). Continuous aeration in the wastewater causes aerobic microorganisms to multiply and progressively form suspended flocculation eventually settling them at the bottom of the tank to produce activated sludge. To make sure there are sufficient microorganisms inside the reactor, the activated sludge must be recycled (Xu et al. 2018). Nevertheless, if flocs are insufficient, the active sludge might refuse to deposit on the tank bottom side (Bakar et al. 2018), and microorganism-based contaminants cannot be successfully removed by the activated sludge method (Gaur et al. 2018; Alvarino et al. 2018). Based on the aforementioned concerns, researchers are examining a novel biotreatment device called a moving bed biofilm reactor (MBBR) (Bering et al. 2018).

MBBR is a biological unit having a biofilm developing on the transmission surface. An aerobic outer layer and an anoxic inner layer combine to produce the biofilm, which has a significant amount of active biomass. Therefore, nitrification and denitrification can occur in both, the MBBR and organic carbonaceous materials can be destroyed. In order to increase overall wastewater treatment, the carrier can also travel across the tank by stirring or aeration, which enhances oxygen usage and benefits the interaction of the biofilm with the contaminants. From start-up until the treatment of the contaminants, the physical characteristics of the carrier, such as its size, shape, dimension, voidage, and protective surface area, as well as its hydraulic efficiency (HE), are crucial. In general, spherical carrier medium exhibits more voidage, quicker biofilm production rate, and fewer inactive or stagnate areas, which significantly aid in the removal of chemical oxygen demand (COD) and ammonia. The rates of COD and ammonia removal biofilm development and oxygen mass transfer were slightly linked with the protected surface area. Dimensionality, voidage, and HE exhibit significant relationships with oxygen mass transference and biofilm generation ratios for heterotrophic and nitrifying bacteria. The commission of MBBR will benefit from knowing the physical effects of the media well and will result in a more effective treatment procedure. MBBR has been successfully used in developing nations with minimal land resources because it is a small, simple, adaptable, and dependable technology that can be modified based on already-built wastewater treatment facilities. When treatment is done for the industrial wastewater, urban wastewater, and wastewater including micropollutants, MBBR performs well. For instance, under stable circumstances together with organic and hydraulic shock loadings, MBBR plated with activated sludge and the right microorganisms could perhaps eliminate 67.79% of COD, 61.12% of soluble COD (sCOD), 76.26% of particulate COD, and 56.97% of total ammonia nitrogen (TAN) from primary settled wastewater. Virgin polyethylene carriers with a 70% filling percentage have been employed in MBBRs; 225 mg L^{-1} of COD, 133 mg L^{-1} of sCOD, 15 mg L^{-1} of TAN, and 102 mg L^{-1} of total suspended solids (SSs) are the characteristics for primary settled wastewater, which has a pH of 7.2. At pharma hospital wastewater, MBBR exhibits great breakdown efficiency together with COD and nitrogen removal. A portion of hospital wastewater was treated using a three-stage MBBR. The identical 500 AnoxKaldnes™ K5 carriers were used to fill each of the three identical 3 L reactors in the MBBR. An 80 ml filter was used to initially filter the raw hospital wastewater. In order to balance the flow, the filter wastewater was stored in a 100 L reactor and kept between 15 and 18 °C. X-beam contrasted medium was more successfully debased in MBBR than in activated slop treatment. The composite half-life for diclofenac expulsion is also much shorter than in conventional wastewater bioreactors, at just 2.1 hours. MBBR is equally amazing for its fortitude under extreme circumstances, such as high or low weight and extraordinary temperatures. The MBBR cycle's financial reality can be increased by decreasing the beginning time. A carrier with outstanding execution is beneficial to reduce starting time. Additionally, it is anticipated that the implementation of a framework for association further development, such as expanding the connection of anammox microbes (AnAOB) to the carrier media, will shorten starting time. Additionally, compared to a single-phase MBBR, an MBBR updated with granular waste reduced starting period from 90 days to 50 days, considering how granular ooze can more quickly transmit a biofilm (Yi et al. 2020).

Generally, MBBR shows five advantages for treating wastewater:

- A brief sludge retention period
- A substantial biological concentration
- Less area is needed
- Why removing activated sludge is not done
- Steadiness under adverse conditions

10.1.2 Biological Nutrient Removal

In 1999, Utena Wastewater Treatment Plant underwent refurbishment. At the Utena Wastewater Treatment Plant, in which nitrogen was eliminated in a nitrification/denitrification chamber as well as a biological phosphorus elimination anaerobic zone is installed prior to the nitrification/denitrification chamber, the latest cutting-edge "BioBalance" technology is used. The nature of wastewater affects the biological elimination of phosphorus, specifically the amount of whole phosphorus to biochemical oxygen demand (BOD7/Total-P) in wastewater following mechanical treatment. The biological phosphorus elimination process may be negatively impacted by nitrates in the anaerobic zone. Nitrates are denitrified using volatile fatty acids. The *Acinetobacter* may be able to absorb volatile fatty acids. For the factors listed above, it is necessary to assess the influence on biological nitrogen and phosphorus elimination. The project's objective was to assess the effectiveness of biological nitrogen and phosphorus elimination at the Utena Wastewater Treatment Plant utilizing the "BioBalance" technology. Throughout this experiment, the "BioBalance" technology for biological nitrogen and phosphorus elimination and technology before rebuilding were used to assess and contrast biological nitrogen and phosphorus elimination. The relationship between the proportion of total phosphorus inside the effluent as well as the biochemical oxygen demand and total phosphorus (BOID7/Total-P) postmechanical treatment was assessed. Additionally, the effectiveness of phosphorus elimination was assessed together with the correlative regressive study of nitrates in the anaerobic zone upon this aeration tank (Vaboliene and Matuzevičius 2005).

10.2 Superbug

Superbugs include viruses, bacteria, fungi, and parasites which really are tough for treatment with conventional antibiotics and various treatments, which make them a major health threat. Superbugs are a kind of resistant bacteria that can result in pneumonia, urinary tract infections, and skin infections. A critical public health problem is the multidrug-resistant bacteria's rapid global spread and growth. The development of antibiotics reduced mortality in humans and animals, resulting in increased life expectancy. However, due to indiscriminate antibiotic usage and selection pressure, microorganisms have retained resistance. It has become increasingly prevalent in recent decades. Hospital-acquired MRSA, community-acquired MRSA, and multidrug-resistant tuberculosis (MDR TB) have all become more challenging for physicians as methicillin-resistant *Staphylococcus aurous* (MRSA) has evolved. The introduction and spread of acquired carbapenemases among Gram-negative bacteria are seen as a serious public health concern across the world. Gram-negative bacteria, such as *Escherichia coli, Klebsiella pneumonia*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii*, are among the leading causes of severe illness. Bacterial infections in humans, both hospital-acquired and community-acquired, are becoming more common, and antibiotic resistance in these bacteria is becoming a bigger issue. Recent advancements in nanotechnology-based medication delivery systems may prove to be a viable alternative in the fight against antibiotic-resistant bacteria. Antibiotic laws and regulations, on the other hand, should be developed to prevent the spread of resistance among bacteria (Uddin et al. 2017).

Antibiotics have been used to treat infectious diseases since Alexander Fleming's time. The advent of resistant microorganisms coincided as antibiotics progress to more complex synthetic groups. Antibiotics are used to treat infectious infections, but their overuse and misuse has resulted in the emergence of superbugs, which has become a serious global concern. The word "superbug" refers to antibiotic-resistant microorganisms that have recently emerged. Due to hospital-acquired illnesses, superbugs' resistance to antibiotics generates economic losses by lengthening the period of infection, increasing treatment costs, and lowering the efficacy of surgical treatments. Multidrug-resistant (MDR) Gram-negative "superbugs" such as *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, and *Klebsiella pneumoniae* are posing an increasing threat to the globe. This loss of morbidity and mortality has an indirect negative impact on a country's economic development. According to earlier statistics, the cost of treating resistant bacterial infections and multidrug-resistant tuberculosis (MDR TB) in the medical sector is between 4 and 7 billion dollars per year and 180,000 dollars in the United States. MBL makers discovered high antimicrobial resistance to all-lactam and no lactam drugs. Antibiotic resistance strains have arisen in developing nations as a result of antimicrobial overuse and underuse due to a lack of awareness among patients, medical personnel, and budgetary constraints. Because of increased globalization of human population due to travel and other factors, resistant strains easily move across developed and poor nations, posing a worldwide concern by lowering antibiotic concentrations within bacterial cells. It is important to conduct thorough study and use nanotechnology to the treatment of superbugs and the discovery of resistant microorganisms. MRSA contamination in the food and beverage industries as well as in hospital rooms can be decreased by ultraviolet-C irradiation. Hospital wards may also effectively eliminate resistant bacterial groups by using hydrogen peroxide vapor (Uddin et al. 2017).

10.3 Biofiltration

A biological air pollution control (APC) technique is biofiltration. Passage of waste gases via a biologically active porous media is used to treat them. Biofilters were developed in Europe to eliminate odors. Biofilters have evolved over the last two decades from odor-controlling devices to highly complex and regulated machines that remove particular pollutants from industrial sources. The Clean Air Act modifications of 1990 fueled biofiltration research even further. The biofilter market in the United States has been rising for these reasons, as well as the economic and environmental benefits of biofiltration. The goal of this study is to give a high-level overview of the important elements that influence biofiltration design, operation, and performance. Several case studies are given to demonstrate various applications, process obstacles, and solutions to these issues. This publication does not attempt to provide a complete review of contemporary biofiltration research. Rather, it is aimed for professionals who are unfamiliar with the technology, its applications, or the variables that influence its success. Biofiltration is governed by the same principles as typical biofilm processes. Within the bed of a biofilter, a three-step process takes place. Additionally, the activities that take place inside and outside the biofilm, as well as typical concentration profiles for the substrate [volatile organic compounds (YOCs)] and oxygen. First, a gas-phase chemical bridges the interface between pore-space gas and the aqueous biofilm that surrounds the solid medium. The chemical then diffuses across the biofilm to a group of bacteria that have become adapted to it. Finally, the microbes get their energy by oxidizing the chemical as a main substrate or metabolizing it using nonspecific enzymes. Within the biofilm, there occurs simultaneous diffusion and absorption of nutrients such as nitrogen and phosphorus in accessible forms, as well as oxygen. The use of chemicals, electron acceptors, and nutrients maintains concentration gradients in the biofilm, which drives diffusive transport. Target waste gas compounds are converted to end products such as CO_2, H_2O, inorganic salts, and biomass by a well-built and -maintained biofilter. To maintain optimal biofilter functioning, waste gases are often pretreated (Swanson and Loehr 1997).

Pretreatment processes may include the following:

1. Removal of particulates. For waste gases with high particle concentrations, a particle removal procedure protects downstream units from clogging and/or sludge formation.
2. Equalization of load. A load equalization reactor [such as a short residence time granular-activated carbon (GAC) unit] to reduce peak loadings may be required if the waste gas VOC content is extremely variable over time. The importance of biofilter acclimatization and responsiveness to dynamic loadings (which may be sluggish) is therefore reduced.
3. Temperature control. It is possible that the waste gas will need to be heated or cooled to the right temperature for microbial activity. The humidification process is frequently combined with temperature modification. If not, and waste gas heating is necessary, temperature regulation should come first to avoid lowering the gas's relative humidity.
4. Humidification. To avoid removing water from the biofilter medium, the waste gas should be thoroughly saturated with moisture when it enters the biofilter. The most important pretreatment procedure is humidification, which must achieve approximately 100% relative humidity in the waste gas.

10.4 Biosensors

Biosensors are analytical devices that combine a biomarker in the form of an enzyme, an antibody in close proximity to the transducer, and a transducer to link an analyst's concentration to a detectable electrical signal (Reiss and Hartmeier 2001; Rodriguez-Mozaz et al. 2004). Because of the rising levels of pollution in the environment, biosensing research has gotten a lot of interest in recent years. To assess pollution levels, biosensing devices generate signals based on the specificity of living substances. Biosensors, in a larger sense, are any system that generates a measurable signal when a biological component detects a substrate. The biosensor's biological component, which might be a complete cell, enzyme, antibody, or genetically altered organism, is the most important aspect. Biosensors are a fantastic synergistic blend of microelectronics and biology (Verma and Singh 2005). Both chemical and biological pollutants can be detected with biosensors. Combining biological activity with nanoelectronics resulted in the development of a microchip biosensor with extremely high selective sensitivity (Cui et al. 2001). Environmental contamination is detected by microalga whole cell biosensors based on (chlorophyll fluorescence or phosphatase and esterase inhibition). Endocrine disruptors such as estrogen and 17-oestradiol are detected using a biosensor based on genetically engineered yeast. It was created with the intention of being used in humans for medicinal purposes. However, it was eventually discovered that it might be used to identify environmental toxins. Biosensors have solved a number of critical environmental concerns that could not be solved using other means (Tucker and Fields 2001).

10.5 Biotransformation

The capability of microbial communities to break down nongrowth substrates which could not be utilized as an only source of nutrients and vitality in the absence of a main substrate is known as biotransformation. The latter is more readily accessible, acts as an electron donor, helps to sustain the microbial community, and stimulates the synthesis of enzymes and cofactors that, because of their diverse catalytic activity, can biotransform OMPs (Fernandez-Fontaina et al. 2014, Fischer and Majewsky 2014; Krah et al. 2016). Co-metabolism is predominantly considered by the scientific group to be the primary biotransformation pathway in actual environmental settings (Fischer and Majewsky 2014; Tran et al. 2013).

OMPs cannot be fully mineralize through metabolic as well as co-metabolic biotransformation mechanisms, turning them into transformation products (TPs) which might have even more detrimental implications on aquatic environments and human health (Gulde et al. 2016). Therefore, in order to accurately quantify the environmental effects, a thorough examination of the route and transformational responses of the OMPs with in biological segments of WWTPs is essential (Men et al. 2017).

10.5.1 Biotransformation Process

Almazroo et al. (2017) stated that biotransformation process is mainly divided into the three phases, i.e., phase-I, phase-II, and phase-III. These phases can take place at same time and sequentially also.

10.5.1.1 Phase-I

In phase-I, water-soluble, polar, metabolite is yielded that is often active still. Many of the output products can become the substances for the phase-II.

- Reduction
- Hydrolysis
- Oxidation with P450 cytochrome (most common)

10.5.1.2 Phase-II

In phase-II, a large polar metabolite is yielded by adding hydrophilic groups in order to form water-soluble inactive compounds which can be released from the body.

- Acetylation
- Sulfation
- Methylation
- Conjugation with amino acids
- Conjugation with glutathione
- Glucuronidation (most common)

10.5.1.3 Phase-III

Phase-III happens after the phase-II, in which a chemical substance can go for further metabolism, so it can easily be excreted. Phase-III is classified into following families.

1. ABC (ATP-binding cassette)
2. SLC (solute carrier transporters)

10.5.1.4 Mechanism

Meyer (1996), Wrighton et al. (1996), and Guengerich (2001) stated that phase-I reactions consist of the oxidation, hydrolysis, and reduction reactions. These reactions are performed to convert the lipophilic compounds into the most polar molecules by the addition of the polar functional group, i.e., OH. Active metabolites are often created by these reactions which are beneficial in activation of the pro-drugs into their different states, i.e., therapeutic and active states. Drugs with the polar functional groups can easily bypass the phase-I and can enter direct into the phase-II to become conjugated. Mainly, phase-II reactions consist of the addition of the hydrophilic groups to a toxic intermediate, original molecule, or nontoxic metabolite that are formed in phase-I. Ultimate goal of the phase-II reactions is the formation of the water-soluble products that can easily be released from the body. In phase-III, drugs are transported through ABC transporters, which require energy to actively uptake the compound from one side to another side of cell membrane. It can also be transported through SLC transporters which improve the pathway of specific solute across membrane. Transfer of the molecules into the cells is the function of uptake transporter and transport of the molecules outside of the cells is the function of efflux transporters.

10.5.1.5 Importance of Biotransformation

A crucial step in both detoxifying and mitigation of the environmental effects for trace organic micro pollutants (OMPs) is the biotransformation of these contaminants through intricate microorganisms in wastewater treatment plants. Furthermore, comprehension of the metabolic processes and mechanisms underlying their biotransformation is crucial while creating strategies aimed at reducing its disposal (Kennes-Veiga et al. 2022). Biotransformation has been discovered as a significant factor contributing to the elimination of PhACs within WWTP effluents (Nguyen et al. 2021). The most significant method of eliminating synthetic chemicals by the environment is biotransformation, and still the strategies underlying this crucial ecosystem function are still poorly understood (Desiante et al. 2022). Even though this is comparatively negligible in shallower surface waters, biotransformation must be taken into consideration as a possible key attenuation strategy for WWDCs in big rivers. Consider the destiny of naproxen in river water with three distinct beam attenuation coefficients, varying from a low-DOC, and particle-free river to a turbid, highly colored water, to demonstrate the distinctions among the two kinds of systems (Fono et al. 2006).

10.6 Bioplastics

Bioplastics are plastic polymers that are made from renewable biomass sources, are totally biodegradable and bio-based, and are completely broken down by natural processes. Plastic poses the greatest threat to the environment and ecology owing to its nonbiodegradable nature and manufacture from synthetic polymers, which uses a massive amount of nonrenewable resources (Stevens 2020; Reddy et al. 2003). Bioplastics are made from natural materials (proteins, fibers, sugar, etc.). As a result, nonrenewable resources (such as coal and oil) are avoided, lowering global warming. Releasing hazardous gases into the atmosphere microbes play a crucial part in the human body and turning plant and vegetable matter into bioplastic building blocks (Luengo et al. 2003; Moldes et al. 2004). Many environmental challenges, such as plastic waste reduction and nonrenewable resource use, have been addressed through bioplastic manufacturing from organic waste and enzyme-assisted plastic reduction. The extensive dissemination of industrial biotechnology was analyzed in a 2001 OECD report based on 21 enterprises from various industries such as chemical, paper, pharmaceuticals, and textiles. Industrial biotechnology was discovered to be beneficial in this investigation.

10.7 Biofuel

Excellent research and development for the generation of biofuels by the enzymatic conversion of various substrates (agricultural waste, municipal waste, and vegetable oils) into bioethanol and biogas, among other things, is currently underway across the world (Dale and Kim 2008; Willke et al. 2005). Anaerobic digestion of agricultural and food wastes for methane generation has been proposed in a variety of applications. Anaerobic bacteria break down complex organic compounds in trash to produce methane-rich combustible biogas with an energy value ranging from 21 to 28 MJ m^{-3} (Doble et al. 2004).

Although the concept of chemical synthesis from natural renewable resources is still in its early stages, the conversion of biomass feedstock into biofuels has the potential to be both economically and environmentally beneficial (Gavrilescu and Chisti, 2005; Willke et al. 2005; Chisti 2007). Several corporations (e.g., DuPont) have begun to manufacture their products using renewable resources (Willke et al. 2005). Traditional ways of producing fine compounds have resulted in serious environmental issues. Environmental groups conducted research to examine two production processes: chemical and biotechnology. It was discovered that the biotechnological method (e.g., vitamin B_2 production process) is more cost-effective and efficient. Biotechnological techniques have been discovered to cut the cost of producing riboflavin by 50% (BIO–PRO 2008). The development of steroid drugs for arthritis is based on the hydroxylation of steroids by microorganisms (Dutta and Samantha 1997). Six-aminopenicillanic acid is a critical step in the synthesis of penicillin's used in chemotherapy (6-APA). The biological synthesis of aminopenicillin acid (6-APA) was shown to be 20% cheaper than the chemical.

11 Biotechnology for Sustainable Future

Human life hinges on the environment, and organisms need it for survival. The physical environment's protracted sustainability reveals how affluent a civilization is and if everyone is well-off. Nearly every day, disposing of hazardous substances is still a huge task. Minimizing waste output and maintaining a good balance between esthetics and health are the greatest ways to sustain the environment. An analysis of existing biotechnological technologies is used to investigate biological aspects of environmental sustainability. Environmental biotechnology is providing significant advancements in remediation technology which might help to reduce waste discharge from industrial operations. These technologies will also develop goods that will aid in the prevention of waste discharge. Using microbial communities or simply enabling microorganisms and plants to breakdown these wastes as safe metabolites, biotechnology has well been for converting toxic waste and pollutants into valuable by-products (Ghahari et al. 2021).

Karl Rekey used the word "biotechnology" to describe this type of progress. Environmental biotechnology is associated along with the development of products and services that assist people or offer technical assistance for them via the use of biological systems. Additionally, it exerts a significant influence on a number of technologies, including manufacturing, food production, environmental protection, agriculture, pharmaceuticals, and resource preservation. At the beginning of the twenty-first century, environmental biotechnology was seen as the foremost important technology for protracted environmental preservation. Long-term environmental management and conservation can be achieved through the use of environmental biotechnology, for example, by using living organisms to clean up polluted areas (Fahmideh et al. 2014).

Emerging concern about previous economic development patterns' lack of environmental sustainability, as well as increased awareness of the possibility of a future climate crisis, has made it evident that the environment and the economy could not long be studied in isolation. Simultaneously, the financial and economic outbreak has acted as a catalyst for policy reforms targeted at promoting recovery and more sustainable growth (Singh and Singh 2017).

Environmental sustainability is one of the most significant challenges that mankind is now facing. The globe's land resources are in danger due to the rapid and widespread industrialization and urbanization. In addition to correcting current practices, we should use natural methods to restore contaminated natural resources in order to maintain our world as a viable ecosystem and a sufficient habitat for future generations. Waste reduction, energy recovery, biomass recycling, and the development of resource-efficient production methods can all benefit the environment (Dervash et al. 2020).

Sustainable development is defined as an increase in human well-being that can last for multiple generations as opposed to a short period of time. The World Commission on Environment and Development defines sustainable development as "meeting present demands without compromising the ability of future generations to satisfy their own needs." Sustainable development requires a framework for combining environmental policies and development strategies in a global perspective. Together, the social, environmental, and economic advantages contribute to the development of a society that is more sustainable. Compared to conventional manufacturing, sustainable processes and systems should be more profitable because they utilize less energy and resources inefficiently, which reduces emissions of greenhouse gases and other pollutants and allows for a greater and more effective use of renewable resources, resulting in less reliance on nonrenewable resources (Ghahari et al. 2021).

Environmental biotechnology has enhanced the potentials for pollution prevention, solid waste and wastewater treatment, producing goods of fewer pollution or fewer raw materials, environmental health monitoring, and genetic engineering for environmental protection and control, as well as holding commitment for more development of bioremediation. Environmental biotechnology can also be utilized to minimize toxicity by bioimmobilizing hazardous wastes, generate biodegradable materials for environmental sustainability, manufacture fuels from biomass and organic wastes, and prevent hazardous waste creation by using biotechnological analogues. The design, process optimization, and cost minimization of a biotechnological application determine its efficiency (Singh 2017).

12 Conclusion

There are reportedly hundreds of environmental issues in the globe, and more and more new ones are always emerging. While numerous known technologies continue to gain foothold in actual use, new ones are always being created. A technology that can make use of plants and bacteria's strength and eco-efficiency is needed in a variety of real-world situations. Biotechnology is leading the charge and will continue to contribute significantly to the production of environmental protection, food, renewable materials, and bioremediation, along with a vast array of other technologies to achieve the objectives of sustainability. Creating effective methods, clean processes, and low-impact products over the long run requires environmental biotechnology. Biotechnology's environmental and economic benefits in production, monitoring, and waste management are counterbalanced by technological and economic issues that must be addressed. All of this is accomplished while minimizing environmental effect and increasing long-term viability. Both politicians and the industry benefit from an understanding of the repercussions, opportunities, and problems of modern biotechnology (Manzoor 2020). The sustainability of the environment is among the most important concerns confronting humanity. Excessive and uncontrolled industrialization has put tremendous strain on natural resources. To restore our world a healthy environment that is livable for future generations and provides equitable chance for all living things, we must not only adjust but also rehabilitate degraded natural resources. Low-input biotechnology approaches combining bacteria and plants may hold the key to reviving ecosystems. To ameliorate the state of contaminated soil and water bodies, bioremediation and biodegradation can be applied. To tackle pollution and global warming, green energy based on biofuels must replace fossil fuels. To ensure the sustainability of agroecosystems, biological substitutes (bioinoculants) must be used to replace toxic chemicals. It is obvious that all biotechnology developments are contingent on adequate laboratory and institutional support. It is envisaged that this new method of material production will be environmentally beneficial and will not harm the environment (Mishra et al. 2019).

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Chapter 35
Fungal Nanobionics: Principles and Applications in Environment

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Abstract Because of numerous applications of nanoparticles, nanotechnology is a rapidly emerging subject for biotechnology field. Environment friendly techniques for developing nanoparticles (NPs) offer various benefits, including more surface area, potent catalytic activity, and the ability to put the metal salt and enzyme into optimal contact. Among many protocols of developing NPs, mycoproteins, enzymes, and reducing agents may be used to synthesize metal NPs from metal salts. In recent years, scientists have investigated the intracellular and extracellular chemistry of fungi which is helpful to produce metal NPs. Metal NPs have garnered considerable attention due to their cytotoxic effect on cancer cell lines and their potential as an antibacterial agent to inhibit the development of dangerous pathogens. Several research studies have examined the possibilities of metal NPs in health care, pharma, and agriculture. To recover contaminated environments, scientists may use bioremediation; however, this is not guaranteed to be successful. Nanoparticles may be effective for bioremediation because they have a lower toxicological impact on microorganisms and can boost the biological activity of the materials. Mycoremediation is often studied because it is a way to clean up polluted areas by using NPs to neutralize dangerous chemicals.

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1 Introduction

Fungi, a diverse and abundant kingdom of eukaryotes, are used in several biotech applications. About 5% of the 1.5 million species in this kingdom includes are known to science (Hawksworth 2001). Hyphal forms, which are tubular and polarized cells, can continually grow whereas yeast forms are solitary and small cells; these are the two main types of fungi (Sievers et al. 1999). The hyphae have diameters of 2–10 m and lengths of just a few centimeters. The multinucleated portions of these cells may be coenocytic (connected by pores) or septate/septa (separated by walls). When these hyphae divide and re-divide, they can produce then complex networks of mycelium (Mcconnaughey 2014). There are several interconnected matrices inside the organelles found in the fungal cytoplasm: the cell wall, plasma membrane, and extracellular or capsular matrix are all linked matrices. There is a mucilaginous substance in the extracellular matrix that helps in cell growth. Nanotechnology is a rapidly expanding field that spans several disciplines and focuses on the manufacture of nanometer particles comprising a wide variety of materials (Cotica et al. 2018). Many science disciplines, such as applied physics, chemistry, environmental studies, mechanics, electrical and biological engineering, robotics, and medicine, have all benefited greatly from this field of study. Food preservation and efficient use of water resources are just a few examples of the numerous issues that may be ameliorated by the use of this technology in agriculture (Baruah and Dutta 2009; Lodhia et al. 2010; Prasad 2014; Bera and Belhaj 2016; Parisi et al. 2015; Sangeetha et al. 2017).

1.1 Nanotechnology

Nanotechnology is the study of novel applications for material (organic and inorganic) nanoparticles (NPs). A nanoparticle in measuring is 10^{-9} m in size that displays autonomous behavior with respect to its physical properties and its mode of action (Mukherjee et al. 2010; Gholami-Shabani et al. 2016). In nanotechnology, a particle extremely small in size has the characteristics and behaves as a single entity throughout its entire journey. Although nanotechnology may appear like a cutting-edge breakthrough, NPs really have a lengthy history. In the ninth century BC, Mesopotamian potters used NPs to give their works a glimmering effect. Amazing red coloration was achieved in late Bronze Age glasses made in Rovigo, Italy, thanks to surface Plasmon resonance of copper NPs (Angelini et al. 2004; Lee et al. 2013). Glasses with a coating of copper crystals were made in the ancient period by subjecting the material to reducing conditions. Nanoparticles of copper and gold were also widely used throughout the Roman Empire (Amin et al. 2011). The famous Lycurgus Cup of ancient Rome is one example of such an artifact (Kreuter 2007; Ueda et al. 2014; Bulte and Modo 2017). The cup itself had a greenish-yellow color, but when illuminated from inside, it took on a deep crimson hue. Colloidal metal and nanocrystals often a silver–gold alloy, dispersed throughout the crystalline substrate produce an observable color shift (Barber and Freestone 1990). As NPs, whether they are made naturally, synthetically, or biologically, have a great potential for the betterment of humanity in a broad variety of fields and businesses, such as medical, pharmacology, genetic engineering, agriculture, commerce, and environmental cleaning. From a remediation standpoint, nanoremediation is a rapidly expanding field of nanotechnology. It is now being deployed in 44 sites throughout the world. Since this method works for toxic chemicals in any setting, a wide range of NPs can be used to fix the issue in quickly and sustainable way.

1.2 Nanotechnology and Environment

Nanotechnology has become a subject of extensive research and practical use in environmental sustainability. Given the growing number of environmental problems, one of biotechnology's primary priorities is environmental decontamination and preservation. This may be observed through bioremediation by employing microorganisms like fungi or their enzymes to break down hazardous compounds into less harmful ones. By combining nanotechnology, it may be possible to make bioremediation systems that are good for the environment.

1.3 Nanomaterials

A nanomaterial is defined as a material with at least one dimension on the nanoscale. When evaluating different systems, the "Nano" scale is an essential factor to consider. Nanomaterials are even smaller than atoms, while microbes are much larger. Because their properties (optical, magnetic, electrical) may be altered in response to environmental stimuli, these substances are used in a wide range of technical products, instruments, and gadgets. From the Stone Age to the Bronze Age and then to the Iron Age, humans had control over a wide range of valuable materials. This shows that these changes were necessary for survival (Sengupta and Sarkar 2015).

As a consequence of modernity's fast development, globalization, and technical achievements, new fields of study have emerged, such as "Nano Science and Nanotechnology". The study of materials with dimensions in the nanoscale range has expanded the boundaries of traditional academia and industry (Sengupta and Sarkar 2015). Nanomaterials, as a cross-disciplinary technology drawn from physics, chemistry, biology, medicine, and nanobiotechnology, offer many ways in which nanotechnology can be applied.

1.4 Nanoparticles

Nanotechnology provides a new trend in the creation and control of nanometer-sized features in materials and technologies across a wide range of industries, including the food, cosmetic, personal care, pharmaceutical, medical device, agricultural, and environmental sectors (Prasad et al. 2014). However, a major emerging problem in nanotechnology is enhancing the technique's potential for producing safe and cost-effective synthetic NPs or nanocomposites with dimensions smaller than 100 nm (Thakkar et al. 2010). The physical characteristics of a substance in bulk do not change significantly based on its size (Husen and Siddiqi 2014). However, when present as nanoscale particles, they undergo specific variations in their electric, magnetic, optical, and chemical characteristics due to changes in size and shape (Castro et al. 2014; Chan and Don 2013). Silver and gold are two of the metals that have garnered the greatest interest because of their possible use in the beauty and pharmaceutical industries (Schröfel et al. 2014). To increase the effectiveness of other antimicrobial compounds, silver nanoparticles (Ag-NPs), which are generally accepted to be safe, function by increasing the formation of reactive oxygen species like hydrogen peroxide (Deepak et al. 2011). Therefore, they may function as antimicrobial agents, lowering the risk of infection from pathogens during surgery and helping to battle the issue of antibiotic resistance in microbes. Recent studies have demonstrated that Ag-NPs have anti-inflammatory, antiangiogenic, and antipermeability properties (Zare et al. 2012; Schröfel et al. 2014; Park et al. 2016), which make them valuable for the health-care business. Several reports have shown that gold nanoparticles (Au-NPs) may be effective in the treatment of cancer and bacteria, in addition to a variety of skin disorders (Schröfel et al. 2014; Zare et al. 2012; Li et al. 2011; Srivastava and Constanti 2012). Due to technical advances, Au-NPs with unique optical, electrical, and photo thermal capabilities and high stability have been developed, and they have found use in medical diagnostics and health care (Shedbalkar et al. 2014; Yang et al. 2006). In addition to silver and gold nanoparticles, the techniques that are good for the environment have been used to make platinum, magnetite (Fe_3O_4), zinc oxide (ZnO), and cadmium (Cd) NPs (Ding et al. 2015; Mirzaei and Darroudi 2017; Bharde et al. 2006; Velusamy et al. 2016).

2 Development of Nanoparticle

Historically, NPs have been synthesized using conventional physicochemical techniques. The fact that these technologies leave postprocedure residues that are very harmful to humans and their disposal causes massive environmental damages that is a major drawback. These procedures also required the use of complex apparatus and enormous contents of energy, which limit their applicability (Enshasy et al. 2018; Pantidos and Horsfall 2014). Wet technology refers to newly established approaches for NPs developments that make use of biological systems like plants and microbes. Many benefits, such as low cost, great energy efficiency, and the manufacturing of nontoxic and greener NPs, distinguish this procedure from the traditional physicochemical approach. Significantly, NPs' stability and optical characteristics, such as Plasmon resonance (Mock et al. 2002), antibacterial effects (Wani and Ahmad 2013), and catalytic capabilities, may all be modified by tailoring their size, shape, composition, and morphology using this wet technique (Zhou et al. 2010).

2.1 Eco-Friendly Production of Metal Nanoparticles

An emerging demand exists for environmentally safe manufacturing of NPs and the synthesis procedures do not require the use of toxic organic compounds due to the expanding use of metal nanoparticles in human health–related areas (Shams et al. 2013). The primary disadvantages of physicochemical synthesis of NPs are mainly the slow production rate, structural particle deformation, and impediment to particle growth. Thanks to the adaptability and usefulness of nanotechnology, we can now produce Ag-NPs with precisely specified and controlled features. The two most common approaches to develop NPs are known as the "Top-Down" and "Bottom-Up" approaches, respectively. To synthesize nanoscale materials in bioprocessing conditions that include stabilizers and optimal temperatures, exposure times, and pH with the appropriate metal ion, the "Bottom-Up" method makes use of a homogeneous system where catalytic agents, such as reducing agents and enzymes, can control catalytic activity (Oza et al. 2012; Iravani 2014; Das et al. 2014). The morphology, surface chemistry, and physicochemical properties of the resulting nanoparticles are all influenced by the initial precursor concentrations and reaction circumstances (Mason et al. 2012). The "Top-Down" technique for synthesizing nanoparticles, on the other hand, often makes use of the material in bulk form by subjecting it to targeted physical, chemical, or combination treatments to reduce its size to nanoscale. Physical treatments such as lithography, thermal decomposition, laser ablation, mechanical milling, etching, and sputtering that cause breakdown of silver compounds are not recommended normally due to the high energy they require. There is no evidence that aided by radiation, electricity, sound, or microwaves are any more efficient than those that rely solely on these natural mechanisms (Varshney et al. 2009; El-Nour et al. 2010; Elzatahry et al. 2012). Chemical reduction is therefore the most common synthetic route for creating NPs of the metals (Pal et al. 2011; El-Faham et al. 2014). Ag-NPs can be made positively charged by reacting with branched polyethyleneimine, formaldehyde, alkali metals in ammonia, borohydrides, ascorbic acid, free radicals, mono-alcohols, polyols, acetonitrile, hydrazine, citrate, or ethylene diamine tetra acetic acid, and negatively charged by reacting with ethylene diamine tetra (Varshney et al. 2009). Thakkar et al. (2010) say that the main problem with chemical and physical synthesis is that the surface does not have enough structure. This may affect the surface chemistry and physical properties of nanoscale materials in terms of the ratio of surface area to volume.

2.1.1 Top-Down

Many of the reducing agents, solvents, and additives employed in the reduction process during "Top-Down" NP production offer significant environmental and biological concerns, rendering the resulting nanoparticles unfit for human use. Since the synthesis of nanoparticles on a wide scale presents unique challenges, it is essential that ecologically friendly, nontoxic precipitation procedures be devised. Varshney et al. (2009) stated that physicochemical techniques also include slowing down the rate of production, changing the shape of particles, and stopping the growth of particles.

2.1.2 Bottom-Up

Due to the relatively limited possibilities of water-soluble precursor chemicals in the "Bottom-Up" process, most efforts to generate nanoparticles via green synthesis by microorganisms concentrate on choosing capping and reducing agents, which are the metabolites formed by the bacterium and the cell mass itself. To improve the NPs optical properties, this concentration is primarily intended to facilitate the synthesis of homogenous NPs with known sizes and shapes. This is important for optical, medical, and electrical devices, as well as for the chemical and biological industries (Suresh et al. 2010; Gurunathan et al. 2014; Prasad 2014).

2.2 *Biosynthesis of Nanoparticles by Fungi*

Decomposer organisms, or fungi, are common eukaryotic creatures thanks to their ability to secrete extracellular enzymes that hydrolyze complex macromolecules. Metallogenic fungi have attracted a lot of interest as a source of NPs for bioprocesses because of their unique metabolic capabilities and widespread applications (Dhillon et al. 2012; Jain et al. 2015; Parisi et al. 2015; Prasad et al. 2016; Bhargava et al. 2016; Kitching et al. 2016). Their metabolism may either directly contribute, as in the case of on-cell/intracellular nanoparticle generation, or indirectly, as in the case of secreted metabolite-mediated extracellular nanoparticle synthesis (Jain et al. 2011; Bhargava et al. 2015). Therefore, metal NPs may be either nano- or meso-structured, depending on the production method, the intra- or extracellular reducing enzymes, and the biomimetic mineralization. The potential for metal bioaccumulation and cell tolerance are also factors to consider (Sastry et al. 2003; Kitching et al. 2016). Isolated fungal strains from metal-rich habitats are well suited for this purpose (Jain et al. 2013).

3 Nanofabrication

The process entails modifying the surface of nanoparticles and giving them a certain shape and size. Bottom-up and top-down nanofabrication methods are both feasible. The bottom-up approach, also known as the "atomic layer deposition" or "molecular layer cluster growth" technique, is used to precisely construct nanomaterials. Here, the "bottom-up" technique is used to precisely direct and control the synthesis process. The bulk of chemistry is produced using a bottom-up method. The concentration ratio of components, chemical kinetics, and other physical features must be optimized for the production of homogenous, desirable nanoparticles. In the top-down method, the bulk of nanomaterial is sliced or etched to the desired dimensions. Traditional lithography is the impetus behind the top-down method. Nanoparticles can only serve their purpose if they have been engineered to have certain characteristics. The top-down approach is very important because it helps to redefine the nanoparticle and makes it acceptable for its intended purpose. In many different ways, nanoparticles are used in many different ways, and to get the right shape and size, both bottom-up and top-down methods are used.

Fungal NPs are produced either in the fungal cell's extracellular or internal environment by a bottom-up process. Metal NPs, or multisized and shaped s are a kind of biological material. If the uncontrolled or semi-controlled creation process of myconanoparticles is not interrupted, the particles tend to expand in size. Depleting myco-NPs from a fungal extract or culture is the simplest way to halt myco-NPs production. In addition to the compounds required for myco-NPs, the fungal cell/extract includes a plethora of additional substances. After being extracted, it is not required for NPs to still have the chemicals needed to produce them. For this reason, it might be challenging to determine which specific materials are needed to synthesize certain NPs. Therefore, it is challenging to locate NPs that are homogeneous in shape and size, both of which are essential for their large-scale practical application. The problem may be fixed by making the changes in the nanoparticles at the top side. The etching may be as harsh as you want or as gentle as you like. The optimized device could have full control over the etching process, making it possible to make nanoparticles that are exactly the right size and shape.

3.1 Nanoscale Deposition

A variety of techniques are utilized in order to cover monolayer or multilayer surfaces with nonreactive or functional materials, including evaporation, sputtering, chemical vapor deposition, and electrochemical deposition. When just certain areas of a surface are to be etched, the value of deposition rises. When working with the nanoparticles, it becomes sometimes necessary to etch one end, while on other times, it is necessary to shield that end from etching. So, deposition at the nanoscale is performed as needed to get nanoparticles with the right shape and size.

3.2 External Functionalization

Many different approaches to surface modification may be used for nanofabrication. Effective interaction between the modifier and the substrate surface, which is governed by the surface bonding chemistry, is crucial to nanofabrication processes. One must take into account a number of factors in addition to a surface's hydrophilicity or hydrophobicity. Several depositions are generated as necessary to prevent etching or corrosion of the surface. Spin-coating and vapors deposition are often employed to create surface layers that are thicker than a monolayer. It is possible to alter multilayer surfaces using processes such as diazonium reduction, electro polymerization, and the painstaking deposition of molecular and atomic multilayers (Stepanova and Dew 2011). Nanometer-thick, highly conformal, and hole-free sheets may be made using this technique. This strategy has several applications outside of display technology, such as in the manufacture of integrated circuits, solar cells, catalysis, etc. Low-temperature deposition of oxides and nitrides, as well as metal deposition, is also possible using plasma-enhanced atomic layer deposition. When the geometry is complicated, atomic layer deposition nevertheless creates ultra-thin films effectively (Kim and McIntyre 2006; Foroughi-Abari and Cadien 2012). Excellent adhesion, repeatability, and broad-area homogeneity are also provided by the self-limiting growth. Leskelä and Ritala (2002) found that the atomic vapor deposition (AVD) method has a fewer flaws because the process temperatures are lower and there is no gas phase nucleation.

4 Toxicological Effects

4.1 Potential Hazards of Metal Nanoparticles

In view of their small size, generally, NPs are dangerous to humans and also cause a wide scope of gastrointestinal, cardiovascular, and respiratory problems through the foundational course, and then through the olfactory pathway of axons in human blood mononuclear cells. Shin et al. (2007) have also demonstrated cytotoxicity (Hussain et al. 2006) to collect inside human organs such as the testicles, lungs, liver, kidney, mind, and stomach (Kim et al. 2008).

NPs of zinc oxides (ZnO) are widely used in beauty care products, and people are exposed to those nanoparticles through oral, dermal, and inward breath every day in antimicrobial coatings for food holders for 14 days (Sharma et al. 2020). Hence, security evaluations ought to be considered before items containing nanoparticles are given endorsement.

4.2 Cytotoxicity

In recent years, a huge assortment of nanomaterials has been assessed to achieve better viability in malignant growth treatment as well as to lessen incidental effects compared with customary treatments. In recent years, the harmful effects of contagious nanoparticles have been measured mostly by changes in metabolic movement and the shape and function of mitochondrial cells (Li et al. 2005).

Oxidative stress, primary and secondary damage are caused by the confinement of NPs. The observed damage to the mitochondrial functional utility may affect the mitochondrial respiratory chain, which in turn affects the metabolic restraint of the cell. The size, shape, and potential for fictionalization of the surface are discussed by experts in nanoparticles. Their physical and chemical characteristics largely determine NP cytotoxicity (Li et al. 2005). It has been demonstrated that particles between 20 and 50 nm diffuse more quickly than particles larger this size, and productive masking has been observed with these sizes (Iram et al. 2016). Because they are so small, nanoparticles can get into pores, move around the nucleus, and bind to certain response elements. In any case, the use of bioreactors to grow cell, tissue, organ, and woody root cultures on a large scale has only covered a small number of secondary metabolites (Weathers et al. 2010).

5 Applications of Nanobionics

5.1 Environmental Nanocomposites

In the field of environmental science, nanotechnology has been extensively investigated and applied. This “new” research subject, when combined with existing fields of knowledge, has the potential to considerably contribute to new environmental discoveries and applications. As it is clear (Kango et al. 2013), nanotechnology has the potential to significantly enhance both human health and environmental protection. This integrative science has changed the basic sciences and how they are used (Lodhia et al. 2010). This includes applied physics, applied chemistry, mechanics, biological and electrical engineering, robotics, and medicine.

Environmental decontamination may be accomplished by the use of microorganisms such as fungi and their enzymes. Breakdown of toxic chemicals into innocuous ones is one of the primary concerns of biotechnology as environmental challenges become more prevalent (Yadav et al. 2015). Bioremediation is a sustainable way to clean up areas that are contaminated with harmful metals and organic compounds that are hard to break down (Purohit et al. 2018).

Despite the low price and ease of acquisition, they produced vast volumes of biomass that may be genetically and morphologically altered. There are several species that have been used to detoxify environmental toxins (Kaushik and Malik 2009; Fu and Wang 2011). According to Ryan et al. (2005), one benefit of the fungal process is the enzyme-mediated activities that are generated during the whole fungal life cycle and may be seen even at extremely low levels of pollutants. In terms of manufacturing extracellular enzymes, fungal mycelia have an advantage over eukaryotes by solubilizing the insoluble and having a greater physical and enzymatic interface with the environment owing to a larger cell-to-surface ratio. Because it is outside of the cells, a mycozyme also helps the body deal with high doses of toxins (Kaushik and Malik 2009). Fungi remove color from the environment through biosorption, bioaccumulation, and biodegradation (Kaushik and Malik 2009; Varjani and Patel 2017; Varjani et al. 2018) and even in minute quantities, it is very dangerous and undesirable in effluents (Saharan et al. 2014).

5.2 Eradication of Heavy Metals from Soil–Water Surface

Heavy metals are constantly leaked into the soil groundwater, contributing to another environmental issue. Due to rising discharge, environmental effects, acute toxicity, nonbiodegradability, and a tendency to bioaccumulation, all of which are generated by a variety of sources including industrial and agricultural activities as well as mining, these metals have long been a reason for worry (Gupta et al. 2010; Feng et al. 2010; Xu et al. 2012). Lead's toxicological and neurotoxic effects on the liver, kidney, brain, and central nervous system are well known among heavy metal poisons (Southichak et al. 2006; Xu et al. 2012). Due to the lack of economical treatment alternatives and the great resistance and persistence of heavy metals in the environment, their removal from the ecosystem has become one of the most important environmental issues. Consequently, the pursuit of more stringent wastewater treatment has stimulated the development of traditional treatment approaches (Gupta et al. 2010). Because they have a lot of functional groups, fungi can hold on to heavy metals all the way through the process of getting rid of them (Cheng et al. 2015).

According to several research studies found in the literature, iron oxides (FeO, Fe_2O_3) are used in the study of magnetic NPs for biological purposes (Huang et al. 2015; Ding et al. 2015; Su 2017). Iron oxide NPs, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_2O_3), have been used for the separation and removal of organic and inorganic contaminants because of their low cytotoxicity and high biocompatibility (Yang et al. 2006; Hafeli and Chastellain 2006). According to Xu et al. (2012), iron oxide NPs are excellent biosorbents for the removal of heavy metals and organic pollutants. In addition, a number of studies demonstrate how customized magnetic NPs may be utilized to remove various colors (Saharan et al. 2014; Kaur et al. 2014; Tan et al. 2015). Therefore, combining nanotechnology with other types of particles and organisms, such as fungi, may potentially result in bioremediation solutions that are environmentally beneficial. Rispail et al. (2014) found that *Fusarium oxysporum* hyphae are capable of interacting with nanomaterials. Several studies have shown that the fungus is not very harmful to different nanomaterials.

As seen by the deterioration of the quality of the soil and water, nanobiotechnology may be used to solve challenges that have reached catastrophic proportions due to human activities (Kunz et al. 2002). Another use is for locations polluted by dyes, heavy metals, or radioisotopes, which may cause harm to human health and the environment, as well as impair soil and water quality. Technological advances in nanocatalysts, nanobiocomposites, and bioactive NPs (Tratnyek and Johnson 2006; Karn et al. 2009) have been added to methods and processes for cleaning up and keeping an eye on chemical waste-contaminated systems.

5.3 *Nanocomposites in Agriculture*

Pesticide use has been detrimental to agriculture for decades. The accumulation of pesticides across the food chain has negative consequences on land and water. Certain pesticides have been linked to hormone problems, an increased risk of cancer, impaired immunological function, and abnormalities in several terrestrial and marine organisms (Prasad et al. 2014; Parisi et al. 2015). Additionally, more plants and insects are growing resistant to these pesticides (Rai and Ingle 2012), resulting in plantation losses and billions of dollars in damage (Rai and Ingle 2012). The agricultural sector is confronted with issues such as climate change, urbanization, and the unsustainable use of natural resources (Gordon and Waterhouse 2007). The increasing food consumption necessary to sustain population growth from the current level of around six to nine million people by 2050 exacerbates these problems (Chen and Yada 2011).

Agriculture has benefited from genetics and nanotechnology since it is now feasible to program DNA structures via the use of nucleic acids and metal NPs. Their structural characteristics may have specific applications, affording nucleic acids additional possibilities (Mohri et al. 2014). By mixing genetic material with metals NPs, a unique approach for transferring DNA to insects may be developed. Khandelwal et al. (2016) illustrate the practicality and safety of employing nanotechnology to transfer genetic material. It is also a simple way to get rid of pests because it stops transgenic plants from growing. The so-called nanosensors are one of the uses of nanotechnology in the agricultural industry. They can detect nutrient and water levels, allowing them to better protect crops with pesticides, fungicides, and herbicides (Cotica et al. 2018). It is feasible to detect low levels of pathogens, and chemical compounds may be broken down (Baruah and Dutta 2009). These nanosensors might be used to discover techniques for eliminating persistent pollutants. Due to the many challenges associated with the use of pesticides in agriculture, nanotechnology has the potential to fundamentally revolutionize this industry, since it may be used to improve the quality of life for people. As an example, the application of this technology has contributed to the promotion of sustainable agriculture and improved food quality, hence lowering community dangers (Rai and Ingle 2012; Prasad et al. 2017).

Nanoencapsulation is a further use of nanotechnology in agriculture. Currently, it provides the greatest opportunity for detecting pest insects on hosts. The use of pesticides and herbicides that may be coupled to nanoparticles to target specific parts of a plant, such as the cell wall, cuticle, or a particular tissue, while minimizing side effects, may dramatically affect the "smart" supply of important nutrients to plants (Cotica et al. 2018; Nair et al. 2010; Bhattacharyya et al. 2016). In biotechnology, viral nanocapsules are seen as powerful weapons because they can contain nucleic acids that stop weeds from growing or change how they use energy (Ghormade et al. 2011; Pérez-de-Luque and Diego 2009).

According to Prasad et al. (2014), some of the nanoparticles found as plant disease controllers are made of carbon, silver, silica, and aluminosilicates. In this case, the sheer abundance of materials used by nanotechnology has astonished the scientific world. The growing use of silver particles as antibacterial agents is a result of developments in synthesis technology that have decreased the cost of production. For example, the *Xanthomonas perforans* bacterium is responsible for the bacterial stain on tomatoes, which causes substantial food damage. Ocsoy et al. (2013) used silver nanoparticles as a treatment, which helped the disease a lot.

Furthermore, silver NPs have been utilized to control *Blaberus discoidalis*, a neotropical cockroach. According to this study, the presence of silver NPs in the cockroach's central nervous system caused changes in motor performance. Soni and Prakash (2012) used the fungus *Chrysosporium tropicum* to make silver and gold NPs to kill mosquito larvae (*Aedes aegypti*). The treatment was more helpful when gold nanoparticles were utilized, according to the results. In comparison to the silver NPs treatment, larvae mortality increased by almost three times. In conclusion, when compared to traditional insecticides, nanoparticle-based insect treatments result in higher mortality. In addition, when the number of NPs used in the therapy grows, insect mortality also rises.

6 Mycoremediation

6.1 Biosensors in the Soil

The identification of pollution sources is a crucial aspect of pollution prevention. There are a variety of methods for detecting pollution, but they are either time-consuming or insufficient for providing significant information on the composition and behavior of pollutants in real-world settings. Today, nanotechnology plays a vital role in the detection of toxins by enhancing the precision and sensitivity of environmental monitoring sensors. This might be accomplished by concentrating on the attachment of the contaminant-recognition element or by enhancing the propagation and electrical connection to the sensing layer. A sensor may be used in order to detect anything. Organic pollutants, inorganic pollutants, and microbes may all be classified as contaminants. Quantum dots, a method for fluorescent labeling, are used in a broad range of applications. As described by Zhu et al. (2004), antibody conjugation to quantum dots may be used to identify dangerous bacteria such as *Cryptosporidium* and *Giardia*, as well as *Salmonella*, *Escherichia coli*, and *Staphylococcus endotoxins*. Quantum dots are more photostable than organic dyes and may be employed in multiplex analysis. As a result of the vibrant hues they create, they may also aid in the diagnosis of diseases (Liu et al. 2007). Using silica nanostructures, insecticides, such as gold and silver nanoparticles, and heavy metals, such as lead, mercury, and cadmium, have been identified. Sugunan et al. (2005) functionalized gold nanoparticles with chitosan and 11-mercaptoundecanoic acid for the detection of heavy metal ions such as lead, mercury, and cadmium. Chelation of metals by chitosan and mercaptoundecanoic acid initiates the attachment of heavy metal ions to these metal chelators leading to an aggregation of the metal nanoparticles is triggered, resulting in a shift in wavelength absorption and a change from red to blue color. In general, the detection of heavy metals was rather sensitive, but it lacked accuracy for a particular ion. Liu and Lu (2004) created a lead detection sensor by coating gold nanoparticles with a lead-dependent DNA enzyme. Combining the remarkable optical properties of gold nanoparticles (Au-Nanoparticles) with the inherent advantages of microfluidic systems should enable the detection of ziram [zinc bis dimethyldithiocarbamate], a broad-spectrum fungicide belonging to the dithiocarbamate (DTC) family of insecticides (Lafleur et al. 2012). SnO_2 and In_2O_3 are two metal oxides that have sensing application potential. Depending on crystallite size and other variables, SnO_2 may be sensitive to reducing gases (such as CO) during manufacture, while In_2O_3 may be sensitive to oxidizing gases (e.g., NO_2). SnO_2 and In_2O_3 were deposited without the use of an adhesive or activation in order to examine the sensing capabilities of the nanocrystals in their native state. SnO_2 and In_2O_3 have powerful capabilities in chemical transformations, biosensing, and bioremediation due to their selectivity and enzyme-targeted specificity (Duran and Esposito 2000). Similarly, the production of microbial enzymes might stabilize them. Several nanometer-sized, enzyme-cantered nanoparticles exhibit an organic/inorganic porosity network (Kim et al. 2006).

6.2 Environmental Pollutant Cleansers

Although NP-based materials are a relatively recent occurrence, the concept is ancient. While their bulk chemical composition may be the same, their nanoscale sizes, high surface-to-volume ratios, and the presence of quantum phenomena may cause them to act quite differently (Yan et al. 2013). For instance, titanium dioxide (TiO_2) has been widely used as a white pigment in opaque paintings, for instance. In contrast, the small TiO_2 particles let visible light flow through them (wavelength 400–800 nm). Due to their high combustibility, aluminum nanoparticles may be used as rocket fuel. Aluminum in its bulk form is nonhazardous. At lower pH levels, hematite particles with a diameter of 7 nm absorb more Cu ions than particles with a diameter of 25–88 nm. This is only one example of how particle size affects the surface reactivity of iron oxide particles (Madden et al. 2006). Because their ratio of surface area to mass is greater than that of larger particles, nanomaterials may be excellent for use in environmental cleanup, because they react with chemical and biological agents more rapidly than larger particles (Hochella et al. 2008). In a number of regions throughout the globe, it has been reported that zerovalent iron (ZVI) is used in reactive barriers to filter out organic and inorganic impurities (Fu et al. 2014). Wang et al. (2014) show that ZVI is a powerful dechlorinator of a variety of halogenated hydrocarbon compounds. The deterioration is caused by redox processes in which iron donates electrons to pollutants, therefore reducing their toxicity. In addition, ZVI may diminish nitrate, selenite, perchlorate, arsenate, arsenate, and chromate concentrations (Fu et al. 2014). Nanoscale zerovalent iron (nZVI possesses a greater sorption capacity than granular iron and a 25–30 times quicker reaction rate in the micrometer to millimeter range (O'Carroll et al. 2013). nZVI particles have much greater surface areas relative to their masses, and they may be 10–10,000 times more reactive than larger granular iron powders. nZVI spontaneously combusts in the presence of oxygen. Granular iron reacts slowly with oxygen gas, so it oxidizes slowly on its surface.

6.3 Soil and Water Remediation

Green remediation techniques based on adsorption or reaction may be characterized as either in situ or ex situ (Table 35.1). Research on nanomaterials has been conducted in each of these environments. In situ solutions for restoring soil and water are typically the most promising since they are less costly (Hodson 2010). It is necessary to develop either a stationary in situ NPs-rich zone or a reactive NPs plume that may be directed to contaminated areas for in situ treatment. Normal agricultural practices, such as applying topsoil to contaminated soil, may result in the release of metallic NPs to the earth's surface. Even though reducing soil pollution might affect groundwater quality and vice versa, not much has been said about cleaning topsoil with metal NPs. Metals and chemicals known to cancer may have polluted land and water on a global scale. In groundwater, insecticides and halogenated compounds are prevalent. Agriculture, chemical mishaps, and seepage from landfills are the primary sources of these poisons. Some of the most common ways

Table 35.1 Classification of bioremediation approaches involving nanoparticles

Activity	In situ	Ex situ
Adsorptive	Binding agents, such as iron oxides, are added to the environment to capture contaminants.	Extracting a tainted solution and then treating it with adsorbents is a process that is similar to nanofiltration
Reactive	In-site reaction of a nanomaterial like nZVI with the target pollutant	After a dirty solution is extracted, it is treated with reactants, like in the TiO_2 photo oxidation process

Table 35.2 Samples of the use of nanoparticles in bioremediation

Process used	Nanomaterials are employed	Objective compounds
Photo catalysis	TiO_2	Organic contaminants
Adsorption	Iron oxides, dendrimers	Metals, organic compounds, and arsenic
Redox reactions	Nanoscale zerovalent iron (nZVI), nanoscale calcium peroxide	Halogenated organic complexes, metals, nitrate, arsenate, oil

to clean up a site are to clean the soil and use pump-and-treat, iron treatment, and in situ heat treatment (Hodson 2010).

The restoration of groundwater and soil is often very expensive, and common treatments are either ineffective or take a long time to become effective. According to Bezbaruah et al. (2009), pump-and-treat operations take an average of several years to complete, whereas nZVI only takes 1–2 years. Consequently, new and more effective applications are required. The utilization of nanoparticles in remediation is outlined in Table 35.2.

7 Future Perspectives

The framework of NPs consequently influences their organic reactions and might change the properties of NPs consequently on the surface. Studies on imaginative strategies, interesting systems of the nanobiointerface, and applicable biointelligent applications are critical (Li et al. 2017) to stay away from their destructive effect on human well-being and the climate. NPs use and release into living systems is a big risk that needs to be looked into before they are used more widely (Thul et al. 2013).

The eventual fate of nanotechnology provides a window of opportunity for monetary growth via engaging and innovative products. Nonetheless, there is a deficiency of in vitro assays and in vivo toxicity data; there is only a limited evaluation of the risk profile (Tiwari et al. 2015). Consequently, in this particular circumstance, the following focal points should be considered going forward:

- To keep an eye on the control and development of new technologies to know safe and dangerous NPs
- To acquire definitive information and knowledge of nanotoxicity
- To investigate permissible levels of NPs fraction within safety limits
- In horticulture, a clear sketch of the physicochemical properties of the soil where

Evaluation of NPs risk to soil biota and plants is to be used (Mishra et al. 2017). Before widespread use, legislatures around the globe should establish reasonable and stringent norms and procedures (Baig et al. 2021). Extreme susceptibility is linked to the safety of NPs for human health (Agrawal and Rathore 2014). Nevertheless, it is a challenging endeavor to make the structure economically viable in a substantial way.

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Chapter 36
Plant Parasitic Nematodes: A Silent Threat to Agricultural Output and Sustainable Approaches for Their Management

Taruba Ansari and Mohd Saleem

Abstract Plant parasitic nematodes (PPNs) are widespread biotic stress constraints which cause significant quantitative and qualitative economic losses to agricultural production, as they substantially affect the overall health of plants. Globally, they are considered as a silent threat due to their wide-range geographic distribution and potency to parasitize almost all agronomic crops. The loss triggered by PPNs has been expected from 80 billion to 157 billion US dollars per year. This immense loss caused can be minimized by using different management strategies. Usage of compound nematicides is one of the utmost recognized and active approaches but shows an unfavorable cost–benefit ratio and damaging effects on living organisms and environment. So, there is an urgent requirement for safer alternatives to manage these nematodes. Control practices such as the application of resistant varieties, botanicals, biocontrol agents, and amendment of soil are considered effective and an important eco-friendly approach to withstand against PPNs. The beneficial effects of these strategies might be due to improved plant growth, tolerance to nematodes, proclamation of toxic chemicals from decomposed resources, activation of nematodes natural foes, etc. Thus, the key emphasis of the current chapter is to provide an overview of various management strategies used in combating the harmful effects of PPNs.

Keywords Biocontrol · Organic farming · Plant parasitic nematodes · Sustainable management

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1 Introduction

The population of globe is expanding greatly at a percentage of 1.09% annually (Anonymous 2018). It is due to enormous increase in population, meeting the enough food for the entire populace is the biggest concern of the current era. Agriculture and its related products play a vital role in eliminating scarcity and starvation, so there is a necessity to upsurge the production and efficiency of agriculture. For this, agricultural systems need to be improvized by handling the threats of diseases and pests and improving the superiority and usage of exterior inputs. However, a number of pests and pathogens have significantly decreased the output of agriculture meant for consumption of humans. Among several pests and pathogens, nematodes have hardly been regarded or known as main limiting cue till all other limitations on yield have been checked (Bridge 1978). It is difficult to estimate precisely the loss of crop yield caused by nematodes. Still, several workers have tried to estimate the vitality of nematodes in production of crops globally and at separate nation basis. Nematodes are believed to induce yearly yield loss of 12.30% in various states of the biosphere (Singh et al. 2015). In tropical and subtropical regions, yield losses in developing countries were predicted at 14.6% as compared to 8.8% in developed nations. The estimated crop losses were between $80 and $157 billion per year (Abad et al. 2008; Nicol et al. 2011). Out of which $10 billion is reported from the United States (Gianessi and Carpenter 1999), $70 million from the United Kingdom (Nicol et al. 2011) and $40.3 million from India (Singh et al. 2015).

Nematodes are microscopic organisms round in form (roundworms) which were revealed in the fourteenth century (Tranier et al. 2014). More than 4000 species of PPNs have been recognized (Decraemer and Hunt 2006), and still new species of PPNs are frequently being discovered (Nicol 2002). PPNs are largely unnoticed from the perspective of plant defense, resulting in decline in crop yield. This is because of their minute size, short life cycle, wide host range, and triggering of cryptic damage symptoms, as well as absence of farmer's awareness to deal with them as devastating budding pests. Several agricultural crops, vegetables and fruits are severely affected by PPNs and posing threat to the agricultural sector (Li et al. 2015). For decades, nematicides and chemical soil fumigants have been the primary approaches used to control PPNs in intensive crop production systems. Merely classifying the nematodes and using the suitable nematicide is not a stable/long-term solution for controlling the plants from nematodes. Using synthetic compound nematicides can affect human health and harm flora and fauna, besides posing serious threat to the environment. These chemicals eventually degrade the quality of the soil and contaminate the groundwater. Furthermore, severe changes in the climate can render the useful nematicides useless against nematodes. The price of these chemical nematicides is not economical, which is also a key hindrance for poor farmers. As a result, the usage of many chemical nematicidal compounds is already forbidden or extremely limited in many countries (Ahmad et al. 2021). Thus, there is big challenge for present-day biologists to develop alternate management

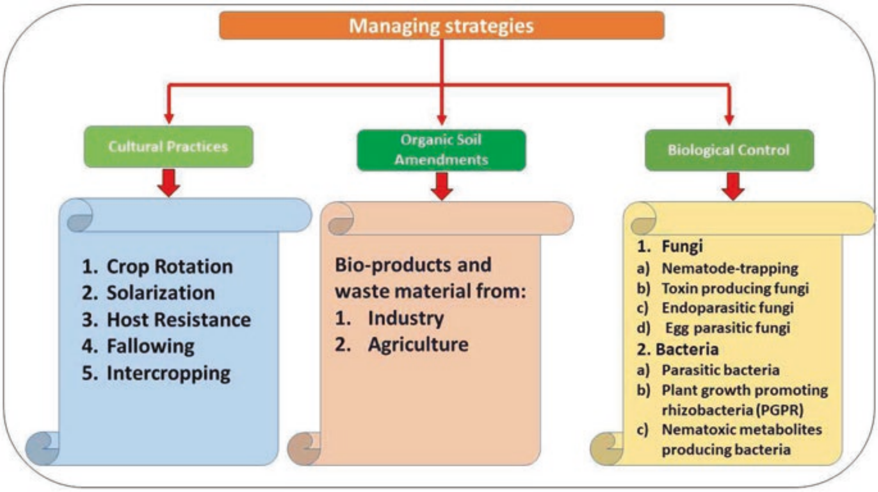

Fig. 36.1 Various strategies used for management of PPNs

strategies against PPNs. Here, we are discussing few managing strategies for PPNs control which are generally divided into three elementary headings: cultural practices, organic soil amendments, and biological control (Fig. 36.1).

2 Cultural Practices

All human activities (except application of chemical nematicides) are intended to decrease the populations of PPNs and can be categorized as cultural practices. These practices show an important character in nematode management approaches for sustainable agriculture. Some of the extensively used and efficacious cultural approaches include crop rotation, soil solarization, host plant resistance, fallowing, and intercropping.

2.1 Crop Rotation

Crop rotation is a classical and most important approach with enormous potential for managing PPN (Nusbaum and Ferris 1973). It is an annual stable categorization and spatial organization of crops or the alteration of crops in a specified area. The two main principles of this approach are (i) to decrease the number of the damaging PPNs to below threshold level, which permits the successive crops to complete their lifecycle before being severely attacked and (ii) conservation of the antagonistic and predaceous nematodes at population levels that are functioning in shielding from the pathogenic species (Bridge 1996; Nusbaum and Ferris 1973). It can be attained by altering poor hosts, nonhosts, or resilient crops with vulnerable or resistant crops (Swamy et al. 1995). One of the earliest documented uses of this technique for nematode management was made by Bessey (1911), who recommended the practice of specific rotation of crops to reduce damages caused by root-knot nematodes in sensitive vegetables. If nonhost crops were planted in rotation, this would eliminate the source of food for PPNs and therefore decrease their number well below par to detrimental points (LaMondia 1999). The efficacy of crop rotation in overturning populations of PPNs is dependent on species type existing the field, its host range, duration of time nematode can live in field without a host, nature and length of duration and associated weed hosts (Claytoy et al. 1944; Halbrendt and LaMondia 2004). The progress of operative rotating programs for the managing of PPNs like *Meloidogyne*, *Ditylenchus*, *Heterodera*, *Pratylenchus,* and *Belonolaimus* has made use of a variety of nonhost crops (Epps and Chambers 1965; Robbins and Barker 1973; Trivedi and Barker 1986; Chen and Tsay 2006; Xie et al. 2016). *Tagetes* is an outstanding option as a rotation crop due to its strong opposed effect on many PPN species (Hooks et al. 2010; Dutta et al. 2019). Rotation crops such as forage legumes (alfalfa and clover), cereals (barley and wheat) and grasses (annual ryegrass and Timothy) have successfully managed nematode populations. Other unconventional rotation crops such as crotalaria (*C. mucronata*) and chrysanthemum have also been used with variable amount of achievement (Brodie and Murphy 1975; Hackney and Dickerson 1975). Crop rotation of *Angelica sinensis* with *Tagetes erecta* decreased the density of second instar larvae of root-knot nematode and increased the yield of *A. sinensis* (Xie et al. 2016). Alternating rice with *Sesbania rostrata* decreased population levels of *Hirschmanniella oryzae* by as much as 67% (Germani et al. 1983) (Table 36.1).

2.2 Soil Solarization

Solarization of soil is a nonchemical disinfection process where the solar rays are trapped below a transparent polythene sheet during an increased ambient temperature, triggering an upsurge of temperature in the top most layer of soil which is

Table 36.1 Some non-host plants used in crop rotation

Nematode	Rotation crops	References
Globodera rostochiensis	Corn, red clover, green beans	Mai and Lownsbery (1952)
Rotylenchulus reniformis	Grain sorghum, corn	Thames and Heald (1974), Braithwaite (1974)
Heterodera schachtii	Cereals, potato, corn	Cooke (1993)
Meloidogyne spp.	Cotton, peanut, sorghum, corn	Otipa et al. (2003)
Pratylenchus coffeae	Rice, taro, tomato	Chen and Tsay (2006)

detrimental to soil-borne pests and pathogens (Abd-Elgawad et al. 2019). The effectiveness of this technique against PPNs was first demonstrated in Israel (Katan et al. 1976; Katan 1987). The factors that determine the effectiveness of solarization are temperature, location, exposure period, soil characteristics (type, moisture content and color), and the orientation of bed and plastic film characteristics (type, color, and thickness) (Stapleton and DeVay 1986). The primary mode of action of solarization is the hydrothermal effect. In highly moist soil deprived of the warming factor, the solarization process imitates the effects of flooding the soil and decreases number of soil microbiome, including nematodes, which ultimately enhance the growth of plants (Stapleton and DeVay 1983, 1984). It also accelerates the breaking of organic material in the soil. Generally, the solarized-soils hold enhanced amount of soluble minerals nutrients like ammonium-nitrogen, nitrate-nitrogen, Ca^{2+}, and Mg^{2+} than untreated soils (Jones et al. 1977). As a result, plants grow earlier and give both greater and better quality yields when raised in the solarized-soil.

Using this method, the population reduction of ten genera of PPNs, including *Meloidogyne*, *Heterodera*, *Globodera*, *Pratylenchus*, *Ditylenchus*, *Paratrichodorus*, *Criconemella*, *Xiphinema*, *Helicotylenchus*, and *Paratylenchus* can be achieved successfully (Wang and McSorley 2008; Sasanelli et al. 2021). Solarization of moist soil using transparent polythene sheets can suppress PPNs by enhancing the temperature of soil by nearly 5–10 °C (Wang and McSorley 2008; Umamaheswari et al. 2020). The method is successful antagonistic to root-knot nematodes, particularly in plastic firms where soil temperatures (30 cm top) of covered soil could be 3–5 °C higher than in mulched soil under an exposed field circumstance, leading to increased mortality of harmful nematode (Candido et al. 2008).

2.3 *Host Resistance*

In terms of disease, resistance is said to be the potential of a plant to suppress the reduction of pests and pathogens (Ansari et al. 2018). Cultivars that possess some mark of battle to one or more species of nematodes are existing in several plants and have been recognized very active in managing nematode growth (Trudgill 1991; McSorley 1998). Resistance is attained by mutating the genetic makeup of the host plant to make it less susceptible to pathogen. The underground part of the resistant plants is not invaded as rapidly as that of susceptible ones (Sasser 1954). Cultivating resistant varieties may suppress the population of nematodes by 10–50% of its harmful density (Oostenbrink 1966). Resistance has been predominantly suitable in endo-parasitic genera of nematode like *Meloidogyne*, *Heterodera*, *Globodera*, and *Tylenchulus* due to their specific life cycle and niche (Taylor and Sasser 1978; Cook and Evans 1987; Roberts 1992). Advancement has been made in recognizing the genes responsible for tolerance against economically significant species of nematode (Williamson and Kumar 2006). Such as *Gpa2* gene confers tolerance against *Globodera pallida* known as potato cyst-nematode, *Hs1pro1* gene offers tolerance against *Heterodera schachtii* known as sugar beet cyst-nematode, and *Mi*-gene confers resistance to four species of *Meloidogyne* known as root-knot nematode (Williamson 1998, 1999). Plants which are tolerant against nematode carrying resistant genes is described by a rapid-localized cell death, which arises close to frontal-end of nematode in the area of underground part of plant where commencement of feeding arises and so both the feeding site and nematodes are restricted from moving to the succeeding stage of development (Williamson 1999; Branch et al. 2004). Strategies are needed to screen out and discover the genes responsible for resistance against specific PPN, and breeding methods are desirable to combine this tolerance with other vital characteristic features (Cook and Evans 1987).

2.4 Fallowing

Fallowing has long been used against nematodes and other soil pathogens. It is a common practice of keeping the land free of all vegetation for a certain period of time by occasional ploughing during hot and dry weather. Poor farmers widely adopt this practice for controlling diseases in plants. It kills considerable sum of populations of soil-borne pests, pathogens, and weeds. The key objective of this practice is to suppress the population of PPNs in the field prior to plantation of the next crop (Weaver et al. 1995). This method ensures that PPNs will have no hosts to feed and there will be no reproduction. Due to starvation, nematodes die after consuming reserved food in their bodies (Sitaramaiah and Naidu 2003). Duncan (1986) observed that fallowing in short-growing periods suppressed the large densities of population in particular the five genera of PPNs to just the measureable levels. Kandji et al. (2001) reported that by using long-term natural fallow in cultivated plots, the biodiversity of PPNs was decreased from 69% to only 18%.

2.5 Intercropping

It is a method of growing one or more crops between rows of another crop in the same area and time (Andrews and Kassam 1976). The incidence of nematode damage is often less in mixed cropping plantings than in monocultures. It is because the space between similar crops is greater than in more intensive growing systems. So, it is less likely that propagules of pathogens will successfully move from one host to another. This practice does not effectively reduce the nematode attack if the spacing between the rows of sensitive crops is too small (Noe and Sikora 1990). The reduction in nematode damage in intercropping might be:

(i) Due to reduced population of host plants, there is adequate space in between the plants and the probabilities of interaction among the unhealthy and healthy plants are significantly decreased.

(ii) The underground part the of non-host plant action as a blockade and control the entry of pathogen in rhizosphere. The toxic substances may release from the underground part of non-host plants, which leads to suppression of pathogen development.

Intercropping has proved to be useful in controlling insects; however, it is less effective against PPNs. But numerous results have displayed the suppressing impact of intercropping on the nematodes. In mixed culture, *Tagetes minuta* considerably repressed the growth of *Meloidogyne incognita* in *Solanum lycopersicum* and *Solanum melongena* and also decreased the development of *Rotylenchulus reniformis* and *Tylenchorhynchus brassicae* on *S. lycopersicum*, cauliflower, eggplant, and cabbage (Siddiqui and Alam 1987). Berry et al. (2009) reported that intercropping of sugar bean reduced nematode infestation *Meloidogyne javanica* and *Pratylenchus zeae* infestation on sugarcane.

3 Organic Soil Amendments

Since ancient times, it has been the habit of farmers to add any available waste of animal or plant origin into soil. It has been studied that adding organic matters to the soil also decreases the level of soil pathogens. Amendments are chiefly the bioproducts and waste material from the activities in industries, agriculture, biological, or other actions. The use of organic amendments for managing plant–parasitic nematodes has been revealed in many findings (Khan et al. 2019; Ansari et al. 2020; Nadeem et al. 2021). Mode of action proposed by different workers to explain the positive impact of organic amendment in suppressing nematodes are:

(i) Improving soil physical properties, nutrient status, and fertility enhance the plant-vigor and resistance against PPNs.
(ii) During decomposition of organic matters, certain chemical compounds are released that may be nematicidal or nematostatic.
(iii) Stimulate the microorganisms that are antagonistic to PPNs.

The commonly used biological matter for controlling PPN are green manure, previous crop residues, oilseed cake, defatted seed meal, poultry and cattle manure, yard waste compost and composted municipal soil waste (Rehman et al. 2014, Ansari et al. 2016; D'Addabbo et al. 2019; Karimipour Fard et al. 2019). The plant parts, extract and oil cake derived from *Azadirachta indica* has been extensively revealed due to its nematicidal properties (Ntalli et al. 2009; Galadima et al. 2015; Aminisarteshnizi 2021). Amendments obtained from the decomposition of *Ricinus communis*, *Tagetes* and *Brassica* species have also been recognized to be very detrimental to the growth of nematodes (Bhattacharyya 2017; Dura et al. 2018; Dutta et al. 2019). Amendment of soil with animal manures increases texture of soil by decreasing bulk compactness, and improving aggregate stability and soil porosity. They have very low C:N ratio thus have sufficient nitrogen for the supply of decomposing microorganisms and plant use (Mbah and Onweremadu 2009). Application of steer and chicken composts decreased the cyst and citrus-nematodes and enhanced the yield of plants (Gonzalez and Canto-Saenz 1993). Likewise, oil cake organic amendments have proved very active in managing PPNs on many crops (Sumbul et al. 2015; Devi and Das 2016). Oil-cakes like *A. indica*, *R. communis*, *Brassica campestris*, flax (*Linum usitatissimum*) and cotton (*Gossypium* spp.) are found efficacious in decreasing the multiplication of nematodes and thus help in increasing yield of plants (Parihar et al. 2015; Sahu et al. 2018). During decomposition, they release toxic chemicals like ammonia (NH_3), hydrogen sulfide (H_2S), aldehyde, amino acids, fatty acids and carbohydrates, which have been found deleterious to PPNs (Alam et al. 1979). The amino acids released from oil cakes are not toxic, but they combine with other compounds, such as amino acids, chlorogenic acid complex or glycosides of phenols, that are detrimental to nematodes (Clark et al. 1959). Apart from this, increased phenolic content in plants results in increased host resistance, which protects roots from nematode attack (Alam et al. 1979) (Table 36.2).

Table 36.2 Some organic matters used for controlling plant parasitic nematodes

Organic matters	Target nematode	Crop	References
Leaves of *C. procera*, *R. communis*, *L. camara*, *A. aspera*, *W. chinensis*, *C. esculenta*	*M. incognita*	Spinach	Hasan et al. (2021)
Leaves of *C. grandis*, *C. benghalensis*, *L. cephalotes*, *P. amarus*, *T. portulacastrum*	*M. incognita*	Carrot	Khan et al. (2019)
Extracts of *A. indica*, *W. somnifera*, *T. erecta*, *E. citriodora*	*Helicotylenchus multicinctus*, *Hoplolaimus indicus*, *M. incognita*	Papaya	Khan et al. (2008)
E. globulus essential oil	*Pratylenchus* spp.	Maize	Fabiyi et al. (2020)
Mustard seed cake	*M. javanica*	Tomato	Nadeem et al. (2021)
Oil cake of neem, castor, mahua	*Pratylenchus delattrei*	Crossandra	Jothi et al. (2004)
Leaves powder of neem, karanj, lantana	*Heterodera zeae*	Sweet corn	Baheti et al. (2015)
Chicken, sheep, cow manure	*M. incognita*	Grapevine	El-Ashry (2021)
Poultry, cow dung and domestic waste	*M. incognita*	Ethiopian egg plant	Abolusoro et al. (2015)

4 Biological Control

In recent few years, the biological control has rapidly evolved and gained the interest of researchers in managing PPNs. It involves identifying and utilizing beneficial microorganisms, their genome or metabolites which decrease the harmful impact caused by plant pathogens and enhance crop production sustainably (Noureldeen et al. 2021). It has the potential to manage plant diseases with no or minimal detrimental impact on the environment and is accepted as a main practice in achieving the sustainable agricultural goals. Culture filtrates of various microbes like bacteria, fungi, and actinomycetes were tested against PPNs (Ahmad et al. 2021; Khan et al. 2022) (Table 36.3).

4.1 *Fungi as Biocontrol Agent*

Nematode-destroying fungi involve a broad variety of fungi that can capture, kill and digest nematode. At present, around 700 species of nematode-destroying fungi have been designated (Yu et al. 2014). On the basis of their nematicidal action, they are classified as:

Table 36.3 List of biocontrol agent used for managing PPNs

Biocontrol agent	Mechanism of action	Target nematode	References
P. Chlamydosporia	Direct parasitism on eggs of nematode	*M. incognita*	Khan et al. (2021)
T. virens	Toxin secretions	*M. incognita*	Khan et al. (2022)
M. thaumasium	Protease	*M. javanica*	De Souza Gouveia et al. (2017)
Paecilomyces sp.	Chitinase	*Bursaphelenchus xylophilus*	Liu et al. (2009a, b)
P. fluorescens	Production of metabolites, defense activator	*M. incognita*	Noureldeen et al. (2021)
B. thuringiensis, *B. amyloliquefaciens*	Lipases	*Xiphinema index*	Kohl et al. (2019)
B. pumilus L1	Protease and chitinase	*Heterodera glycines*, *M. arenaria*	Forghani and Hajihassani (2020)
B. subtilis	Lipopeptide-antibiotics, hydrolytic-enzymes, secondary-metabolites	*Helicotylenchus multicinctus*, *M. graminicola*, *M. incognita*, *M. javanica*, *Rotylenchulus reniformis*	Basyony and Abo-Zaid (2018), Mazzuchelli et al. (2020)
Serratia marcescens, *P. aeruginosa*	Chitin and protein hydrolysis	*M. incognita*	Hegazy et al. (2019)
Streptomyces bingchenggensis	Milbemectin production	*M. javanica*	Talavera-Rubia et al. (2020)

4.1.1 Nematode-Trapping or Predacious Fungi

It includes soil-borne fungi, which form hyphal structures to trap nematodes. They develop different types of traps such as:

4.1.1.1 Adhesive Knobs

Here, the fungal hyphae form globose or subglobose cellular structure, which is either without stalk or with a slender stalk which forms an adhesive knob. This knob gets detached from mycelia, travels with PPNs, penetrates its cuticle and produces an infection-bulb. This infection-bulb multiplies in the nematode, then digests and assimilates the body contents of nematode. They breakdown the nematode-cuticle and produces peripheral hyphal-structure that looks like vegetative-mycelium. The adhesive knobs forming fungi are *Monacrosporium ellipsosporum*, *Dactylella lobata*, *Arthrobotrys oligospora,* and *Arthrobotrys dactyloides* (Khan et al. 2006; Kumar and Singh 2006; Niu and Zhang 2011).

4.1.1.2 Constricting Rings

It is the best sophisticated type of trapping device. An erect branch from hypha curves over apex and follows a circular pathway until it fuses with the original hypha to form a three-celled ring on a short and stout stalk. The inner diameter of the ring is about 20 mm. When a nematode enters the ring, swells rapidly, and firmly loops the prey, then assimilative hyphae fill the nematode body, digest and absorb its internal contents.

4.1.1.3 Nonconstricting Rings

These are formed in the same way as constricting rings, but the cells do not inflate when the nematode enters it. The supporting stalk is comparatively longer and often breaks when nematode is wedged into the ring.

4.1.1.4 Adhesive Network

It is also one of the common trapping devices. An upright horizontal branch grows from vegetative hypha and then curves around to fuse with parent hyphae forming a loop. Appressoria develops from hyphae and penetrates the entangled nematodes. Infection-bulbs and infection hyphae are formed, which digest the contents of nematode body.

4.1.1.5 Adhesive Branch/Hyphae

These are short and erect trapping structures that are only a few cells tall. They develop from short lateral hyphae that arise from prostrate hyphae.

4.1.2 Toxin-Producing Fungi

These fungi secrete inhibitory volatile compounds like ethylene, hydrogen cyanide (HCN), alcohol, carbonyls, and non volatile compounds like peptides without any direct contact among fungi and nematodes (Tariq et al. 2020). These toxins immobilize the nematodes before penetration of hyphae through cuticle of nematode. The filtrates of such fungus have strong proteolytic and chitinolytic activities, resulting in increased larval death or prevent hatching of eggs (Westphal and Becker 2011). The toxic compounds of fungi either induce some variation in build-up of eggshell resulting in abnormalities in development of embryo. Such malformed eggs vary in mass and form and they don't hatch.

Trichoderma is a cosmopolitan filamentous fungus found in soil. The fungal hyphae, spore and chemical compounds (metabolites) formed by diverse isolates of *Trichoderma* display antagonistic impact against *M. javanica* (Al-Hazmi and TariqJaveed 2016). The volatile compound namely, 6-pentyl-α-pyrone formed by *Trichoderma harzianum* has hostile effect on PPN (Sarhy-Bagnon et al. 2000). Zhang et al. (2017) reported that *Trichoderma longibrachiatum* can act as potent biocontrol agent for *Heterodera avenae* as it enforces direct parasitism and toxic effect on eggs and J2 activities. Other fungi like *A. dactyloides* also form a nematotoxin, the vigorous compound is ammonia (NH_3). Nematotoxins formed by class ascomycetes include oligosporons, talathermophilin-A and -B, aurovertins-D and -F, phomalactone, paeciloxazine and leucinostatins (Thomas and Andreas 2016).

4.1.3 Endoparasitic Fungi

It is an assemblage of nematophagous fungi which suppresses nematodes through a variety of special spores. Either the spores are absorbed by nematode or get adhered to their body surface; after then mycelium grows from these spores in nematodes endogenously (Liu et al. 2009a). Conidial spores of *H. rhossiliensis* fungus get attached to nematode, and after infection, fungal hyphae then enter cuticle and consume the endogenous content of nematode (Devi 2018). However, few endophytic fungi like *Acremonium*, *Syncephalastrum,* and AM (arbuscular-mycorrhizae) have capacity to decrease nematode infection, in spite of not continuously displaying nematophagous action, but relatively by improving the growth of infected plant (De Freitas Soares et al. 2018). AM fungus increased growth of plants by enhancing the intake of mineral nutrients, especially phosphorus and water uptake (Vos et al. 2012). Colonization of AM fungi before invasion of nematodes may decrease nematode growth rate to a greater extent than after invasion.

4.1.4 Egg Parasitic Fungi

It includes saprophytic soil inhabitants mainly found in the underground part of plants. The sedentary endoparasitic nematodes like *Meloidogyne*, *Heterodera*, *Globodera*, *Rotylenchulus,* and *Tylenchulus* are more susceptible to the outbreak of such fungi than the migratory nematodes and aid as a selective substratum for successful settlement. They act on the eggs of nematode on two levels, directly as true parasites via penetration and poisoning eggs and indirectly via distorting nematode embryos or larvae (Morgan-Jones and Rodríguez-Kábana 1988). In the initial stages of infection, hyphae entirely occupy the embryonic part of egg, consume its content and make it vacuolated. The extracellular enzymes such as chitinases, proteases and lysozyme are formed and secreted by fungal antagonist to damage the cuticle and eggshell of nematode (Yang et al. 2007). Most of these fungi belong to genera *Paecilomyces* and *Pochonia*. *Paecilomyces lilacinus* has demonstrated to be an excellent biocontrol agent in contrary to several PPNs (Cannayane and Sivakumar 2001; Oclarit and Cumagun 2009). A commercial formulation is available for *P. lilacinus* 251 (Brand et al. 2004). *Pochonia chlamydosporia* also penetrates and infected the eggs and uncovered females of economically important PPNs in several crops (Manzanilla-López et al. 2013; Khan et al. 2021).

4.2 Bacteria as Biocontrol Agent

Application of bacterial biocontrol agents has great potential in controlling the PPNs. Several soil-borne saprophytic bacteria, rhizospheric or endorhizum has been revealed to play antagonistic role against nematodes. They act against plant pathogens using different mechanisms like parasitism, production of toxins and antibiotics and activating plant defense mechanisms. Various commercial bacterial products have been generated to check the population of PPNs (Hallmann et al. 2009). *Bacillus subtilis*, a rhizobacterium, has been successfully employed as biopesticidal agent in controlling phytopathogenic nematodes (Ahmad et al. 2021).

4.2.1 Parasitic Bacteria

It includes Gram-positive, mycelial, obligate endoparasitic bacteria belonging to genus *Pasteuria* and is parasitic to economically vital species of plant parasitic nematodes (Timper 2009). It is reported that members of this genus parasitize 323-nematodes species belongs to 116-genera, like root-knot nematodes, root lesion nematodes, cyst nematodes, foliar nematodes, and burrowing nematodes (Abd-Elgawad and Askary 2018). As of now, four species of *Pasteuria* have been described, out of which three species, *Pratylenchus penetrans* acts against *Meloidogyne* spp., *Pratylenchus thornei* against *Pratylenchus* spp., and *P. nishiza* parasitize cyst nematodes (Atibalentja et al. 2000; Stirling 2014). *P. penetrans*, form extremely resilient endospores that get attached to nematode's cuticle and develop with infection pegs to enter cuticle of nematode. Terminal area of infection peg spreads into nematode body and grows a mycelial-ball or microcolony. Growth of microcolony in female nematode triggers considerable decrease in fertility rate. Every female nematode release around 106-endospores in soil and get adhered to cuticle of nematodes, causing mortality of PPNs.

4.2.2 Plant Growth Promoting Rhizobacteria (PGPR)

It comprises a huge assemblage of free-living bacteria which inhabit in rhizospheric region and help in the growth and development of crops (Kohl et al. 2019). These microorganisms include *Rhizobium*, *Bacillus*, *Bradyrhizobium*, *Pseudomonas*, *Serratia*, *Agrobacterium*, and *Azotobacter*, which are commonly found in rhizosphere (Tailor and Joshi 2014). Among them, dominant genera *Bacillus* and *Pseudomonas* are considered detrimental against PPNs (Castaneda-Alvarez and Aballay 2016). Various modes of actions of rhizobacteria to decrease damage caused by nematodes in plants have been proposed, such as maintain behavior of nematodes, interference with recognition of host-nematode, struggle for nutrition, plant growth elevation, induced systemic acquired resistance (ISR), and production of exudates that kill directly (Xiang et al. 2017, 2018). They also improve the formation of PGRs (plant growth regulators: auxins, cytokinins, and gibberellic acid) and facilitate nutrient uptake (nitrogen fixation and phosphorus solubilization). Beneduzi et al. (2012) observed that rhizobacteria induce systemic resistance (ISR) in plants which looks like pathogen-induced SAR (systemic acquired resistance) that rendered uninfected plants more resistance to pathogens in many plant species. *Pseudomonas fluorescens* is identified to secrete siderophore, which is low molecular weight Fe binding complex. Siderophores compete with pathogens for available iron, making iron unavailable to phytopathogens, thus causing their death (Noureldeen et al. 2021). *Bacillus* spp. trigger a phenomenon known as ISR in plants contrary to pathogens via increased activity of defense-related enzymes like peroxidase (POX), polyphenol-oxidase (PPO) and phenylalanine-ammonia lyase (PAL) (Abbasi et al. 2014; Saleem et al. 2021a, b; Saleem and Fariduddin 2022).

4.2.3 Nematoxic Metabolites Producing Bacteria

Certain groups of bacteria suppress the PPNs by producing toxic metabolites. The nematoxic compounds like ammonia and hydrogen sulfide produced by *Nitrosomonas*, *Nitrobactera* and *Desulfovibrio desulfuricans* were found to be nematicidal for *Hirschmanniella oryzae* and *Meloidogyne* spp. (Rodriguez-Kabana et al. 1965). Butyric acid produced by *Clostridium butyricum* leads to a decrease in the number of *Tylenchorhyncus martins* in rice fields (Johnston 1957). Fluorescent pseudomonads produce antibiotic 2,4-diacetylphloroglucinol (DAPG), which decrease mobility of juveniles and enhance hatching of eggs of potato cyst nematode (Siddiqui and Shaukat 2004). *Bacillus thuringiensis* (Bt) secretes Cry protein (proteinaceous-protoxin crystals), which is accountable for nematicidal effect in a wide range of nematodes (Ghahremani et al. 2020). Luo et al. (2013) reported the three types of Cry proteins viz., Cry-5, Cry-6, and Cry-55, which kill the larval stages of nematodes and retard their growth. Out of all these three different types of Cry protein, Cry-5B is one of the greatest effective protein counter to nematodes which triggers lysis of intestines due to its lytic pores.

5 Conclusion

PPNs cause severe crop loss in the modern intensive farming system. In the current era, advancement has been made in creating natural management and control strategies to reduce their detrimental effects. Cultural practices and biocontrol agents are eco-sustainable methods to control and manage the parasites and pathogens in achieving the sustainable agricultural goals. A detailed study of different managing approaches shows the significance and prospective of cultural practices, organic matters, and biological materials in regulating and managing PPN infections. So, the integrated use of one or more techniques can prove to be very handy in the management of plant parasitic nematode and improving the overall health of plant and, hence, the yield.

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Chapter 37
Accelerating Crop Improvement Through Speed Breeding

Ibrahim Al-Ashkar, Abdullah Al-Doss, and Najeeb Ullah

Abstract The progress of conventional plant breeding programs is restricted primarily due to the time and space limitations required for multiple evaluation phases. Biotechnological tools are among the major contributors to the recent advances in crop improvement. Plant breeders and seed companies have extensively studied and used these techniques to counteract climate changes and steady population increase and achieve global food security. This chapter discusses the fundamental principles and methodologies used in modern breeding programs. It also covers the technological progress in plant breeding from conventional to molecular breeding. The key limitations of these techniques have also been discussed to provide a complete understanding of the importance and difficulty of combining utilizing biotechnology tools and conventional for accelerating plant breeding, which strives to produce new crop varieties with desired traits. In order to advance the agronomic traits of crops such as yield, quality, and stress tolerance, strategies to accelerate breeding speed, genetic selection, mutagenic breeding, doubled haploid methods, inducer technology, and molecular markers are commonly used. Unlike traditional breeding methods, molecular marker-assisted breeding is a more robust tool for improving breeding efficacy and speed. It is not an alternative to traditional breeding but a valued supplement, resulting in a combined optimistic strategy for future crop

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improvement. Therefore, the application of modern breeding techniques such as speed and molecular markers in global crop breeding programs has significantly increased.

Keywords Speed breeding · Doubled haploids technology · Molecular breeding · Mutation

1 Introduction

The United Nations expects the world human population will reach billion by 2050, with 70% of the population living in urban areas. Consequently, a 70–100% increase in food production is needed in just 40 years (Bradshaw 2017). Thomas Robert Malthus famously predicted the possibility of a population increase exceeding food supplies in 1798 in his book "An Essay on the Principle of Population," a time when the world population was about 1 billion (Malthus 1798). Nevertheless, increased food supplies are needed to meet the future demand to feed 9 billion people by mid-century. This challenge is further complicated by factors such as changes in the human diet, use of crops for biofuel production, lack of new agricultural lands and climate changes. Therefore, more investments are needed in the current farming systems to increase the yield and quality of the crops to withstand agroecological and socioeconomic shocks under changing climate (Bradshaw 2017; Abu-Zaitoun et al. 2018; Al-Ashkar et al. 2020b, 2023). These factors must be considered while searching for sustainable food production solutions. Considerable progress and a comprehensive, integrated approach will be required to narrow the productivity gap between the currently achieved and feasible in the foreseeable future, particularly with the expected environmental degradation and climate change (Najeeb et al. 2019; Al-Ashkar et al. 2021, 2022; Ahmad et al. 2022).

Most plant species reach significant bottlenecks in their breeding programs and applied research, thus creating the need for rapid technological advancements in plant growth and the replacement of generations. In the early 1990s, technological advancement inspired a generation of plant scientists worldwide. For example, the term "speed breeding" was coined in 2003, combining methods developed to accelerate crop breeding progress. Speed-breeding techniques are optimized and used for many commercial crops (Watson et al. 2018; Ahmar et al. 2020; Kishii and Singh 2020). Developing new high-yielding superior crops and cultivars tolerant to climate factors such as heat, drought, salinity, and poor water quality or adapted to different regional environments and growing conditions is essential for ensuring food security (Ahmar et al. 2020; Barakat et al. 2020a; Al-Ashkar et al. 2023). Thus, new cultivars should be compatible with multiple stresses and complex conditions. One of the most critical challenges the new generation of plant breeders and researchers currently faces is the evolving knowledge of plant molecular physiology and biotechnology. Novel plant breeding techniques such as mutation breeding, wide crosses, doubled haploid (DH) technique, molecular markers, and high-throughput phenotyping are commonly used in breeding programs for shortening crop reproductive cycles and for accelerating breeding progress (El-Hennawy et al. 2011; Mujjassim et al. 2019; Ahmar et al. 2020; Kishii and Singh 2020). Many breeding programs use tissue-culture-based methods, such as somatic embryogenesis, embryo and ovule rescue, and protoplast fusion (Shepard et al. 2019; Marthe 2018; Germana 2011). Thus, the breeding programs must be comprehensive, exploring new genetic resources and candidate genes/traits for crop improvement and cultivar development through speed breeding and mutation breeding (Watson et al. 2018; Hickey et al. 2017; Barakat et al. 2020a). Induced mutations can be a promising source of generating genetic variability for breeding programs and contribute to the search for target traits during the breeding cycle.

Male or female gametes are used for producing haploid plants. The gamete doubling process may occur spontaneously or via chemicals to generate fertile and homozygous plants known as doubled haploids (DH) (Reynolds 2001; Broughton et al. 2014). During the DH production system, homozygosity is achieved within one generation (used directly for hybrid-seed production), and 3–5 years are required to develop a cultivar in self-pollinating crops. DH system improves the accuracy and reliability of phenotypic evaluations and increases the desirable segregate proportion (Touraev et al. 2001). The significant value of high-purity lines produced from DHs has led to their use in crop breeding and gene mapping (Cakir et al. 2011). The DH techniques use immature microspores and/or megaspores (ovary culture), and after a broad and far/interspecific hybridization, the haploid embryo (in vitro) is rescued. The technique is instrumental for breeding crops to generate populations as useful and novel genetic resources for gene-mapping purposes in wheat breeding programs (Al-Ashkar 2013; Al-Ashkar et al. 2019, 2020a).

The conventional screening procedures in traditional breeding methods are labor-intensive, expensive and time-consuming. Molecular markers have provided new and valuable tools to increase the efficiency and effectiveness of traditional breeding techniques. These tools can assist in increasing the production capacity of developing new crops/cultivars adapted to a broad range of environmental conditions. For example, significant progress in breeding crops for multigenic agronomic traits has already been achieved using marker-assisted selection (MAS) programs (Jiang 2015; Collard et al. 2005; Barakat et al. 2020b). Tagging the candidate genes using tightly linked molecular markers is less expensive, as it reduces the time needed to transfer these genes from one genotype to another. The associated molecular marker would indicate evidence of the intended gene, and molecular markers that are very closely related to the candidate genes can be used as tags for the indirect selection of genes in multiple-breeding programs. For example, the MAS allows early generation selection in a segregating population. Thus, individuals can be selected for multiple traits within a year with marker-based backcrossing, significantly shortening the breeding cycle compared with traditional backcrossing (Jiang 2013; Frisch et al. 1999; Collard et al. 2005; Barakat et al. 2020a). Integrating MAS techniques into current breeding programs will enable plant breeders to precisely access, transfer and combine desired traits/genes into new crops.

Researchers use different speed-breeding approaches to improve crop performance and beneficial traits, such as crop productivity, stress tolerance, and high nutritional value. By choosing the candidate plant and crossbreeding it with a genotype that holds the desired trait or introducing new gene resources when none are available naturally, a target trait (e.g., stress tolerance, yield) might be improved.

2 Mutation Through Traditional Breeding

Abiotic factors impede high productivity and may be overcome by genetic changes that can neutralize the effect of the abiotic stresses. When no source of genetic variability is available naturally, it is impossible to develop new genotypes without discrepancies in natural genetics caused by spontaneous mutations. Mutation breeding is one way to speed up traditional breeding by inducing unexpected heritable changes into the genetic material. It usually occurs via one of the following pathways: (1) spontaneously; (2) exposure to physical mutagens, e.g., radiation (α-rays, gamma rays, X-rays, ion beams, γ-rays, and ultraviolet (UV) radiation); (3) exposure to chemical factors, such as ethyl methane sulfonate, methyl methane sulfonate, ethylene imines, diethyl sulfate (DES), sodium azide, acriflavine, acridine orange, and other direct-acting compounds (nitrous acid and mustard gas); (4) via biological factors, as a consequence of DNA insertions (Roychowdhury and Tah 2013; Forster and Shu 2012; Oladosu et al. 2016; Al-Ashkar 2013). Chemical mutagens can merge into DNA during the replication process (Najeeb et al. 2011; Xu et al. 2012) and induce genetic mutations through transitions of bases (i.e., pyrimidine to pyrimidine or purine to purine) via replacement with cytosine byuracil (through deamination). For instance, cytosine byuracil can pair with adenine and induce mutations in the first iteration of cells. During reactions with bases, ethyl or methyl groups are added to yield a baseless site, resulting in mutations upon DNA replication (Mba 2013).

Mutation breeding relies primarily on the accurate assessment of the first plant generation, followed by selecting benign and valuable mutants in the second or third generations (Fig. 37.1). The mutation could probably be introduced in every plant material, such as seeds, seedlings and whole plants, coupled with in vitro cultured cells. Many novel mutants have been selected to use directly as crop varieties or as parental lines for producing superior germplasm in many parts of the world (Kharkwal and Shu 2009; Gulfishan et al. 2015; Ahmar et al. 2020). This demonstrated that mutant varieties and their cultivation contribute significantly to achieving food and nutritional security, including improved yield and grain and protein quality, enhanced uptake of specific metals, lower agricultural input, and tolerance to different abiotic stresses. Mutant crop varieties such as rice in India, China, Pakistan, Japan, Philippines, and Australia; wheat in Pakistan and USA; cotton in Pakistan; durum wheat in Italy; sunflower and maize in the USA; barley in many European countries; sorghum in Mali have been developed through mutational breeding. These mutants have played pivotal roles in preventing food scarcity (Mba

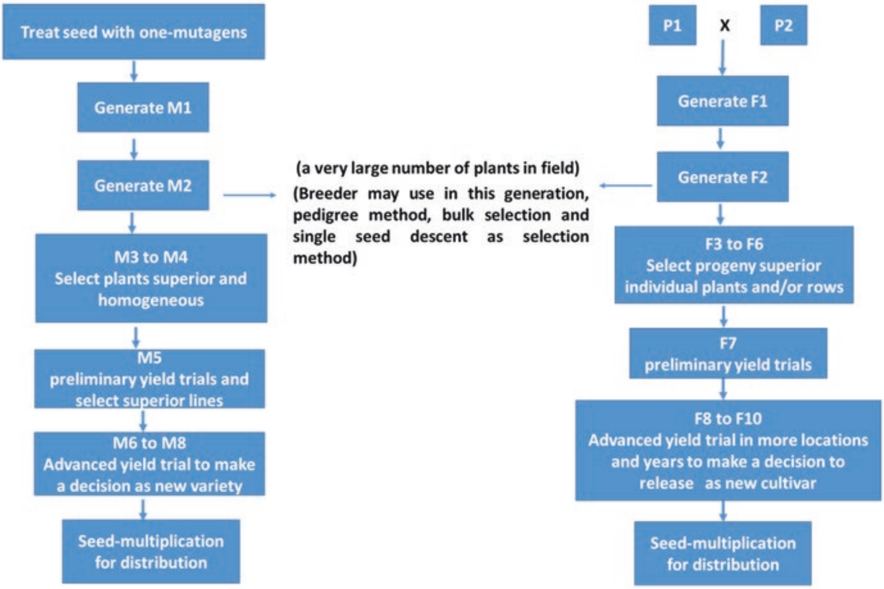
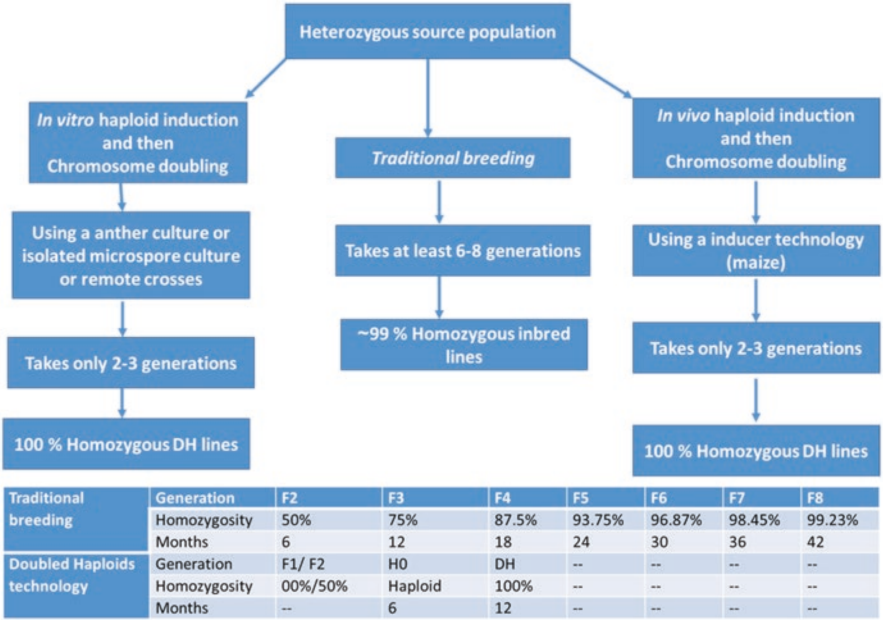


Fig. 37.1 General steps for traditional breeding and mutation breeding of plants

2013; Ahloowalia et al. 2004; Ahmar et al. 2020). These features render mutant varieties part and parcel of food systems worldwide. An alternative approach includes more accurate mutation breeding via introducing gene-specific mutations using engineered nucleases. Allelic variations in the candidate genes also significantly contribute to breeding programs by providing new genetic combinations (Wilde 2015).

3 Doubled Haploids Technology

Doubled haploid (DH) technology has significantly accelerated the speed of plant breeding programs by shortening the gene combination cycle from many to a single generation (Fig. 37.2). This technology could also be used to expedite the development of germplasm by introducing new genes of interest to increase tolerance to environmental stresses and create cytogenetic stocks (Xu et al. 2007). Numerous DH-derived cultivars have been created globally, and each year 30% of the area occupied by spring wheat in Canada corresponds to DH-derived cultivars. The future of DH technology is promising because DH techniques are now available, and future applications will experience increased integration with MAS. DH plants are produced through different methods, including DH production from paternal organs (microspore/anther culture), maternal origin (ovules, placenta-attached ovules, ovaries, or whole flower buds), remote crosses (wheat × maize and wheat ×



Traditional breeding	Generation	F2	F3	F4	F5	F6	F7	F8
	Homozygosity	50%	75%	87.5%	93.75%	96.87%	98.45%	99.23%
	Months	6	12	18	24	30	36	42
Doubled Haploids technology	Generation	F1/ F2	H0	DH	--	--	--	--
	Homozygosity	00%/50%	Haploid	100%	--	--	--	--
	Months	--	6	12	--	--	--	--

Fig. 37.2 General steps indicate the number of generations to reach homozygosity in traditional breeding and doubled haploid technology

Hordeum bulbosum), and inducer technology. Gynogenesis methods are normally employed only when further means, such as remote crosses, are ineffectual; moreover, their use has been mainly confined to sugar beets and onions (Murovec and Bohanec 2012; Humphreys and Knox 2015). Four methods and techniques are presented in this chapter: (1) anther culture (wheat), (2) isolated microspore culture (wheat), (3) remote crosses (wheat), and (4) inducer technology (maize).

4 Anther Culture (Wheat)

Anther donor plants are cultivated under optimal temperature conditions (18 °C/13 °C, day/night temperature), nutrition, and water, because plant stress may negatively impact androgenic development. Spikes with pollen at the mid-to-late uninucleate stage are harvested. This developmental phase could be inferred by leaf sheath morphology when the beginning exit of the spike (~1–2 mm) (Szarejko 2003; El-Hennawy et al. 2011; Broughton et al. 2014). Selection of the precise pollen developmental stage is essential to reprogram gametophytic development into calli or embryoids successfully. After harvesting, spikes are stored in a beaker of water for 4–8 days at 4 °C as a stress-induction treatment to induce androgenic response and spontaneous doubling (El-Hennawy et al. 2011). After removing awns, sterilized spikes are immersed for 7 min in commercial 20% chlorax, followed by rinsing with sterile water for 4–5 min. The spikes are placed in a Petri dish and allowed to dry under laminar flow (Broughton et al. 2014). Anthers are dissected from either side of each spike, cultured in jars or Petri dishes containing induction medium (Fig. 37.3), and stored in the dark for 5–6 weeks at 28 °C. Calli can generate embryoids using appropriate culture media, and the induced embryoids/calli are shifted to the jars containing regeneration medium to evolve into plantlets (Fig. 37.3). These cultivars are incubated for 5–6 weeks at 25 °C ± 2 °C with 16 h of light. The green plantlets are transferred to a root-stimulating medium before being transferred to soil.

5 Isolated Microspore Culture (Wheat)

Microspore culture depends on immature full-fledged microspores. Selecting the right harvest stage is the critical first step to achieving greater success in microspore culturing (Zheng 2003; Kishii and Singh 2020). The plants growing under optimally controlled conditions (17 °C/14 °C (day/night) with 14 h of light) are used as microspore donors. The spikes containing pollen at the mid-to-late uninucleate phase are harvested because, during this developmental phase, they are suitable to study

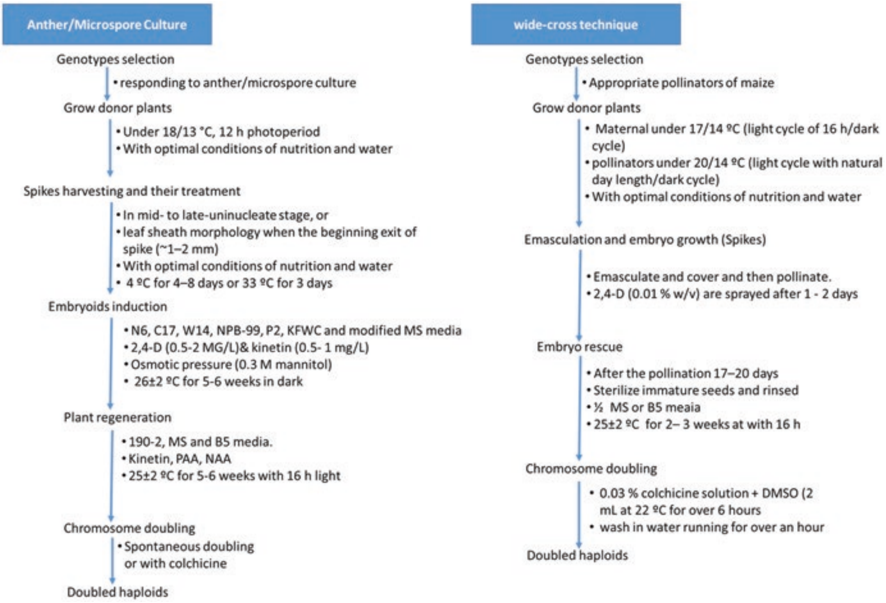


Fig. 37.3 General steps to the procedure of anther/microspore culture and wide-cross technique for doubled haploid production

androgenic response, and the developing pollen can be identified microscopically and/or morphologically (Zheng 2003; Al-Ashkar 2013).

The harvested spikes are stored at 4 °C for 21 days (Fig. 37.3). The cold treatment provides the conditions to induce sporophytes and spontaneous doubling and reduce albinism (Humphreys and Knox 2015). Immature spikes are collected, their outer blade and sheath are removed, and sanitized with 70% ethanol in a laminar-flow cabinet. The spikes are homogenized in a Waring blender and filtered through a 100 μm sieve, followed by the cultivation of the isolated microspores on an induction medium in the dark for 4–5 weeks at 28 °C (Broughton et al. 2014). Embryos are shifted to a regeneration medium; allowed to grow for 5–6 weeks at 25 °C ± 2 °C with 16 h of photoperiod under cool white fluorescent lamps. The shoot growth becomes visible in 3–4 weeks. Subsequently, the green plantlets are transferred to a solid medium (MS) to promote root growth before their transfer to soil.

Androgenic techniques (anther and microspore culture) are preferred due to the ease of cultivating many pollen grains from a single spike/anther. Theoretically, androgenic techniques can yield high numbers of DH plants compared with one haploid per floret in the remote-cross method. In large-scale DH production, androgenic techniques are more cost-effective than remote-cross methods (Snape 1986; Humphreys and Knox 2015). The advantages of the microspore culture are primarily the spontaneous doubling of chromosomes. The success rate in wheat ranges from 25% to 70% (Castillo et al. 2009), with lesser labor and chemical applications. The main drawback of microspore culture in some plant species, including wheat, is that the genotype is the key determinant of the response (El-Hennawy et al. 2011; Murovec and Bohanec 2012). Those authors found that some genotypes respond well to microspore culture, whereas specific genotypes exhibit a total lack of response. Therefore, the lack of knowledge regarding whether crosses will yield plantlets or not renders this method inefficient compared with the wide-cross method, in which culturing does not rely on genotype. A further impediment is the high ratio of albino plants and the difficulty in adequately staging all microspores in culture (Redha and Talaat 2008; Ankele et al. 2005; Asif et al. 2013). Nevertheless, the androgenesis techniques are more efficient and effective and yield greater productivity than the wide-cross technique.

6 Remote Crosses (Wheat by Maize)

The wheat wide-cross technique requires transferring maize pollen to emasculated wheat spikes. The importance of this technique lies in its consistency regarding haploid production across a set of wheat genotypes, which vary their response capability in the generation of haploid plantlets (Fig. 37.3). This consistency is necessary as a breeding tool to avoid wasting potential on unresponsive crosses. The efficiency of wheat–maize pollen technique depends on the growth of both maize and wheat parent plants under optimized conditions (Knox et al. 2000). Light intensity and quality are crucial to produce vigorous plants and for maximizing physiological and/or phenotypical development (Knox et al. 2000; Humphreys and Knox 2015). Wheat plants (maternal) are grown in rooms at approximately 17 °C/14 °C (16 h light cycle/dark cycle). Maize plants (pollinators) are grown under controlled environments at approximately 20 °C/14 °C (light cycle with a natural day length/dark cycle). General plant health is vital for efficient haploid production process. The growth conditions can be optimized by cultivating plants in appropriately sized pots for each stage, fertilizing regularly, and providing sufficient water.

Approximately 3 days before anthesis, the primary spikes of wheat plants are selected, emasculated then covered with a glassine paper bag for 2–3 days. Subsequently, the glassine paper bag is removed, and the spikes are checked to identify abandoned anthers and florets, which are ready for pollination after an additional 2–3 days. Maize pollen is collected and hybridized with maternal florets before emasculation using a small paintbrush. The spikes are covered again after pollination to prevent the intercrossing of maternal plants. Pollinated spikes are sprayed 1–2 days after pollination with a solution of 2,4-D (0.01% w/v); 2 days later, the covers are permanently removed. The success of this technique depends on embryo rescue (Laurie and Bennett 1988). Thus, exceptional sterilization skills are critical for successful plant regeneration and decreasing contamination by bacteria and fungi. The haploid plants are treated with a chemical chromosome doubling (colchicine). The treated plantlets are generally weak and need extra care for survival. Then, 17–20 days after pollination, spikes are harvested from the base and stored in distilled water for 5–8 days at 4 °C (ideally, the embryos should be removed on the day of harvesting). Immature seeds are carefully removed using tweezers and placed in sterilized bottles, then rinsed in 70% ethanol for 30 s, followed by a 7-min incubation in commercial 20% chlorax with occasional agitation. Seeds are sterilized using distilled water and placed in a Petri dish under sterile conditions. Sterile tweezers are used to cut and separate embryos from the seed under a dissecting microscope, followed by their transfer to an embryo rescue medium (Fig. 37.3). Embryos are incubated for 2 days at 4 °C in the dark and then at room temperature. Finally, the embryos are transferred to an incubator at 25 °C ± 2 °C with 16 h of light for 2–3 weeks to stimulate leaf and root growth.

Plantlets are transferred to pots containing soil, compost, and sand and allowed to grow for 4 weeks under controlled environments (18 °C and 16 h of light). Plantlets are irrigated with MS without vitamins. Haploid plantlets from androgenic techniques (anther culture and microspore culture) and all plantlets of remote wide-cross are treated with colchicine to restore fertility (by redoubling the number of chromosomes). The colchicine was applied using a protocol of Cistué et al. (2006). The roots of plants are washed to remove the attached soil particles, and the oldest leaves are removed to expose young shoots, followed by clipping roots to 1 cm. In a narrow tall beaker, the trimmed plants are placed in 150 mL of colchicine solution (0.03%) + DMSO (2 mL). The roots are fully immersed in the solution at 22 °C. Subsequently, the plants are removed from the colchicine solution and washed in running water for over 1 h. Treated plants are retransferred to small pots in controlled growth rooms for an additional week and are then transferred to a greenhouse to simulate natural growth conditions and left until maturity. The seeds obtained from DH lines are harvested.

7 Inducer Technology (Maize)

Luckily for maize breeders, the first inducer in maize was detected by Coe Jr. (1959) and termed as inbred Stock 6 line. This line completely revolutionized corn breeding, showing a 1–2% haploid maternal induction. Subsequently, new inducers with greater haploid induction rates, for instance, RWS, RWK-76, KEMS, MHI, WS14, PK6, HZI1, CHUHOI and PHI were identified (Röber et al. 2005; Shatskaya et al. 1994; Lashermes and Beckert 1988; Eder and Chalyk 2002; Barret et al. 2008; Zhang et al. 2008; Li et al. 2009; Rotarenco et al. 2010). The inducers are used as the parental (male) plant to pollinate maternal (female) plants, resulting in maternal haploid production with an average haploid progeny of 8% (Prigge et al. 2011; Vanous et al. 2017). The inducers were distinguished based on a visual marker carrying a dominant anthocyanin gene (Chase and Nanda 1965; Nanda and Chase 1966; Neuffer et al. 2009; Vanous et al. 2017). This provides a unique opportunity for the selection of mature haploid kernels. Both haploid and diploid kernels contain a purple-colored endosperm, but embryos of haploid kernels are colorless. Haploids have actual value when experts double them to be homozygous breeding lines in just one step, and all genes on pairs of chromosomes in the plant are completely identical (Boerman et al. 2020). The haploid technology allows plant breeders to produce lines within two generations compared to traditional methods, which require 10 generations. Doubled haploid plants are obtained via colchicine treatment. A haploid occurs when one copy of either parental chromosome remains, with the elimination of the chromosome from the other parent. The reduced time and increase in the expertise of this technology regarding the development of new hybrids that can afford higher-yielding and better-adapted seeds constitute an important step for growers (Vanous et al. 2017; Chaikam and Prasanna 2020). All commercial companies engaged in hybrid-seed production use haploids to shorten the pure lines production cycle, which is employed as parents in hybrid production. Haploid seeds are selected, cultivated in greenhouses, and injected with colchicine before transferring them to the field. Plants that exhibit a fertility-restoration ability are self-pollinated to generate a DH line. Haploid male fertility remains the greatest challenge to the success of this technique, with an average of 20–25% of haploids exhibiting pollen shedding and, therefore, the ability to become DH lines (Vanous et al. 2017; Boerman et al. 2020).

This technology involves four basic steps, in the following order: (1) in vivo haploid generation by maternal induction, (2) haploid kernels production and seedlings roots using a coloration marker, (3) doubling of the chromosomes using a mitotic inhibitor, and (4) production of self-pollinated doubled haploids. For a haploid generation in vivo by maternal induction and the selection of a donor female for the induction process, plants are cultivated in the field when the weather is appropriate. The inducer genotype is cultivated at a rate of one plant for six donor plants, and the inducer plantings are delayed for 1–2. The donor genotypes are either an F_1, F_2, or a randomly mating population. When flowering begins, precautions should be taken to prevent cross-pollination, and tassels can be removed from donor plants, followed the use of inducer parent (male) to pollinate the female genotype. Providing an adequate number of pollinations is essential because only 8% of haploids on average yield progeny. The haploid kernels are selected after reaching full maturity with 30% moisture (Nielsen 2001) and kernel dormancy before harvesting. Haploid kernels are identified and selected based on the phenotypic marker is dominant anthocyanin (R1-nj), which provides red pigmentation to aleurone grains and purple pigmentation to embryos, thus indicating the generation of a hybrid between the inducer parent and the female genotype (Eder and Chalyk 2002; Chaikam and Prasanna 2020). The pigmentation of aleurone grains and its absence in embryos indicate a putative haploid kernel possessing only the female genotype (Fig. 37.4). With a female genotype carrying a dominant anthocyanin inhibitor gene, such as C2-Idf, C1-I, and In1-D, precise determination of haploid kernels based on the R1-nj marker would not be possible (Eder and Chalyk 2002). Pl1 (Purple1) is another phenotypic marker used for selection, which confers red pigmentation to the seedling roots as another indicator that can be used for haploid/hybrid discrimination and more accurate selection (Vanous et al. 2017; Boerman et al. 2020).

A hybrid between the inducer parent and the female genotype may produce red roots, although the haploid seedling may still produce white roots. The oil content

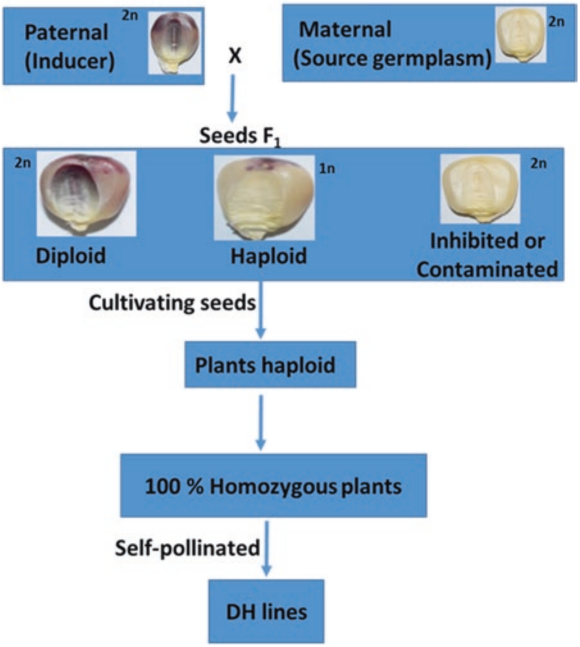


Fig. 37.4 General steps of producing DHLs in maize by using an inducer and chromosome doubling of the genome

of the kernel (using high-oil inducers) is another recently established phenotypic marker of haploid kernels, as they have a higher oil content compared with the female genotype (Melchinger et al. 2013). High-quality mutants of commercial crop mat rush were developed by colchicine application (Xu 2010). Near-infrared spectroscopy allows the selection of single haploid kernels based on composition and pigmentation (Jones et al. 2012). In turn, nuclear magnetic resonance spectroscopy can identify haploid kernels in the hybrid with at least 2% lower oil content than the inducer (Melchinger et al. 2013). Seeds are germinated in trays using limited soil while maintaining the level of soil moisture. The tray bottom must be sealed because of the possibility of producing light-induced anthocyanin in roots. A female genotype carrying a recessive gene to light (pl1), the tissue that is exposed to light develops a “sun-red” phenotype (Eder and Chalyk 2002; Vanous et al. 2017). One week later, root coloration allows the selection of haploid seedlings, which should be gradually withdrawn from the trays to limit the damage. Seedling roots are washed to remove the attached soil and better observe their coloration. Diploid seedlings with red/purple roots or false positives of kernel color selection (R_1-nj) are eliminated, while haploids are screened for white roots (Fig. 37.3). Seedlings are retransferred to pots until they reach the two- to three-leaf stage. The next step consists of genome doubling, representing the major obstacle to DH production. The doubling of haploid plants shows 20–25% male and female fertility with an 8–10% DH line generation success rate. Therefore, sufficient haploids must be used to ensure access to an adequate number of DH lines. Each stalk is injected with approximately 100 μl of colchicine solution (0.125%) containing 0.5% dimethyl sulfoxide for successful chromosome doubling (Eder and Chalyk 2002). Watering must be avoided for a couple of hours after injection, and the plants are placed out of direct sunlight for over 4 h. The injection delivers colchicine directly to the shoot apical meristem, the meristematic region from where tassel and silks originate. Colchicine should be handled with caution, and all safety precautions must be taken, as it is a chemical that poses a risk for both the user and the environment. Moreover, many governmental restrictions are in place regarding its usage and disposal (Melchinger et al. 2013). Colchicine inhibits the formation of spindle fibers by inhibiting spindles during mitosis, resulting in one cell in the mitosis phase instead of two cells, albeit with two copies of its DNA (Bartels and Hilton 1973).

Commercial herbicides also interfere with spindle fiber function. For example, amiprophos-methyl, oryzalin, pronamid, flufenacet, propham, nitrous oxide, and trifluralin may mutate crop or weed plants (Melchinger et al. 2013; Bartels and Hilton 1973). A combination of amiprophos-methyl and pronamid has yielded a success rate of DH production similar to that of colchicine. This combination is far less toxic and safe to humans than colchicine, thus holding promise as an alternative to this drug (Melchinger et al. 2013). Recently, several attempts have been made to induce spontaneous male fertility doubling in maize to allow a direct chemical application to putative haploids (Boerman et al. 2020). The final step of DH production process is the self-pollination of developed DH plants. The seedlings are transplanted to the open field 2 days after colchicine treatment and watered if needed. The key to the success of doubled plantlet growth lies in the appropriate care, as the

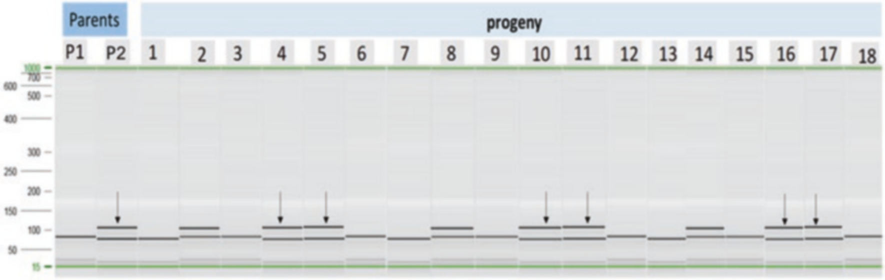


Fig. 37.5 MAS scheme for progeny selection in early generations from the typical breeding program. Using MAS, breeders may substitute large-scale field experiments, eliminate unwanted progeny and retain only the desired progeny (indicated by arrows)

newly developed plants are highly sensitive to any stress. Only weeks after growth, haploid plantlets can clearly be distinguished from the hybrid plantlets as they generally are taller and more robust, usually showing typical growth styles and red/purple stalk coloration (Fig. 37.5). In contrast, haploid plantlets with narrow and erect leaves may produce white stripes (Chase 1969; Vanous et al. 2017). The hybrid plants are left out to avoid shading and competition with the weaker haploids. Once shoots emerge, they should be bagged till pollen begins shedding, and then pollen should be collected directly from the taped anthers. Some anthers may need additional treatments if they do not naturally release pollen during the collection. If silks emerge after pollen shedding, cutting the tip of the husk leaves may be required to detect them, followed by the scattering of the pollen over the silks and their coverage with the bag used for pollen collection. Haploid plants should be monitored every day, as pollination can be repeated a maximum of two times when more fertile anthers reemerge.

8 Marker-Assisted Breeding

Molecular markers are commonly used in many plant breeding programs primarily because they accelerate breeding speed and efficiency. Thus, this represents a creative strategy and an impressive methodology for plant improvement. Plant molecular tools are often used to identify and manipulate genes regulating phenotypic defects (Huang 2016). Furthermore, molecular biological techniques are on a large scale for developing biofortified crops and varieties with high productivity and stress tolerance (Schaart et al. 2016; Ahmar et al. 2020). Molecular markers help plant breeders combine conventional methods with molecular tools to overcome the phenotypic variations of genotypic traits, selection, and genetic advances (M Perez-de-Castro et al. 2012; Barakat et al. 2020a). Molecular markers can facilitate identifying diverse cytoplasmic male sterility sources, which helps increase productivity by hybrid breeding. Several fertility-restorer genes have been identified in maize, sorghum, and rice (Dwivedi et al. 2008). With the progress of molecular marker analysis, it is now possible to analyze both qualitative and quantitative traits and to understand the gene-specific effect. For example, modern analytical techniques such as bulked sergeant analysis, linkage mapping, genome resequencing, and fine gene mapping allow studying the structure and function of target genes in crops (Zou et al. 2016; Bolger et al. 2014; Ahmar et al. 2020). Molecular markers have made a valuable contribution to the breeding programs, and allowed the identification and exploration of single-base-pair polymorphisms based on single sequence repeats, unique biomarkers linked to localized genes or quantitative trait locus (QTLs) associated with important traits, single-nucleotide polymorphisms, and germplasm enhancement (Dhingani et al. 2015; Rahim et al. 2020). MAS is a direct trailing change mechanism that enhances backcrossing efficiency and identifies homologs in the progeny phenotypes (Nadeem et al. 2018). This chapter sets out general protocols for the practical application of marker-assisted breeding (MAB) in plants, such as marker-assisted selection (MAS), marker-assisted recurrent selection (MARS), marker-assisted backcrossing (MABC), and marker-assisted gene pyramiding (MAGP). MAB is not a substitute for conventional breeding; rather, it is complementary to its efficiency, which would afford a comprehensive strategy to the conventional breeding programs, for future crop enhancement.

9 Marker-Assisted Selection

Marker-assisted selection (MAS) combines DNA markers with the traditional breeding method. For example, the general procedures are described through the following steps using a single cross (Jiang 2015):

- Step one: Parents are selected and crossed; at least one parent contains the DNA marker allele for the target trait (Fig. 37.5).
- Step two: F_1 plants are cultivated, and the marker alleles are examined to exclude false hybrids.
- Step three: F_2 plants are cultivated, and the individuals carrying the intended marker allele(s) are segregated and harvested.
- Step four: F_3 plants are cultivated, and the plants containing the target marker(s) and other desirable traits are segregated and harvested.
- Step five: In the F_4 to F_6 generations, the individuals carrying the intended marker alleles are harvested by paying greater attention to superior individual plants within homozygous lines/rows. The desired lines are bulked based on the phenotypic assessment for the target gene and other desired traits and marker data.
- Final step: Comprehensive evaluation and screening of the selected lines for yield, quality, tolerance, and other necessary traits.

In fact, the selection of all QTLs or genes at the same time is almost impossible; therefore, the plants containing the maximum desired QTLs are selected based on available resources and facilities (Jiang 2015; Rahim et al. 2020). A greater number of QTLs in MAS do not preclude a higher prediction accuracy (Zhang et al. 2016), particularly as their heritability decreases in highly complex multigenic traits compared with simple traits (Jiang 2015). The significant progress in genotyping technologies may simultaneously allow SNP markers and QTLs to be selected simultaneously (Kumpatla et al. 2012).

The ideal number of genes/QTLs is three to four in cases where the selected QTLs depend on the linked markers, and it may change range from five to six if known loci are directly selected (Jiang 2015). The QTLs stable across multiple environments and plant populations should be prioritized as they explain the highest percentage of phenotypic variation (Flint-Garcia et al. 2003). The markers close (<5 cm) to the gene/QTL of interest reduce the unwanted recombination between the marker and QTL/gene in selected individuals. A marker distantly linked to a gene of interest may result in poor MAS efficiency, as recombination between the marker and the gene may alter the linkage association during crossover and lead to selection errors (Singh and Singh 2015). Competence is very important for a breeding program; using two markers (flanking markers) rather than a single QTL is suggested for tight linked with the QTL of interest (Singh and Singh 2015). This minimizes the chance of errors caused by a more effective MAS and homologous recombination, resulting in only a double crossover; however, the incidence of double crossovers is extremely low (Jiang 2015).

Most climate-smart crops are polygenic in nature, as multiple QTLs regulate the desired traits. Thus, the application of MAS for improving these traits is a complex task that includes several genes or QTLs, QTL × E interactions, and epistasis (Jiang 2013). The QTL × E interactions reduce the effectiveness of MAS and the epistasis that might have a QTL effect on an intended trait. Hence, phenotyping of the quantitative traits and understanding marker (phenotype interaction) is a complex task. Multilocational/years field trials with appropriate experimental design are needed to accurately quantify the QTLs effect and their stability across environments (Jiang 2015). Composite interval mapping allows the integration of multilocational data for combined analysis to understand QTL–environment interactions and to achieve stable QTLs performance. In the last 20 years, it has been noted that applying MAS to plant breeding has been an important strategy for an effective use of genetic resources. Moreover, many DNA markers are available, thus enabling the development of improved cultivars with increased yield, stress tolerance, and quality in several crops, including wheat, rice, barley, wheat, beans, tomato, and potato. It is envisaged that MAS will become a broader scale application for quantitative trait enhancement in several crops.

10 Marker-Assisted Backcrossing

Marker-assisted backcrossing (MABC) is currently among the most commonly used molecular breeding techniques and has been applied successfully in several crops, e.g., wheat, maize, rice, barley, soybean, tomato, and pear millet for breeding for stress tolerance (Collard et al. 2005; Dwivedi et al. 2007; Xu 2010; Hasan et al. 2015). MABC is critically essential when: (1) phenotyping is complex and/or costly or impossible; (2) the target trait is expressed late in the plant lifetime; (3) low heritability of the target trait; and (4) the traits are governed by genes requiring specific conditions for expression and/or by recessive genes. It is, therefore, an integrated approach and/or a valuable complement to traditional breeding endeavors (Jiang 2015; Rahim et al. 2020). MABC is among the simplest type of marker-assisted selection methods, which is now successfully and widely used in many practical molecular breeding programs (Jiang 2013; Hasan et al. 2015). It allows the transfer of a single or a few genes/QTLs of interest from a genetic source, i.e., donor parent, agronomically insignificant due to unwanted comprehensive performance to an excellent cultivar (recurrent parent) or elite in most agricultural traits (but lack of an intended trait), to enhance the targeted traits. The desired alleles (traits) linked to gene(s)/QTL(s) are transferred to substitute insignificant traits, unlike traditional backcrossing, where target genes of unknown origin are transferred.

The general MABC steps include selection of parents based on the use of one parent with excellent overall performance [used as recurrent parent (RP)] and the other parent (RP) possessing alleles of markers associated with or the phenotypic performance of gene(s)/QTL(s) of target trait. Step two: F_1 plants are cultivated, and the marker alleles are detected to exclude false hybrids, followed by the mating of the actual F_1 plants again to the RP. At an early stage, all BC F_1 plants are checked in search of individuals carrying the intended marker allele(s) (heterozygosity) for remating with the RP. The same procedure is repeated until the fourth generation (BC4 F_1), when individual plants with the intended marker(s) are screened for the target trait, and the individuals carrying homozygous RP marker alleles for the intended trait are eliminated. The plant individuals that exhibit the marker allele(s) are harvested. The BC4 progeny of plants is self-pollinated (BC4 F_2) to detect the markers and harvest plants carrying marker allele(s) of the donor parent (DP) of intended trait (in homozygous status), for further assessment and release. In traditional backcrossing (blind backcrossing only) without the selection of an intended trait during the backcrossing, 50% from RP genome is added in each generation, and the RP genome after n generations of backcrossing is given by $(2^g - 1)/2^g)^n$, where g is the number of backcrossing generations and n is the number of genetic loci. Thus, there is a need for six to eight generations of backcrossing to fully recover the RP genome, and might take more time in cases linkage drag and especially between the target gene and other unwanted traits (Jiang 2015). The MABC program helps speed up QTLs/genes and the recovery of the RP genome via selection using markers flanking the QTLs and evenly spaced markers from other chromosomes of the RP (Collard et al. 2005; Hasan et al. 2015), as some individuals owned more and/or less than 50% of the RP genome in each generation (Fig. 37.6).

In the MABC program, the target DP marker allele(s) is selected to sustain heterozygosity of the intended locus throughout the backcrossing process. Subsequently, the plants containing homozygous for DP allele(s) of the target markers are selected and tested for further assessment and final release as a hybrid/cultivar. Several factors contribute to the efficiency of this selection process. These include the number

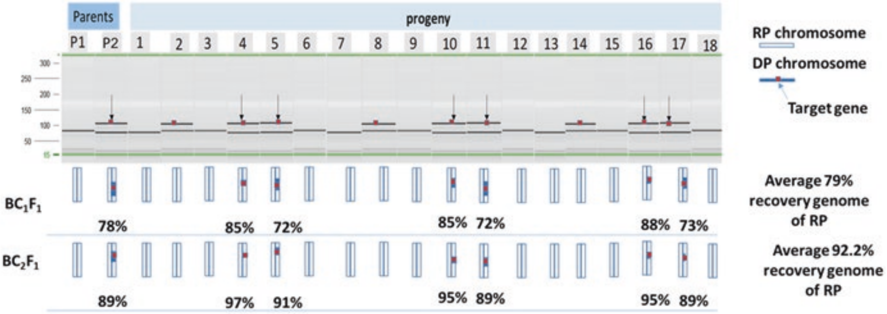


Fig. 37.6 General steps of selecting heterozygous genes through genotyping analysis of RP genome at BC1F1 and BC2F1

of selected genes/loci, the distance between the marker and gene of interest, and the unwanted linkage to the target gene (Jiang 2015). Selection is based on the marker alleles of the RP in whole genomic regions, except the intended locus. Alternatively, the desired plants are selected by eliminating the unwanted genome of the DP. The objective of this approach is the speedy restoration of the RP genome (contingent on the number of markers used and even distribution on all chromosomes) and the elimination of unwanted genes obtained from the DP. In the MABC program, individual plants are selected based on the presence of marker genes/QTLS of the target trait may (selection of the foreground), followed by rescreening for other RP markers (selection of the background). The screening for a target gene/QTL of interest is the crucial point of the backcrossing program, as it excludes unwanted individuals during the initial phase of a breeding program.

Several factors affect the efficiency of MABC, such as the size of the population used, marker-gene linkage (marker distance) with the intended locus, and the number of markers used, as well as unwanted linkage problems. Neeraja et al. (2007) reported that during each breeding cycle, the MABC program allows the selection of heterozygous individuals for the target locus. The RP alleles on the target chromosomes are selected for two flanking markers located approximately 2 cm away from the intended locus. Collard et al. (2005) and Neeraja et al. (2007) signaled that a speedy restoration of the RP genome could be realized through MABC via foreground and background selection, thereby saving time compared with the conventional backcrossing (Fig. 37.7). Linkage drag could be reduced using two markers flanking the intended gene and selecting individuals heterozygous for the intended trait and homozygous for RP alleles at both flanking markers (Jiang 2013). Using tight flanking markers substantially improves the effectiveness of the process, with a rapid reduction in linkage drag. However, at the same time, a lower distance results in a severe shortage of double recombination events; therefore, this requires using larger populations with more genotyping. Therefore, it is crucial to identify the minimum population size required to ensure access to the desired genotypes. Technically, with three to four backcrossing cycles, above 99% of the RP genome is

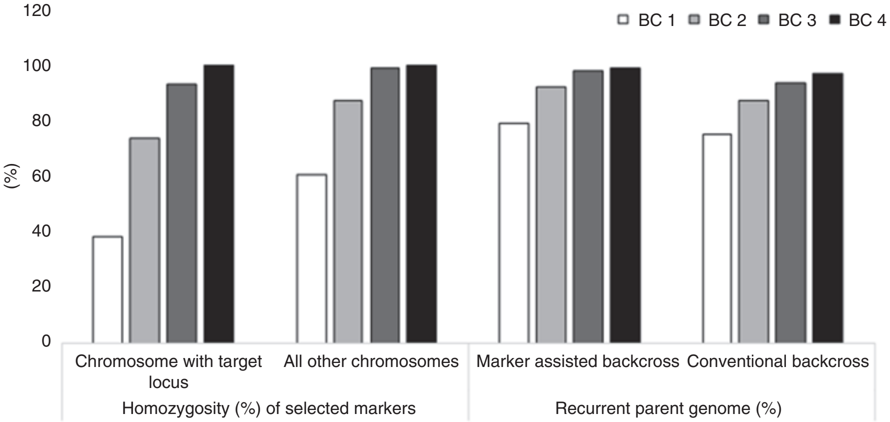


Fig. 37.7 Expected percentage of a MABC program after backcrossing. (Adapted from Jiang 2015)

transferred, provided there are at least two or three markers per chromosome and assuming the involvement of the whole chromosome (Ribaut et al. 2002).

11 Marker-Assisted Recurrent Selection

Recurrent selection is a proactive strategy for improving multifactorial inheritance traits (Jiang et al. 1993). However, this method may not be highly efficient in many cases, primarily because the phenotypic expression depends on environments and genotypic selection for one cycle requires two to three crop seasons (Jiang 2015). The MARS, in contrast, allows genotypic selection (in the early stage) and hybridization (after flowering) in a single season (Fig. 37.6). Thus, it can foster the competence of recurrent selection, accelerate progress toward achieving the plant breeder goals, and help integrate multiple suited genes/QTLs obtained from different plant sources based on a multiple-parental population (Jiang et al. 2007). For polygenic traits such as yield and stress tolerance, MARS-based forward breeding for native genes and pyramiding multiple QTLs are suggested (Crosbie et al. 2006; Jiang 2013). With the use of molecular markers, MARS allows the identification and selection of multiple genomic regions for polygenic traits and screening for an ideotype in a single population or across its populations (Ribaut et al. 2010; Jiang 2015).

The MARS has been found effective in detecting yield-associated QTLs in maize programs through the wide-scale application of molecular markers in same-parent plant populations allowing fast recombination and selection-based markers. This accelerated the selection efficiency over the long run through identification of more frequent favorable alleles (Jiang 2015). For example, genetic gain achieved by MARS in maize showed a twofold increase over phenotypic selection in the same reference populations (Eathington et al. 2007; Crosbie et al. 2006). Moreover, in upland cotton, the effectiveness of MARS was identified regarding the breeding of resistance to *Helicoverpa armigera*, which was more competent after recurrent selection compared with earlier populations (Bankole et al. 2017).

12 Marker-Assisted Gene Pyramiding (MAGP)

In pyramiding breeding based on MABC genes/QTLs, also known as multiline breeding, three modalities may be used for its implementation: consecutive/continuous, simultaneous and convergent backcrossing to transfer the intended genes to an Elite cultivar (excellent) in most agricultural traits, the "RP" (Jiang 2013). Supposing four different genes/QTLs (a, b, c and d) contributing to the intended trait and having identified four different donor genotypes (Donor-1^A, Donor-2^B, Donor-3^C and Donor-4^D), it should be transferred to the excellent cultivar. In consecutive and continuous MABC, one intended gene/QTL is transferred to the RP, followed by another gene/QTL using MABC, until the four intended genes/QTLs have been transferred into the RP (Fig. 37.8). One of the major characteristics of this method is the high accuracy of gene pyramiding and easy implementation as it encompasses only a single gene/QTL, hence keeping the population size smaller. A superior RP may be developed after three or four backcrosses, as long as the integrated genes/QTLs satisfy the requirements (Jiang 2015; Zhong et al. 2019). However, it has shortcomings because it is more time-consuming than the simultaneous or convergent method.

In simultaneous MABC, the excellent cultivar "RP" is first crossed to each of four different donor genotypes (Donor-1^A, Donor-2^B, Donor-3^C, and Donor-4^D) to produce four F_1 hybrids (Fig. 37.9). Every two hybrids are crossed to produce two F1 hybrids, which are recrossed for developing a hybrid combining the four intended genes/QTLs in a heterozygous state. Subsequently, a multiline hybrid is backcrossed to the RP until RP genome restoration is achieved. The selected plants are self-pollinated to restore homozygosity (Jiang 2015). Note that this method is faster. However, it requires a large population size and additional genotyping. In convergent MABC, the excellent cultivar "RP" is first crossed to each of four different donor genotypes (Donor-1^A, Donor-2^B, Donor-3^C, and Donor-4^D) to produce four F_1 hybrids (Fig. 37.10). Subsequently, each hybrid is individually crossed back to the RP until the restoration of the RP genome, and self-pollinating within one generation is performed to obtain genes in the homozygous state. Two improved lines are crossed to produce two F_1 hybrids, which are recrossed to produce a hybrid combining the four intended genes/QTLs in a heterozygous state. Subsequently, the multiline hybrid is self-pollinated within one generation to obtain genes in the homozygous state. It may, therefore, be suggested that convergent MABC is more acceptable because it combines the advantages of consecutive and simultaneous backcrossing (Collard et al. 2005; Jiang 2015). Gene pyramiding by MABC has been applied to many crops, e.g., rice, wheat, cotton, soybean, barley, and pea, especially to increase

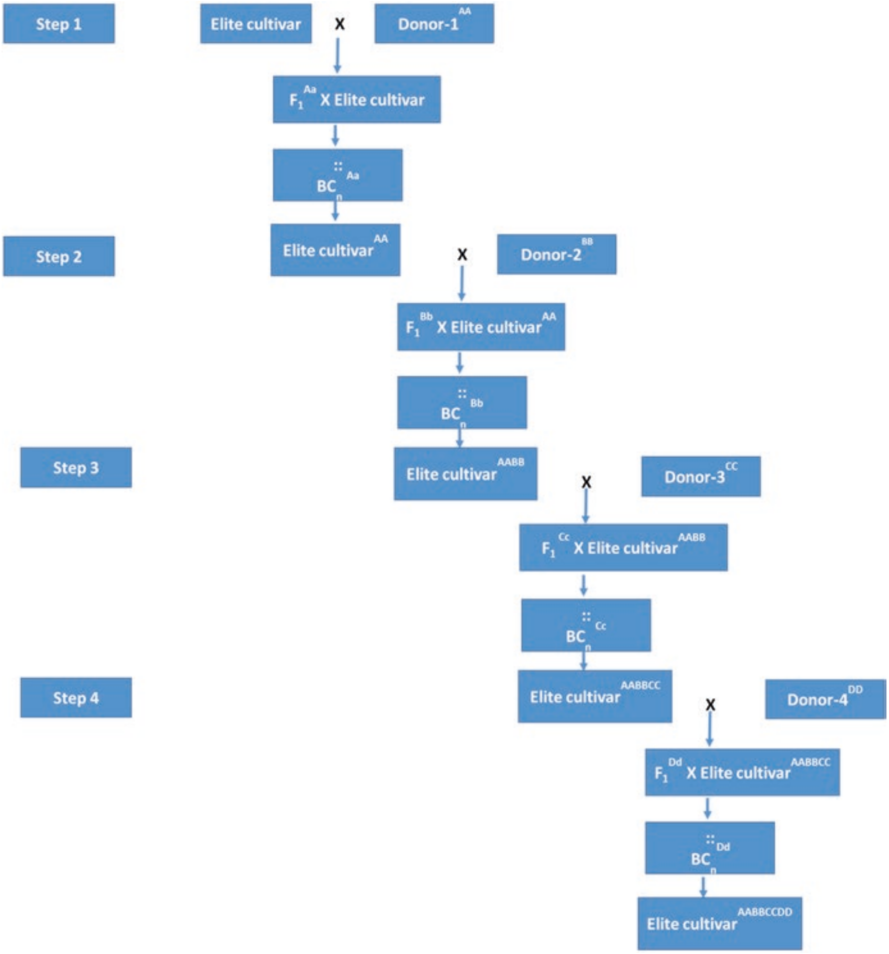


Fig. 37.8 Technique of consecutive/continuous marker-assisted backcrossing

tolerance and persistent resistance to stresses among crop plants (Jiang 2013; Ye and Smith 2008).

Computer-based simulations, i.e., the PLABSIM—a program that can simulate the possible recombination during meiosis, also highlight a relatively higher efficiency of RP restoration of marker-based selection than that of the traditional backcrossing (Frisch et al. 1999; Ribaut et al. 2002; Lecomte et al. 2004; Ye and Smith 2008). Therefore, markers can substantially shorten the cultivar development process compared to traditional backcrossing. However, the research on developing commercial cultivars through gene pyramiding MABC is very limited. Based on their relative importance, varying markers may be used for different breeding cycles to minimize the population size while maintaining the most important genes/QTLs (detectable and selected first in early generations) (Jiang 2015). Once a

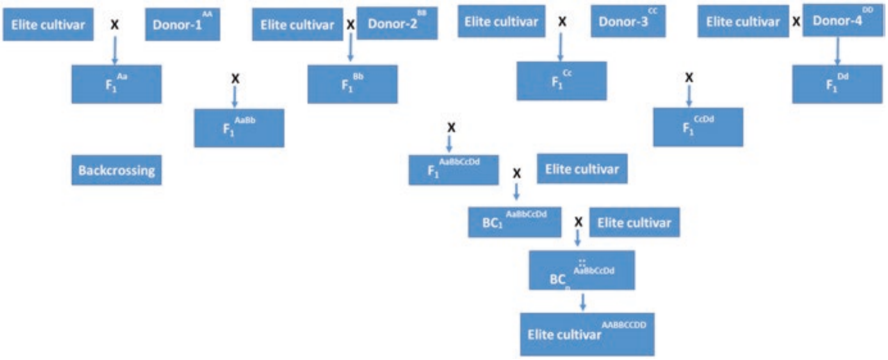


Fig. 37.9 Technique of simultaneous marker-assisted backcrossing

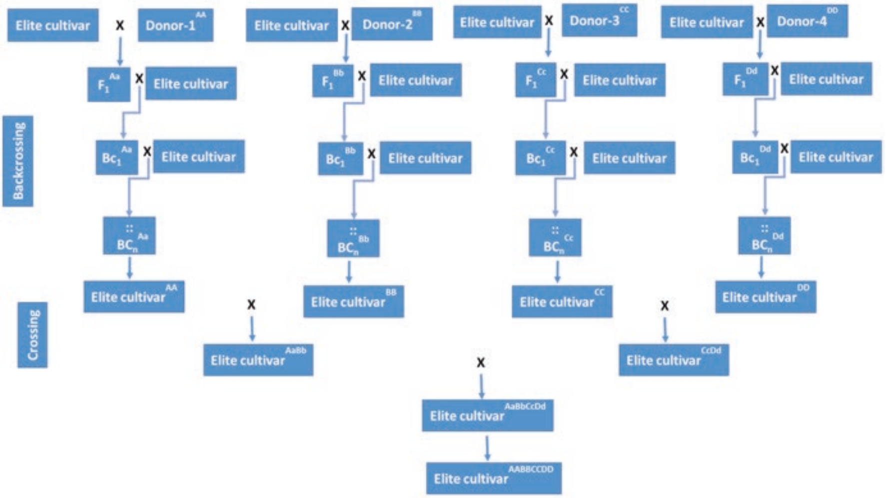


Fig. 37.10 Technique of convergent marker-assisted backcrossing

homozygous allele of the markers for a gene/locus has been detected, a phenotypic evaluation must be carried out.

13 Conclusions

Conventional breeding programs are time-consuming, laborious and expensive, requiring a large area of land for breeding and evaluation processes. However, diminishing nature cannot satisfy the increasing world demand for food, which will be even more complicated by inter-related factors. The commonly used crop improvement techniques in modern agriculture include hybrid and mutation breeding. The breeding programs assisted by fast-breeding approaches, such as the doubled haploid (DH) technique and high-throughput molecular markers, are likely to shorten the crop reproductive cycles. These tools help increase productive capacity when developing new crops and cultivars with for superior yield and tolerance to multiple stresses under complex environments. Plant breeding must always be comprehensive; thus, new genes are required to improve the new crops, cultivars, and desired traits by fast breeding. We conclude that fast-breeding techniques, accompanied by modern genetic tools and resources, allow plant scientists to widen their search in the crop-improvement field for sustaining the future of food production.

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Chapter 38
Crop Improvement of Rice (*Oryza sativa* L.) Utilizing Wild Species and Transgenic Rice

Deepu Pandita

Abstract *Oryza sativa* L., belonging to Poaceae family, is one of the most efficacious crops on the globe and staple food for more than half of the global population. The genus Oryza has 22 wild species and two cultivated species of rice. The wild rice species have novel valuable alleles that have vanished from cultivated rice due to domestication. Wild rice species could be plausible reservoirs of novel genes/ Quantitative Trait Loci (QTLs) to transfer lost diversity at genetic levels in the cultivated rice with elite genetic backgrounds for better agronomically important traits of grain yield, quality, and adaptation to stressors. The rice genome was sequenced under an International Rice Genome Sequencing Project in 2005. The databases for genomic sequences, genes, and QTLs of rice are available. Transgenic rice lines or genetically improved rice showed increased tolerance to salinity, drought, heat, and cold abiotic stresses with improved yields. Rice is genetically modified to combat attacks by bacterial, fungal, and viral pathogens and designing disease-resilient varieties.

Keywords Rice · Wild crop relatives · Transgenic crops · Crop improvement · Genetically improved plants · Stress

1 Introduction

Oryza sativa L. (rice) of family Poaceae is an important staple food for more than half of the global population. Rice accounts for 21% of global calorie intake, uses only 11% of global cropland, and is consumed globally in >122 countries (Awika 2011; Bandumula 2018; Brar and Khush 2018; FAO 2019). The global rice demand will be about 584 million tons or less toward 2050 (Samal et al. 2022). The worldwide production and yield in rice breeding programs are swiftly reaching plateau. Improvements in cultivated rice can be attained by breeding

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selectable genetic variability through infusion of novel alleles and genes present only in wild rice species. But the precise transfer of genomic sequences from wild rice species to cultivated rice is hindered by the barriers of incompatibility (Brar and Khush 2018). Recent biotechnological tools of tissue culture, genetic engineering, and genome sequencing will enhance understanding of functions of genes and Quantitative Trait Loci (QTLs) in wild species for improving the rice germplasm, and the shape of rice agriculture is on the road to change by 2050. Asia may lose about 5 million hectares and Africa may gain about 10 million hectares of rice land by 2050 (Samal et al. 2022). *Oryza* genus has 24 species, out of which 22 are wild (Fig. 38.1) and two are cultivated with different genomes, viz., AA, BB, CC, BBCC, CCDD, EE, FF, GG, HHJJ, and KKLL (Vaughan et al. 2003). High yielding *O. sativa* is cultivated worldwide, and low yielding *O. glaberrima* is endemic to West Africa. These genetic resources can aid in quality and quantity improvement of rice for sustained growth. Wild species have inferior plant type, with properties like seed shattering, reduced yield, and grain parameters, but are pools of novel genes and QTLs for characteristics such as tolerance to various abiotic and biotic stressors (Ikeda et al. 1990; Khush et al. 1990; Brar and Khush 2006; Bhasin et al. 2012; Lei et al. 2013; Luo et al. 2016; Sarao et al. 2016; Zhang et al. 2017; Dong et al. 2020; Yang et al. 2020; Cao et al. 2020), yield (Xiao et al. 1996; Luo et al. 2011; Gaikwad et al. 2014; Balakrishnan et al. 2020), quality of rice grains (He et al. 2017b; Qi et al. 2018; Gaikwad et al. 2018), cytoplasmic male sterility (Zebing and Yingguo 1988; Hu et al. 2016), restoration of fertility (Gaikwad et al. 2014), and heterosis for grain yield (Xiao et al. 1998; Luo et al. 2011; Gaikwad et al. 2019; Guttikonda et al. 2020). The current chapter offers information on wild rice species and their important traits and transgenic rice improved by introduction of transgenes.

Fig. 38.1 Oryza genus has 22 wild species

2 Wild Species of Rice

Oryza genus has 22 wild species (Fig. 38.1) with different genomes, viz., AA, BB, CC, BBCC, CCDD, EE, FF, GG, HHJJ, and KKLL (Vaughan et al. 2003), which are discussed in detail below.

2.1 Oryza rufipogon *Griff.*

Oryza rufipogon (with 2n = 24, and AA genome) is progenitor of *O. sativa* with polyphyletic origin. Indica variety is nearly linked with annual species *O. rufipogon,* and japonica variety is closely associated with perennial species *O. rufipogon* (Yang et al. 2012a, b). Backcross Inbred Lines (BILs), Chromosomal Segment Substitution Lines (CSSLs), Alien Introgression lines (ILs), Near Isogenic Lines (NILs), and Recombinant Inbred Lines (RILs) mapping populations of cultivated rice species were developed, and novel and high-value genes/QTLs for abiotic and biotic stress factors with impending nutritional traits were mapped from inbuilt resistant *O. rufipogon*.

Resistance genes of Bacterial Blight (BB) (causal agent *Xanthomonas oryzae* pv. Oryzae) Xa23 and Xa30; brown planthopper (BPH) bph18, bph19, bph20, Bph21, bph22, bph23, bph24, Bph27, bph29, bph30, Bph36, and Bph38; white backed planthopper (WBPH) resistance QTLs, viz., qWbph2, qWbph5, and qWbph9; and green rice leafhopper resistance gene Grh5 have been mapped from donor *O. rufipogon*. The tolerance to cold stress at seedling stage linked microRNAs (Jiang et al. 2019) and QTL, viz., qCtss11, was mapped from *O. rufipogon* (Koseki et al. 2010; Liang et al. 2018; Li et al. 2019; Shim et al. 2019; Shim et al. 2020; Yuan et al. 2020), whereas the genes and QTLs for tolerance to water deficiency (Luo et al. 2019); high-temperature tolerance (Cao et al. 2020); regions of QTL, i.e., qST1.2 (OsSKC1) and qST1.1 (OsHAK6) for salt tolerance (Quan et al. 2018), efficiency of high phosphorous (P) uptake (Deng et al. 2018); low nitrogen tolerance (Hu et al. 2015); and tolerance to the acidic soils; toxicity to iron (Fe); and deficiency of P (Brar and Khush 2006) have been identified and derived from donor *O. rufipogon*. CSSLs, BILs, and ILs with QTLs for the yield and quality of rice grains have been introgressed from *O. rufipogon* accessions into elite indica and japonica varieties. Chromosomal segment with highly expressed Os11Gsk gene was introgressed into indica rice restorer line (KMR3) and increased yield in rice hybrids (Thalapati et al. 2012).

2.2 Oryza nivara *S.D. Sharma and Shastry*

Oryza nivara (with 2n = 24, AA genome) is progenitor of *O. sativa* and is donor of tolerance to grassy stunt virus (Sharma and Shastry 1965; Khush and Ling 1974). Bacterial blight resistance gene Xa38 was donated from *IRCG81825* and *Xa33* gene from IRCG105710 accessions (Kumar et al. 2012; Bhasin et al. 2012). Cross of rice cultivar Bengal with IRGC100898 and IRGC104705 accessions mapped QTLs for resistance against the sheath blight (qSHB6) and blast (qBLAST8 and qBLAST12) (Eizenga et al. 2013). *O. nivara* is donor for novel and beneficial alleles for the improvement in productivity, yield, and quality of rice grains, and biotic and abiotic stress resistance traits. The genes/QTLs for resistance to BPH insects (Lakshmi et al. 2010; Madurangi et al. 2011; Sarao et al. 2016) and *Grh4* and *Grh6* genes for tolerance to green rice hopper pest have been transferred from *O. nivara.*

ILs cross breeding of Swarna and *O. nivara* (IRGC81848 and IRGC81832) displayed tolerance toward drought (Rai et al. 2010); Cadmium (Ma et al. 2019); heat (Prasanth et al. 2017); salinity regimes in K463, K467, and K478 (Ganeshan et al. 2016); tolerance to submergence in IRGC80507, IRGC101508, and ONIVA01G39120 (IRGC100897) (Dos Santos et al. 2017); fertility restoration (Rf) genes for Wild-abortive CMS (CMS-WA) and Honglian CMS (CMS-HL) systems (Li et al. 2005); and complete fertility restoration for CMS-WA line PMS 17A (Gaikwad et al. 2014). The progeny from cross of IR64 and *O. nivara* exhibited higher total seed protein and arginine content (Mahmoud et al. 2008). *O. nivara*-derived ILs (IL248S) DRR Dhan 40 is a high yielding variety with chromium heavy metal stress tolerance (Nayak et al. 2014), and BB tolerance Xa38 gene was introgressed into “Pusa Basmati 1,121” (Ellur et al. 2016).

2.3 **Oryza barthii** *A. Chev.*

O. barthii (2n = 24, AA) is progenitor of *O. glaberrima* (Zhang et al. 2014; Wambugu et al. 2015). *O. barthii* genome is sequenced by the International Oryza Map and Alignment Project (I-OMAP) (Zhang et al. 2014). *O. barthii* can act as a new food crop due to consumption as whole grains in times of food scarcity and is donor of genes for resistance to Rice Tungro Virus (RTV), stem borer, sheath blight, blast, and BB (Jain et al. 1989; Eizenga et al. 2003; Prasad and Eizenga 2008; Center AR 2010; Neelam et al. 2017). *O. barthii* possesses high amylose content (Wang et al. 2015), lower glycemic index, high nitrogen uptake, and lower efficiency of silicon uptake (Hamaoka et al. 2013; Mitani-Ueno et al. 2014).

2.4 **Oryza glaberrima** *Steud.*

Oryza glaberrima (with 2n = 24, AA genome) evolved in the location of West Africa. *O. glaberrima* is highly resistant to abiotic and biotic stressors (Wambugu et al. 2013). Repeated backcrossing between *O. sativa* and *O. glaberrima* developed new rice for Africa known as the NERICA rice (Somado et al. 2008), with higher yield potential and resistance to various stress factors, responding to low input conditions and competitiveness of weeds. NERICA lines were developed by crossing

TOG5681, TOG5674, and TOG5675 with a variety of IR64 and elite breeding lines of *O. sativa* (Moukoumbi et al. 2015). *O. glaberrima* has genes/QTLs for trait improvement, sterility loci (Li et al. 2018), and resistance and tolerance against BB (Gupta 2010), green rice leafhopper, Rice Stripe Necrosis Virus (RSNV), Rice Yellow Mottle Virus (RYMV), root-knot nematode (Fujita et al. 2010; Gutiérrez et al. 2010; Pidon et al. 2017; Lawilao et al. 2019), drought (Wambugu et al. 2015), salinity (Mondal et al. 2018a), toxicity to iron metal (Sikirou et al. 2016), and flooding (Agbeleye et al. 2019). Gene *xa45*(t) have been derived from IRGC102600B accession for resistance against BB and *Pi69*(t) gene from IRGC100137 accession for resistance against blast (Neelam et al. 2020; Dong et al. 2020). *O. glaberrima* grains have high amylose content due to SNPs, which increases quantity of gradually digestible and Resistant Starch (RS) (Wambugu et al. 2018).

2.5 **Oryza glumaepatula** *Steud.*

Oryza glumaepatula (with 2n = 24, AA genome) is solitary wild species of American native (Vaughan et al. 2003). *O. glumaepatula* is a source of novel alleles of agronomical significance and has been mapped for QTLs which contribute to traits of yield. IL (CNai 9930) which was developed showed highest mean yield in trials at multiple locations, superior grain quality, and high yield stability (Rangel et al. 2008). QTLs for yield of grains and architecture of grains were recognized in *O. glumaepatula,* and this information can be used for improving yield of cultivated rice.

2.6 **Oryza longistaminata** *A. Chev. and Roehr.*

Oryza longistaminata (with 2n = 24, AA genome) is generally dispersed in Africa and has high biomass and tolerates submergence (Melaku et al. 2013; Gichuhi et al. 2016). *O. longistaminata* possesses traits like resistance to BB, blast, green rice leafhopper, nematodes, yellow stem borer (Xu et al. 2015; Neelam et al. 2017; Thein et al. 2019), avoidance to drought (Brar and Khush 2002), lodging (Long et al. 2019), and weed competitiveness (Shen et al. 2016). IL (pLIA-1) has large biomass and panicles possessing primary and secondary branches and tall and thick culms (Gichuhi et al. 2016). The QTL qpsf6 for fertility to pollen grains and spikelet from *O. longistaminata* was mapped in the population of BC7F2 (Chen et al. 2009). *O. longistaminata* has BB resistance-dominant gene Xa21. The introgression of *Xa21* gene developed BB-resistant Xieyou 218, Guodao 1, Guodao 3, ILyou 218, ILyou 8006, Zongbai You 1; Improved Pusa Basmati 1, Improved Samba Mahsuri 1, and Tubigan 7, Tubigan 11 (Khush et al. 1990; Brar and Singh 2011), and Pusa Basmati 1728 and Pusa Basmati 1718 by the transfer of *Xa21* and *xa13* genes from *O. longistaminata* (Singh et al. 2018). *O. longistaminata* also possess Blast-resistant dominant gene *Pi57* (Xu et al. 2015).

2.7 Oryza officinalis *Wall. ex Watt*

Oryza officinalis (with 2n = 24, CC genome) is distributed in South China, Southeast Asia, and Papua New Guinea (Wang et al. 2009). Monosomic Alien Addition Lines (MAALs) for have been developed from this wild species (Tan et al. 2005; Jin et al. 2006). *O. officinalis* is gene reservoir for resistance to abiotic and biotic stressors. The genes for resistance against White backed planthopper (WBPH) (Wbph7, Wbph8), Brown planthopper (BPH) (Bph10, bph11, Bph13, Bph14, Bph15), and BB (Xa29) have been recognized. MTL 98, -103, and -110 introgression lines have resistance to BPH (Brar and Singh 2011).

2.8 Oryza meridionalis *N. Q. Ng*

Oryza meridionalis (with 2n = 24, AA genome) has Northern Australian native (Wurm et al. 2012). *O. meridionalis* has high amylose content and improved kernel elongation after process of cooking (Khush 1997), tolerance to drought, heat, salinity, and toxicity to iron (Gouda et al. 2012; Scafaro et al. 2016; Yichie et al. 2018; Wairich et al. 2020). The yield-increasing traits of *O. meridionalis* were introgressed into the cultivated rice species. The CSSL population and pure lines derived from this population had better yield (Varma et al. 2012).

2.9 Oryza meyeriana *(Zoll. and Moritzi) Baill.*

Oryza meyeriana (with 2n = 24, GG genome) is source of resistance to BB in rice (Fu et al. 2009). The continuous breeding programs developed NIL (Y73) with resistance to BB (Wang et al. 2013), and SH76 and ASH1 with QTLs (qBBR1, qBBR3, and qBBR5) impart resistance to pathogens of BB (Han et al. 2014). Chen et al. (2012) mapped major QTLs responsible for the resistance to BB and yield traits. *O. meyeriana* has spherical starch granules with pinholes which affects digestibility (Kasem et al. 2011).

2.10 Oryza australiensis *Domin*

Oryza australiensis (with 2n = 24, EE genome) has grains of shorter size, with amylose of high content, higher gelatinization temperature, low retrogradation, and low pasting viscosity (Tikapunga et al. 2017). The genes for resistance against BB (xa32) and BPH (Bph10 and Bph18) have been recognized (Kasem et al. 2012). The gene sequences of Granule-bound starch synthase 1 (GBSS1), starch synthase IIa (SSIIa), and starch-branching enzyme IIb (SBEIIb) of this wild species differed from other species of genus *Oryza*.

2.11 **Oryza brachyantha** *A. Chev. and Roehr*

Oryza brachyantha (with 2n = 24, FF genome) is native to Africa and has genome size of 261 megabases (Chen et al. 2013). Brar et al. (1996) reported transfer of genomic segments to *O. sativa*. The resistance to yellow stem borer in *O. sativa* was done by developing MAALs (Narain et al. 2016). *O. brachyantha* is donor of resistance to BB (Brar and Khush 2002) and leaf folder (Yamakawa et al. 2008) and has 251 resistance and 86 defense-related genes (Singh et al. 2015).

2.12 **Oryza latifolia** *Desv.*

Oryza latifolia (with 2n = 48, CCDD genome) is related to *O. grandiglumis* and *O. alta* in traits of morphology and chromosomal homology (Kihara 1964) but differs in genomic and phylogenetic investigations (Bao and Ge 2004). *O. latifolia* shows resistance to BB, WBPH, and BPH (Multani et al. 2003; Angeles-Shim et al. 2020) and is donor of panicles with longer size, plenty of spikelets, production of high biomass, and tolerance to lodging stress (Bertazzoni and Damasceno 2011). MAALs exhibited strong stem (Angeles-Shim et al. 2014), and solitary dominant gene Bph12 was introgressed in B14 (Yang et al. 2002). Putative QTLs exhibit tolerance to the diverse Philippine races of BB (Angeles-Shim et al. 2014).

2.13 **Oryza minuta** *J. S. Presl. ex C. B. Presl.*

Oryza minuta (with 2n = 48, BBCC genome) has BB resistance genes, namely, *Xa27* and *Xa35,* in accessions of IRGC101141 and IRGC101133. *O. minuta* is donor of five dominant BPH resistance genes (Bph16, Bph20, Bph21, Bph22 and Bph23). *O. minuta* accessions show resistance to WBPH (Asaf et al. 2016), sheath blight (Jena 2010), and yellow stem borer (Panigrahi and Rajamani 2008). QTLs for resistance to blast disease were qK1307-2 and qK1209-3 (Rahman et al. 2011), and yield-enhancing QTLs were also present.

2.14 Oryza alta *Swallen*

Oryza alta (with 2n = 48, CCDD genome) wild species has higher biomass and resistance against Striped Stem-Borer (SSB), Bacterial Grain Rot (BGR) (Veasey et al. 2008; Mizobuchi et al. 2016), Sheath Blight (SB), and blast diseases (Eizenga et al. 2009).

2.15 Oryza grandiglumis *(Doell) Prod*

Oryza grandiglumis (with 2n = 48, CCDD genome), native to South America, is very tall, with broad leaves, long ligules, high biomass, and highly tolerant to submergence stress through novel SUB1A-independent mechanism and shows competitiveness to weeds (Niroula et al. 2012; Okishio et al. 2015). *O. grandiglumis* has gene(s) for resistance to various stress factors and QTLs for traits of grain yield.

2.16 Oryza coarctata *Roxb.*

Oryza coarctata (with 2n = 48, KKLL genome) is tetraploid, Asian wild rice and only halophyte with excellent salt tolerance in the genus *Oryza*. *O. coarctata* is native to coastal regions and known as Uri-Dhan in India (Vaughan et al. 2005). It has genes and QTLs linked to tolerance of salt and submergence stresses. The genomic segments have been transferred from this species into IR28 and IR36 (Jena 1994). Marker studies showed *O. australiensis* to be closely associated to this species (Rangan et al. 2002). *O. coarctata* is a model plant to study salt tolerance mechanisms (Mondal et al. 2018b).

2.17 Oryza punctata *Kotschy ex Steud.*

Oryza punctata (with 2n = 24, BB genome) is red rice, native to locations of tropical and Southern Africa and Madagascar (Vaughan et al. 2005), resistant to Brown planthopper (BPH), green leafhopper (GLH) (Jena 2010), and biotic stress and tolerant to high temperature and water deficiency (Sanchez et al. 2013). Jena et al. (2016) developed Monosomic alien addition lines (MAALs) and disomic introgression lines (DILs) by cross breeding between autotetraploid indica rice and this wild species to tap valuable traits for the improvement of cultivated rice. DILs were distinguished with numerous traits linked to resistance to BPH, GLH, blast, and BB diseases.

2.18 Oryza rhizomatis *Vaughan*

Oryza rhizomatis (with 2n = 24, CC genome), native to Sri Lanka, has extensive root system and rhizomes for growth under heavy drought scenarios (Somaratne et al. 2018). *O. rhizomatis* is suitable for development of drought-tolerant rice and has tolerance to submergence and salt stress traits and BPH, blast, and GLH diseases. Blast resistance gene *Pi54rh* of this species leads to broad-spectrum resistance in *Magnaporthe oryzae* (Niroula et al. 2012; Das et al. 2012; Prusty et al. 2018). MAALs and DILs resulting from this wild species showed resistance to BPH and GLH (Hechanova et al. 2018).

By utilization of these wild species, ILs, CSSLs, BILs, NILs, and DH can be generated for mapping of genes and QTLs of vital agronomic traits which can be introgressed to the elite genetic backgrounds. *O. rufipogon* possesses tolerance to acid soils (Mandal and Gupta 1997), *O. meyeriana* and *O. granulata* tolerate shade or low light intensity (Vaughan et al. 2003), and *O. nivara* possesses high content of micronutrient traits (Swamy et al. 2012). Oryza Map Alignment Project (OMAP) is comprehensive genomic repository of wild rice germplasm and provides robust framework of unlocking genetic potential of wild rice species to discover novel agriculturally imperative genes/QTLs (Wing et al. 2005) and introgress in cultivated rice by breeding or transgenic approaches.

3 Transgenic Rice

The rice genome was sequenced (International Rice Genome Sequencing Project 2005), and databases for genomic sequences and genes (Sakai et al. 2013) and expression profiles of genes (Sato et al. 2011; Kawahara et al. 2016) and detected QTLs (Yonemaru et al. 2010) are available. Transgenic rice lines or genetically improved rice plants showed improved tolerance to salinity, water deficiency, and high- and low-temperature stresses with improved grain yield (Chang et al. 2017; Reddy et al. 2017; Sahebi et al. 2018; Fang et al. 2019; Moon et al. 2019; Tang et al. 2019). Rice is genetically modified to combat attacks by bacterial, fungal, and viral pathogens and design disease-resistant varieties (Heinrichs and Muniappan 2017).

3.1 Transgenic Rice for Salt Tolerance

A number of gene/transcription factors used for developing transgenic rice for salt stress tolerance includes OsMYB6 (Tang et al. 2019), SaSRP3-1 and SaVHAc1 (Biradar et al. 2018), ZAT6 (Tang and Luo 2018), IDS1 (Cheng et al. 2018), OsCLC1 (Um et al. 2018), and OsMADS25 (Xu et al. 2018). *Thellungiella halophila* inorganic pyrophosphatase (ThPP1) rice transgenics showed amplified tolerance

(He et al. 2017a). SfIAP (*Spodoptera frugiperda* inhibitor of apoptosis) when used for generating rice transgenics displayed increased tolerance to salinity (Hoang et al. 2014). The overexpression of barley calcium-sensor calcineurin B-like (CBL) protein in rice showed decline in absorption of sodium (Guo et al. 2016). CRISPR/Cas9 editing of *OsRR22* gene generated mutant lines with increased tolerance to salinity (Farhat et al. 2019; Zhang et al. 2019).

3.2 Transgenic Rice for Drought Tolerance

There are a number of examples of transgenic rice lines developed for enhanced tolerance to drought stress by using various genes and transcription factors which includes Flowering Locus T-like (FTL) genes (OsFTL10) (Fang et al. 2019), sugarcane R2R3-MYB genes (ScMYBAS1-2 and ScMYBAS1-3) (Peixoto-Junior et al. 2018), OsbZIP72 (Abreu et al. 2018), OsbZIP23 (Srivastava et al. 2017), DREB2-like TF OsDRAP1 (Drought-Responsive AP2/EREBP gene) (Huang et al. 2018b), DREB and PIF (Kudo et al. 2017), OsDRZ1 (novel zinc finger protein 1) (Yuan et al. 2018), EDT1 (Enhanced drought tolerance 1) gene (Wu et al. 2019), OsbZIP42 (Joo et al. 2019), OsHSP50.2 (Xiang et al. 2018b), OsLG3 (Xiong et al. 2018), OsJAZ1 (Fu et al. 2017), OsNAC6 (Lee et al. 2017), cysteine-rich peptide (CRP) (OsDT11) (Li et al. 2017a), OsNCED3 (Huang et al. 2018a), OsASR5 (Li et al. 2017b), Maize-specific pyruvate orthophosphate dikinase (PPDK) and phosphoenolpyruvate carboxylase (PCK) (Gu et al. 2013), GA2 oxidase (Lo et al. 2017), CLC genes OsCLC1 (Um et al. 2018), phytochrome-interacting factor-like 1 (OsPIL1) and DREB1A (Kudo et al. 2017), WUSCHEL Homeobox OsWOX13 (Minh-Thu et al. 2018), and DEAD-box RNA helicase OsSUV3, and Thermotolerant Growth Required1 (TOGR1) (Tuteja et al. 2013; Wang et al. 2016a; Lee and Kang 2016).

3.3 Transgenic Rice for Cold Tolerance

There are a number of examples of rice transgenic lines developed for enhanced tolerance to cold stress by using various genes and transcription factors, which include OsDREB1G (drought-responsive element binding) (Mao and Chen 2012; Moon et al. 2019), OsDREB1A (Ito et al. 2006), barley (HvCBF4) (Oh et al. 2007), maize (ZmCBF3) (Xu et al. 2011), OsCTZFP8 (Jin et al. 2018), DaCBF4 (Byun et al. 2018), DaCBF7 (Byun et al. 2018), tomato SlCZFP1 zinc finger protein (Zhang et al. 2011), and OsMAPK3 (Zhang et al. 2017). Engineering cold tolerance by CRISPR/Cas9-mediated knocked-out of MYB30 and other two genes improved cold tolerance in rice (Zeng et al. 2020).

3.4 Transgenic Rice for Heat Tolerance

There are a number of examples of rice transgenic lines developed for enhanced tolerance to heat stress by using various genes and transcription factors, which include OsbZIP46 and SAPK6 (Chang et al. 2017), heat-shock proteins (HSPs) OsHSP50.2 (Xiang et al. 2018a), and LEA family (Magwanga et al. 2018; Mertens et al. 2018).

3.5 Transgenic Rice for Tolerance to Bacterial Leaf Blight Disease

Bacterial leaf blight (BLB) is caused by *Xanthomonas oryzae* which has type III effector proteins known as transcription activator-like effectors (TALEs), which target the SWEET gene family mainly SWEET14. TALEN-based genome editing of effector-binding element in OsSWEET14 generated resistance against BLB (Li et al. 2012; Blanvillain-Baufumé et al. 2017). CRISPR/Cas9-based genome editing of OsSWEET13 in rice increased resistance to BLB (Zhou et al. 2015), and OsSWEET14 and OsSWEET11 editing decreased BLB symptoms (Jiang et al. 2013). CRISPR/Cas9 editing of IR64 and Ciherang-Sub1 developed broad-spectrum resistance against BLB (Oliva et al. 2019).

3.6 Transgenic Rice for Tolerance to Rice Tungro Disease

The rice tungro disease is caused by interaction of Rice tungro bacilliform virus (RTBV) and Rice tungro spherical virus (RTSV) (Lee et al. 2010). CRISPR/Cas9 genome editing was used to target eIF4G (translation initiation factor 4 gamma) in a susceptible rice variety for developing RTSV resistance in rice plants (Lee et al. 2010; Macovei et al. 2018).

3.7 Transgenic Rice for Tolerance to Rice Blast Disease

Rice blast is caused by *Magnaporthe oryzae* (Liu et al. 2014). CRISPR/Cas9-targeted OsERF922 reduced blast disease (Wang et al. 2016b).

4 Conclusion

The transgenic crop deployment and the marker-assisted breeding aid in developing robust rice cultivars. CRISPR/CAS genome editing tool box is at its frontline for improving rice plant traits and modifying future agriculture with useful rice varieties.

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Chapter 39
Unlocking CRISPR/Cas-Mediated Editing Potential for Designing Climate-Smart Crop Plants

Deepu Pandita

Abstract Crop stress due to various biotic (insect pests and disease pathogens) and/or abiotic stressors (drought, heat, cold, salinity, nutrient toxicity, etc.) declines crop yields and threatens global food security. Abiotic stress factors contribute up to 51–82%, pests up to 10–28%, and plant pathogens up to 16% in potential crop yield losses globally on an annual basis. CRISPR/Cas is a current frontline revolutionary site-specific genome editing technology in the field of agriculture with wider applicability. Traits of simplicity, robustness, inexpensiveness, high accuracy, and preciseness of versatile CRISPR/Cas toolbox have given new dimensions to research in the arena of plant biology for the manipulation of plant genomes. CRISPR/Cas has laid foundation for designing of plants with genetic improvements for desired novel traits of resilience against both the biotic and abiotic stressors to improve adaptability and increase in yield. This chapter focuses on the classes, mechanism of action, and success stories of the abiotic and biotic climate-resilient crop plants designed by CRISPR/Cas genome editing toolsets.

Keywords CRISPR/Cas · Genome editing · Climate-smart crops · Biotic stress · Abiotic stress

1 Introduction

Crop stress is changes in soil-plant-atmosphere continuum and is caused by various biotic factors (e.g., insect pests and disease pathogens) and/or abiotic factors (e.g., drought, heat, cold, salinity, nutrient toxicity, etc.). The crop stressors decline crop yields and threaten global food security (Oshunsanya et al. 2019). About 51–82% crop yield in agriculture is reduced annually due to abiotic stress factors in different parts of the world (Mantri et al. 2012). On average, pests contribute to 10–28% and plant pathogens up to 16% in potential crop yield losses globally (Ficke et al. 2018;

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Savary et al. 2019). The global climate change will lead to multifactorial stress interactions between the plants and abiotic and biotic factors. The productivity of agriculture has further limitations in terms of water availability, decline in fertility of arable soil, irregular rainfall, heat, insect pests, and viral, bacterial, and fungal pathogens (Singh et al. 2020). Abiotic stresses like water deficiency, flooding, high temperature, and low temperature in current climate change scenarios pose big danger to crop plants (Mushtaq et al. 2018). Secondly, according to the United Nations in 2022, the world population will increase from 7.6 to 8.5 billion in 2030, 9.7 billion in 2050, and 10.4 billion in 2100. That means extra mouths will need to be fed with the current amount of food available. To increase production of food crop, plants in the prevalence of climate change and increasing global population is therefore a salient challenge. That is why the need of the hour is finding ways for alleviation of the direct and indirect impacts of climate change on crops and agricultural systems and production of well-adapted future crops (FAO 2015a, b) by improving genetic resources of food and agriculture.

Charles Darwin's evolutionary theory states that "the most intellectual or strongest species survives, but should be capable of adaption and adjustment best to the changing environments" (Darwin 2009). Traditional plant breeding has greatly improved crop yield and production but is a time-consuming and backbreaking process of refining productivity of crops (Parry et al. 2009; Haque et al. 2018; Nagamine and Ezura 2022). Genetically modified (GM) crop approach has overcome limitations of the conventional plant breeding and improved yield of crops within less time duration. But the disadvantage of GM crops is market acceptance, ethical concerns, and restricted legalization of GM crop plants to limited nations (Cole et al. 2018). Genome editing (GE) is a revolutionary technology for editing plant genomes and has opened new modes to improve tolerance to crop plants. The four site-specific endonuclease systems extensively used are CRISPR/Cas9, zinc-finger nucleases, ZNF, TALEN, and mega nucleases (Baltes et al. 2015; Zaidi et al. 2016; Haque et al. 2018; Mushtaq et al. 2018). Over previous years, clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR associated (CRISPR/Cas) system is a widely used key method for the designing of elite germplasm with increased quantity, quality, and tolerance to abiotic and biotic stress factors and acquisition of perceptions of plant-microbe interactions (Chen et al. 2019a, b; Shelake et al. 2019; Kuang et al. 2020; Pohare et al. 2020; Ali et al. 2020; Fiaz et al. 2020). CRISPR/Cas has revolutionized precise genome editing in a variety of crops worldwide with distinct advantages of being simple, accurate, affordable, precise, cost-effective, robust, reproducible, and efficient and generates predictable and inheritable mutations in specific loci of genome, with minimal off-target effects and no external gene sequence integration (Gaj et al. 2013; Xiong et al. 2015; Aglawe et al. 2018; Islam 2019; Fiaz et al. 2020, 2021; Asmamaw and Zawdie 2021; Bhattacharya et al. 2021; Nagamine and Ezura 2022). The CRISPR/Cas-mediated genome engineering of plants for abiotic and biotic stress resistance has been reported in *Oryza sativa*, *Triticum aestivum*, *Solanum lycopersicum*, *Vitis vinifera*, *Manihot esculenta*, *Cucumis sativus*, banana, citrus, etc. (Zaidi et al. 2020; Pandita 2021a, b, 2022a, b, c; Pandita et al. 2021). The current chapter proposes a comprehensive overview of CRISPR/Cas-mediated plant genetic modifications customized for the designing of climate-smart crop plants against several stress conditions.

2 Classes of CRISPR/Cas System

CRISPR/Cas editing system comprises of dual component machinery. The initial component is regularly interspaced 29 base pair short identical palindromic DNA repeats. The second component is protospacer with a unique 32 bp hypervariable spacer DNA matching with the viruses that infect bacteria (Hsu et al. 2014). The other genes associated with CRISPR are known as cas genes producing Cas protein like nucleases or helicases for DNA manipulations (Hsu et al. 2014). How the two different components of CRISPR/Cas system assemble lead to their categorization into class I and class II. The class I involves complex of many proteins for RNA-guided slicing of target. The class II employs a single RNA-guided endonuclease for the RNA-guided slicing of invading bacteriophages (Brouns et al. 2008). The class I and class II are subdivided into six primary categories, on the basis of their Cas counterpart and degree of interference with foreign genetic material. Class I has types I, III, and IV characterized by multi-subunit effector complexes. Class II has types II, V, and VI with single-subunit effector (Koonin et al. 2017; Shmakov et al. 2017). The type II of class II known as CRISPR/Cas9 from *Streptococcus pyogenes* (SpCas9) is an innovator toolbox for the plant genome editing based on RNA-guided engineered guide RNA (sgRNA) (Jinek et al. 2012). CRISPR/Cas12 nucleases belong to class II, type V CRISPR/Cas system (Zetsche et al. 2015). CRISPR/Cas8 is a hypercompact protein of ~70 kDa and belongs to type V CRISPR (half size of CRISPR/Cas9 or CRISPR/Cas12a) (Nadakuduti and Enciso-Rodríguez 2021).

3 Mechanism of Action

The mode of action of Cas9 has two steps: (1) generation of site-specific DNA double strand breaks (DSB) and (2) DNA repair (Fig. 39.1). Basic components to generate DSB on DNA include a crRNA, tracrRNA, an adjacent conserved PAM (protospacer adjacent motif sequence) sequence, and Cas9 (Deltcheva et al. 2011; Cong et al. 2013). The Cas9 nuclease cleaves target site DNA (PAM sequence) to generate a DSB under guidance of RNA-guided engineered guide RNA (sgRNA). DSB triggers cellular DNA repair machinery which includes the nonhomologous end joining (NHEJ) and/or homology-directed repair (HDR) pathways (Fig. 39.1) (Cong et al. 2013; Chen et al. 2014). In absenteeism of donor homologous repair template, error-prone NHEJ pathway activates. NHEJ repair involves random insertion/deletion or even substitutions of single nucleotide at site of DSB and INDELS or gene knockout due to frame shift and provides upright substitute to other gene

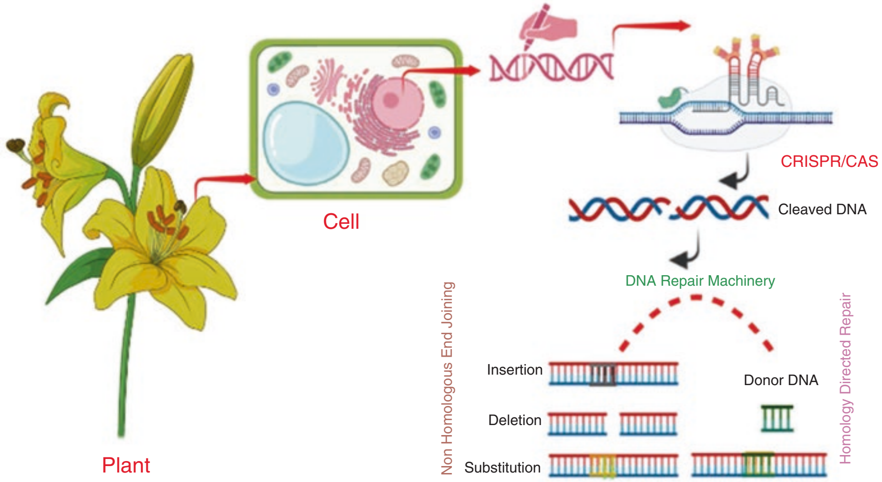

Fig. 39.1 Nonhomologous end joining (NHEJ) and homology-directed repair (HDR) pathways

silencing systems (Cong et al. 2013; Unniyampurath et al. 2016; Chen et al. 2019a, b; Basso et al. 2020). NHEJ leads to disruption of gene function (Yin et al. 2017). In the presence of donor DNA template homologous to DSB site, then error-free HDR pathway initiates. HDR generates mutation or gene knock-in at DSB site by homologous recombination with donor DNA repair sequence. This leads to precise gene modification or gene knock-in or gene insertion (Maresca et al. 2013; Cristea et al. 2013; Yin et al. 2017).

CRIPSR/Cas9 nuclease has source from *Streptococcus pyogenes* (sp.) (Varble and Marraffini 2022). The synthetic single-guide RNAs (sgRNAs) are used for constructing expression cassettes of CRISPR/Cas9 (Liu et al. 2017). The Cas9 is guided to genomic sequence of interest by sgRNAs (~20 nt) to recognize 5′-NGG-3′ type PAM sequence in target DNA and targets DNA by Watson-Crick base-pairing (Liu et al. 2017). The other Cas9 variants with different PAM prerequisites (SpCas9-VQR- 5′-NGA-3′, SpCas9-EQR- 5′-NGAG-3′, Cas9-NG- 5′-NG-3′, and xCas9 3.7- 5′-NG/GAA/GAT-3′) are also available for genome editing in plants (Zhang et al. 2019; Anzalone et al. 2019; Nadakuduti and Enciso-Rodríguez 2021). DNA sequence targeting by base-pairing has quickened approval of CRIPSR/Cas9 for the process of genome editing (Liu et al. 2021; Ahmar et al. 2021). Thus, CRISPR/Cas can do precise genome editing by both the knock-in or knockout of genes and their modifications (Wagh and Pohare 2019) (Fig. 39.1). Cas12a or Cpf1 nuclease (Zetsche et al. 2015; Tang et al. 2017; Zaidi et al. 2017) involves single crRNA of ~42 nt for plant genome editing and no tracrRNA (opposite to ~100 nt Cas9 guide RNA), because of which sgRNA size becomes smaller. Cas12 recognizes 5′-TTTN-3′ PAM sequence whereas Cas9 recognizes 5′-NGG-3′ (Zetsche et al. 2015). Cas12 effectors are deficient of HNH domain and have only RuvC-like domain. RuvC-like domain slices both strands of target site DNA and produces staggered cut with 5′

overhangs of 4–5 nt (Zetsche et al. 2015). LbCas12a variant recognizes T-rich PAM "TTTV" (Zhang et al. 2019). Engineered Cas12a variants are also available (Kleinstiver et al. 2015). The limitations of Cas9 include activity of nuclease inclined by efficiency and size of protein, PAM, and off-target effects (Barrangou and Doudna 2016). These limitations are resolved by the nanoCas9s, Cas12, and Cas13 (Chen et al. 2018; Crawley et al. 2018; Yan et al. 2019). Cas12a is beneficial for transcription, multiplex editing of genes, modulations at epigenetic levels, and base editing (Safari et al. 2019). In multiplexing stage, multiple mutations are generated by co-expression of Cas9 and numerous RNA guides (Cong et al. 2013). CRISPR/Cas8 recognizes 5′-TBN-3′ PAM sequence (where B = T, G, or C), with no tracrRNA, and produces staggered ends with 5′ overhangs (Pausch et al. 2020). CRISPR/Cas8 shows 0.85% of editing efficiency in *Arabidopsis thaliana* (Pausch et al. 2020).

4 Applications of CRISPR/Cas for Abiotic Stress Tolerance

Abiotic stress critically reduces production of crops and is quantitative trait controlled by above single gene (Mushtaq et al. 2018). CRISPR/Cas toolbox has been accepted swiftly for manipulating genomes of crops to design abiotic stress resilient and high-yielding plants (Bhat et al. 2021). CRISPR/Cas9 is powerful tool for generation of tolerance to abiotic stresses (Mushtaq et al. 2018). The tolerance to drought has been described in *O. sativa*, *T. aestivum*, *S. lycopersicum*, and *Brassica napus* through the modulation of various transcription factors (Wang et al. 2015; Shim et al. 2018; Kim et al. 2018; Li et al. 2019; Wu et al. 2020). The overexpression of drought responsive transcription factor (TF) OsNAC14 provides tolerance to water scarcity in rice mutants at their vegetative stages. OsNAC14 transgenic rice lines had more panicle quantity and filling rate under water deficiency (Shim et al. 2018). Synchronized editing of *OsPIN5b* (gene for panicle length), *GS3* (gene for grain size), and *OsMYB30* (gene for cold tolerance) genes by CRISPR/Cas9 generated novel mutants of rice plants with higher crop yield and tolerance to cold stress (Zeng et al. 2020b). Tolerance to various abiotic stresses was induced by editing of *OsNCED3* gene to regulate biosynthesis of abscisic acid (ABA) in *O. sativa* (Huang et al. 2018). Ali et al. (2020) made use of Cas9-VirD2 chimeric protein complex with combined roles of Cas9 and VirD2 relaxase. VirD2 relaxase directs repair sequence adjacent to DSB for the specific allele modification to generate herbicide resilient *O. sativa*. In rice, OsALS1 mutation created novel variety germplasms tolerant to herbicides, and this mutation was transmitted to Nangeng rice cultivars (Kuang et al. 2020). *Arabidopsis thaliana* PARAQUAT TOLERANCE 3 (AtPQT3) encodes E3 ubiquitin ligase. E3 ubiquitin ligase provides off-switch mechanism in *A. thaliana* for balancing their growth and responses to stress conditions (Alfatih et al. 2020). OsPQT3 was knocked out by CRISPR/Cas9 in *O. sativa* (Alfatih et al. 2020). In *O. sativa*, OsPQT3 knockout mutants (ospqt3) exhibited improved tolerance to oxidative stress with increase in grain quantity under salinity conditions (Alfatih et al. 2020).

The transgene-free *T. aestivum* showed tolerance to herbicides (Zhang et al. 2019). The CRISPR/Cas editing of stress-responsive TF in *T. aestivum* displays powerful strength for precise genome modification of *T. aestivum* (Kim et al. 2018). ARGOS8 declines the sensitivity to ethylene and improves yield under drought. CRISPR/Cas-mediated editing of ARGOS8 variants produce more crop yield under water deficiency (Shi et al. 2017). In wheat plants, the CRISPR/Cas9 generated ethylene responsive factor 3 (TaERF3), and dehydration responsive element binding protein 2 (TaDREB2) showed enhanced tolerance to drought (Kim et al. 2018). In tomato, overexpression of brassinosteroid regulator (BZR) resulted in thermotolerance by Feronia (Fer) homolog regulation (Yin et al. 2018). In tomato, nonexpressor of pathogenesis-related gene 1 (SlNPR1) was mutated to generate slnpr1 mutants by CRISPR/Cas9, and overexpression lines of SlNPR1 exhibited less tolerance to water deficiency. This is how NPR1 behaves in response by plants (Li et al. 2019). CRISPR/Cas9 mediated modifications of the genes connected with morphological, flowering, and fruit development traits and biosynthesis of ascorbic acid were done in four stress-tolerant wild-tomato accessions. The Cas9-free progeny of modified plants retained tolerance to diseases and salinity transmitted from the parental plants (Li et al. 2018). CRISPR/Cas9 modification of bnaa6. rga-D and bnarga genes leads to understanding the functions of DELLA proteins in response to tolerance of water deficiency in rapeseed plants (Wu et al. 2020). These bnaa6. rga-D mutant lines showed improved resistance to drought, and BnaRGAs showed physical interaction with BnaA10. A detailed description of abiotic stress related research investigations in plants by editing through CRISPR/Cas is listed in tabulated forms and as success stories in various book chapters (Pandita et al. 2021; Pandita 2021a, b, 2022a, b, c).

5 Applications of CRISPR/Cas for Biotic Stress Tolerance

Plant pathogens like viruses, fungi, and bacteria are the world’s largest challenge in agriculture and cause 20–40% losses in food production (Savary et al. 2012). The CRISPR/Cas approach tackles tolerance of plants to insects and pathogens that cause damage primarily fungal, viral, and bacterial diseases (Arora and Narula 2017; Langner et al. 2018). There are reports of the tolerance against *Fusarium* wilt (in banana), citrus canker (in citrus fruits), *Botrytis cinerea* (in *Vitis vinifera*), brown streak disease (in *Manihot esculenta*), and *Ipomovirus* (in *Cucumis sativus*) (Chandrasekaran et al. 2016; Jia et al. 2017; Dale et al. 2017; Wang et al. 2018c; Peng et al. 2017; Gomez et al. 2019). In *O. sativa*, CYP71A1 cytochrome P450 responsible for serotonin biosynthesis has been edited by CRISPR/Cas9 to increase resistance to insect pests, namely, hoppers and stripped stem borers (Lu et al. 2018).

5.1 Viral Pathogens

Geminiviridae is a large plant virus family and causes worldwide crop loss of various plant families, and *Begomovirus* class of geminiviruses (Zaidi et al. 2016) targets sweet potato and tobacco mainly their phloem (Gilbertson et al. 2015). Various researchers targeted genomes of ssDNA geminivirus by CRISPR/Cas and generated resistance against these viruses in plants (Ji et al. 2015; Baltes et al. 2015; Ali et al. 2016). CRISPR/Cas9 is established for generating tolerance against geminivirus in plants (Ali et al. 2015, 2016). Several geminiviruses can be targeted concurrently by gRNA conserved sequence (TAATATTAC) in intergenic regions (Ali et al. 2015). When gRNA target Replication associated protein (Rep), intergenic region (IR), or coat protein (CP), then symptoms of bean yellow dwarf virus (BeYDV) and beet severe curly top virus (BSCTV) diminish or remove (Ji et al. 2015; Baltes et al. 2015).

Plant RNA viruses depend on the machinery of eukaryotic plants for translation complex with eukaryotic Translation Initiation Factor 44E (eIF4E), for sustaining their life cycle. The eIF4E and isoforms help to recruit ribosome from 5′ untranslated regions (UTRs) of mRNA (Lellis et al. 2002; Denver et al. 2016). Inactivation of this eIF4E disrupts infectivity of viruses. *Arabidopsis* loss-of-function eIF(iso)4E mutant generated by CRISPR/Cas9 had improved tolerance to turnip mosaic virus (TuMV) (Lellis et al. 2002). *Arabidopsis* eIF(iso)4E knockouts were resistant to TuMV, and integrity of plant was also maintained (Pyott et al. 2016). CRISPR/Cas9 edited eIF4E generated virus-resistant cucumber. The eif4e mutant showed immunity to cucumber vein yellowing virus (CVYV), zucchini yellow mosaic virus (ZYMV), and papaya ring spot mosaic virus-W (PRSMV-W) (Chandrasekaran et al. 2016). CRISPR/Cas9-targeting of new allele of *O. sativa* eIF4 G generated resistance to *Rice tungro spherical virus* (RTSV) (Roossinck et al. 2015). CRISPR/Cas9 established wheat dwarf virus (WDV) tolerance in barley. CRISPR/Cas9 modified ncbp-1/ncbp-2 dual mutants exhibited delay in symptoms and reduced after attack by cassava brown streak virus (CBSV) (Gomez et al. 2019). For RNA viral resistance in tobacco and *A. thaliana*, FnCas9 and sgRNAs comparable to cucumber mosaic viruses (CMVs) and tobacco mosaic viruses (TuMVs) were expressed. The transgenic tobacco and *Arabidopsis* plants showed 40–80% decrease in accumulation of CMVs and TuMVs (Zhang et al. 2018c).

CRISPR/Cas13a (C2c2) can edit RNA of single-stranded nature. Tobacco tolerant to TuMVs has been generated by CRISPR/Cas13a which has property of acquisition of viral RNA genome (Aman et al. 2018). Agronomical traits in edited *O. sativa* have been enhanced after inoculation with RTSV. Potential disadvantage of knockout method includes damaging effect on plant vigor and promoting growth of resistance-breaking virus variants (Abdul-Razzak et al. 2009).

CRISPR/Cas9 engineers plants tolerant to tomato yellow leaf curl virus (TYLCV) via target of coat proteins and replicase loci of tomato genome. The transgenic tomato exhibited efficient interference of viruses, and accumulation of less viral DNA and immunity was heritable (Tashkandi et al. 2018). CRISPR/Cas9 can knock out critical genes of resistance pathways like Tomato Dicer-like 2 (DCL2). Mutants of dcl2 showed viral symptoms on infection with potato virus X (PVX), TuMVs, and tomato mosaic virus (ToMV). This suggests role of DCL2 in defense mechanisms against RNA viruses (Wang et al. 2018a, d). Several research investigations have been published on the application of CRISPR/Cas toolbox to fight against various viral diseases in plants (Table 39.1).

5.2 Bacterial Pathogens

Hundreds of bacterial species destroy crops and display signs of their infections (Schloss and Handelsman 2004). The phytopathological bacteria are hard to escape (Kerr 2016). CRISPR/Cas/sgRNA mediated *O. sativa* gene modification constructs target gene promoter region OsSWEET14 and OsSWEET11 responsible for bacterial susceptibility (Jiang et al. 2013). The broad-spectrum resistance Kitaake-1 (bsr-k1) in rice has broad-spectrum tolerance to pathogens, namely, *Xanthomonas oryzae* pv. oryzae and *Magnaporthe oryzae*. The bacterial blight due to *Xanthomonas oryzae* pv. oryzae leads to grain loss in *O. sativa*. The sucrose transporter gene (SWEET1, SWEET3, and SWEET14) expression causes susceptibility to disease (Zhou et al. 2018). The broad-spectrum tolerance was generated in Kitaake, IR64, and Ciherang-Sub1 varieties of rice (Oliva et al. 2019).

In response to *Pseudomonas syringae* pv. tomato and *Phytophthora capsici*, SlDMR6-1 ortholog in *Solanum lycopersicum* shows high regulation, and null SlDMR6-1 mutants created by genome editing displayed tolerance to pathogens (de Toledo et al. 2016). This suggests DMR6 as a competent gene for plant tolerance to various diseases. CRISPR/Cas9 generated CBC-resistant citrus plants showed resilience to citrus canker caused by *Xanthomonas citri* subsp. *citri* through gene modification of promoter region of lateral organ boundaries 1 (LOB1). With Lateral Organ Boundaries 1 (CsLOB1) family of transcription factors or Xcc S gene, canker-mutants in Duncan grapefruit were developed with decreased symptoms of canker (Hu et al. 2014; Jia et al. 2016; Peng et al. 2017). CsLOB1 produces an EBE that Xcc effector PthA4 detects and stimulates CsLOB1 expression to fast-track canker growth (Jia et al. 2017; Peng et al. 2017). The lob1 mutant lines exhibited higher tolerance to *Xanthomonas citri* which causes citrus canker (Jia et al. 2016; Peng et al. 2017). CRISPR/Cas inactivated endogenous banana streak virus led to 75% banana plants with no symptoms (Tripathi et al. 2019). In apple, knockout of genes (DIPM1, DIPM2, and DIPM4) leads to tolerance against *Erwinia amylovora* (Malnoy et al. 2016). According to Ortigosa et al. (2019), spatial uncoupling of salicylic acid (SA)-jasmonic acid (JA) antagonism takes place at leaf stomata, and tomato plants tolerant to bacterial speck caused by Pto DC3000 were generated by editing the *SlJAZ2* gene, without compromise in resistance to necrotrophic pathogens (Santillan Martınez et al. 2020). Several research investigations have been reported on the application of CRISPR/Cas toolbox to fight against various bacterial diseases in plants (Table 39.2).

Table 39.1 Plant-virus interactions tailor-made by CRISPR/Cas

Host plant	Disease type	Disease pathogen	Targeted gene(s)	Reference/s
Arabidopsis thaliana	Viral	CYVV	eIF4E1 (of plant)	Bastet et al. (2019)
A. thaliana Nicotiana tabacum	Viral	TMV	ORFCP, ORF1a, 30-UTR (of TMV)	Zhang et al. (2018c)
Cotton	Viral	Cotton leaf curl disease (CLCuD)	Rep and IR, α-Satellite Rep, and β-Sat IR	Iqbal et al. (2016)
Cotton	Leaf curl	Leaf curl Kokhran virus (CLCuKoV)	CP and RCRII domains of Rep	Ali et al. (2016)
Cucumis sativus	Viral	CVYV, ZYMV, PRSV-W	eIF4E. Resistance against CVYV, ZYMV, PRSV-W	Chandrasekaran et al. (2016)
Hordeum vulgare	Viral	Wheat dwarf virus (WDV)	Rep, MP, and LIR	Kis et al. (2019)
Manihot esculenta	Brown streak	Cassava brown streak virus	nCBP-1/-2 (eIF4E) (of plant)	Gomez et al. (2019)
Musa balbisiana	Viral	Banana streak virus	Three target sites (e)BSV in banana streak virus genome	Tripathi et al. (2019)
Oryza sativa	Viral	*Rice tungro spherical virus*	eIF4G of plant for eIF4G translation of RTSV	Roossinck et al. (2015) and Macovei et al. (2018)
Solanum lycopersicum	Viral	Bean yellow dwarf virus	CRTISO, phytoene synthase 1 (PSY1)	Dahan-Meir et al. (2018)
Solanum lycopersicum	Viral	Tomato yellow leaf curl virus	CP and Rep of virus. Resistant to TYLCV	Tashkandi et al. (2018)
Solanum lycopersicum	Viral	PVX, TuMVs, and ToMV	DCL2. Susceptible to TMV, PVX, TMV	Wang et al. (2018a, d)
Solanum lycopersicum		Potato virus Y-N, cucumber mosaic virus	eIF4E1. Resistance against PVYN, CMV	Atarashi et al. (2020)
Solanum lycopersicum		Tomato yellow leaf curl virus	SlPelo. Resistance against TYLCV	Pramanik et al. (2021)
Nicotiana tabacum	Viral	TuMV	Proteinase silencing suppressor (HCPro), TuMV-GFP, helper component, CP (of TuMV)	Aman et al. (2018)
Nicotiana tabacum	Viral	CLCuKoV, TYLCV, TYLCSV, MeMV, BCTV	IR, coat protein, Rep	Ali et al. (2016)

Table 39.2 Plant-bacteria interactions tailor-made by CRISPR/Cas

Host plant	Disease type	Disease pathogen	Targeted gene(s)	Reference/s
Citrus paradisi and *Citrus sinensis*	Citrus canker	*Xanthomonas citri*	CsLOB1 (transcription factor of plant)	Jia et al. (2017) and Peng et al. (2017)
Malus pumila	Fire blight	*Erwinia amylovora*	DIPM-1, DIPM-2, and DIPM-4 (of plant)	Malnoy et al. (2016)
Oryza sativa	Rice bacterial blight	*Xanthomonas oryzae*	OsSWEET11, OsSWEET14	Jiang et al. (2013)
Oryza sativa	Rice bacterial blight	*Xanthomonas oryzae*	OsSWEET14 (Os11N3) (sugar transporter). Broad-spectrum resistance to this disease.	Zafar et al. (2020) and Zeng et al. (2020a)
Oryza sativa	Rice bacterial blight	*Xanthomonas oryzae*	OsSWEET13 (Xa25) (sugar transporter)	Zhou et al. (2015)
Oryza sativa	Rice bacterial blight	*Xanthomonas oryzae*	OsSWEET11 (Xa13 or Os8N3)	Kim et al. (2019) and Li et al. (2020)
Oryza sativa	Rice bacterial blight	*Xanthomonas oryzae*	OsBSR-K1 (TPRs-domain; RNA-binding). Broad-spectrum resistance	Zhou et al. (2018)
Solanum lycopersicum	Capsici bacterial speck, blight, and spot of tomato	*Pseudomonas syringae*, *Xanthomonas* spp., *Phytophthora*	SlDMR6–1 (knockout of plant)	Thomazella et al. (2016)
Solanum lycopersicum	Bacterial speck DC3000	*Pseudomonas syringae*	SlJAZ2 (in plant)	Ortigosa et al. (2019)

5.3 *Fungal Pathogens*

Fungal infections cause substantial decrease of quantity and quality of crops (Doehlemann et al. 2017). According to Giraud et al. (2010), fungal diseases contribute to about 30%. Fungi cause drastic loss in yield of grapevine and quality of grape berry. The mildew resistance locus O7 (MLO7) and WRKY transcription factor 52 (WRKY52) play important role in resistance of *Erysiphe necator* and *B. cinerea*, respectively. Their CRISPR/Cas9 generated loss-of-function mutants displayed increase in immunity (Malnoy et al. 2016; Wang et al. 2018b). CRISPR/Cas9 in *Theobroma cacao* and *Carica papaya* increased resistance to *Phytophthora tropicalis* and *P. palmivora* (Fister et al. 2018; Gumtow et al. 2018). Synchronized mutation of three TaMLO homeoalleles confers heritable broad-spectrum tolerance to powdery mildew in hexaploid bread wheat (Wang et al. 2014). The wheat edr1 mutants generated by the simultaneous modification of three TaEDR1 homoeologs confirmed its negative role in powdery mildew resistance (Zhang et al. 2017). Wang et al. (2014) modified Mlo wheat genes by TALEN and CRISPR, and modified plants showed resistance to *Blumeria graminis* f. spp. For designing of Taedr1 *T. aestivum* mutants, all three EDR1 homologs of *T. aestivum* were targeted concurrently by CRISPR/Cas9. *Arabidopsis* edr1 mutants have resistance to bacteria and oomycetes. Similarly, Taedr1 wheat mutants can also fight other pathogens of wheat plant (Zhang et al. 2017).

CRISPR/Cas9 knockout mutants of OsERF922 were designed in *O. sativa* (Wang et al. 2016). OsRDR6 is a negative regulator of rice blast resistance and contributes to increase in *Xanthomonas oryzae*, *Magnaporthe oryzae*, RNMV, and CMV resistance (Dean et al. 2012; Wagh et al. 2016a, b). CRISPR/Cas9 mediated editing of WRKY52 transcription factor generated grapevine defense (Wang et al. 2018c). The ethylene reaction factors (ERFs) of APETELA2/ERF (AP2/ERF) aid in adaptation to several biotic and abiotic stresses in rice (Mizoi et al. 2012). *M. oryzae* induce expression of OserF922 whereas OsERF922 increases *M. oryzae* resistance, which indicates that OsERF922 is a negative regulator of the rice blast resistance (Liu et al. 2012). DMR6 (downy mildew resistance 6) *Arabidopsis* mutant showed increase in levels of salicylic acid (SA) and tolerance to pathogens (Zelimaker et al. 2015).

In *A. thaliana*, downy mildew resistant 6 (DMR6) participates in SA homeostasis, and DMR6 overexpression enhances downy mildew susceptibility (Zelimaker et al. 2015). CRISPR/Cas9 inactivated DMR6 ortholog in *Solanum lycopersicum* and generated dmr6 mutants displaying resistance to *Phytophthora capsici*, *Pseudomonas syringae*, and *Xanthomonas* spp. (Thomazella et al. 2016).

Powdery mildew resistance 4 (PMR4) gene encodes callose synthase and provides resistance to *Oidium neolycopersici* (Koseoglou 2017). The knockout lines of PMR4 and mlo1 mutants of tomato generated by CRISPR/Cas9 exhibited improved tolerance to *Oidium neolycopersici* which is a pathogen of powdery mildew (Nekrasov et al. 2017; Santillan Martınez et al. 2020). *Solanum lycopersicum* is susceptible to *Botrytis cinerea* which causes gray mold disease (Yu et al. 2018). Mitogen-activated protein kinase 3 (MAPK3) confers resistance to *B. cinerea* by use of CRISPR/Cas9 (Zhang et al. 2018b). *Fusarium oxysporum* causes *Fusarium* wilt disease (Chaudhary and Atamian 2017) and impacts yield of tomato fruit. CRISPR/Cas9 knockout of Solyc08g075770 gene (with function in *Fusarium* wilt tolerance) was susceptible to disease (Prihatna et al. 2018). Several research investigations have been reported on the application of CRISPR/Cas toolbox to fight against various fungal diseases in plants (Table 39.3).

6 Conclusion

CRIPSR/Cas-mediated genetic improvement offers a promising alternative method of pesticide usage and crop breeding without disrupting a desired genetic background for crop protection/tolerance and agriculture from abiotic and biotic stress

Table 39.3 Plant-fungal interactions tailor-made by CRISPR/Cas

Host plant	Disease type	Disease pathogen	Targeted gene(s)	Reference/s
Brassica napus	Stem rot	*Sclerotinia sclerotiorum*	BnWRKY70 (TF)	Sun et al. (2018)
Brassica napus	Blackleg disease	*Leptosphaeria maculans*	Histidine kinase (in fungi)	Idnurm et al. (2017)
Carica papaya	Oomycete virulence	*Phytophthora palmivora*	Cystatin-like cysteine protease inhibitor 8 (PpalEPIC8)	Gumtow et al. (2018)
Citrullus lanatus	*Fusarium* wilt	*Fusarium oxysporum*	ClPSK1 (phytosulfokine peptide hormone)	Zhang et al. (2020a, b)
Glycine max	Damping-off	*Phytophthora sojae*	Avr4/6 (in fungi)	Fang and Tyler (2015)
Gossypium hirsutum	*Verticillium* wilt	*Verticillium dahlia*	Gh14–3-3d (14–3-3 signaling)	Zhang et al. (2018a)
Helianthus annuus	Black molds	*Alternaria alternata*	Phosphate decarboxylase pyrG, polyketide-synthase, pksA, 1,3,8- THN reductase, brm2 (in fungi)	Wenderoth et al. (2017)
Oryza sativa	Rice blast	*Magnaporthe oryzae*	OsERF922 (TF of plant)	Wang et al. (2016)
Oryza sativa	Rice blast	*Magnaporthe grisea*	OsMPK5 (in rice plant)	Xie and Yang (2013)
Oryza sativa	Rice blast	*Magnaporthe oryzae*	OsSEC3A (exocyst subunit of rice plant)	Ma et al. (2018)
Oryza sativa	Rice blast	*Magnaporthe oryzae strains*	OsBSR-D1(TF of plant)	Zhu et al. (2020)
Oryza sativa	False smut	*Ustilaginoidea virens*	USTA ustiloxin and UvSLT2 MAP kinase (in fungi)	Liang et al. (2018)
Solanum lycopersicum	Powdery mildew	*Oidium neolycopersici*	SlMlo1 (calmodulin binding of plant)	Nekrasov et al. (2017)
Solanum lycopersicum	Downy mildew	*Pseudomonas syringae*, *Phytophthora capsica*, *Xanthomonas* spp.	DMR6	Thomazella et al. (2016)
Solanum lycopersicum	Powdery mildew	*Oidium neolycopersici*	MLO1	Nekrasov et al. (2017)
Solanum lycopersicum	Powdery mildew	*Oidium neolycopersici*	PMR4	Koseoglou (2017)
Solanum lycopersicum	Powdery mildew	*Oidium neolycopersici*	SlPMR4 (callose synthase)	Santillan Martınez et al. (2020)

(continued)

Table 39.3 (continued)

Host plant	Disease type	Disease pathogen	Targeted gene(s)	Reference/s
Solanum lycopersicum, legumes, cotton	Wilt	*Fusarium oxysporum*	FoSso1 and FoSso2 (in fungi)	Wang and Coleman (2019)
Theobroma cacao	Black pod disease	*Phytophthora tropicalis*	TcNPR3 (in plant)	Fister et al. (2018)
Triticum aestivum	Powdery mildew	*Blumeria graminis*	MLO-A1, MLO-B1, and MLO-D1	Wang et al. (2014)
Triticum aestivum	Powdery mildew	*Blumeria graminis*	Three homologs of TaEDR1 (in plant)	Zhang et al. (2017)
Triticum aestivum	*Fusarium* head blight	*Fusarium graminearum*	TaNFXL1 (TF)	Brauer et al. (2020)
Vegetables, *Glycine max*	Powdery mildew, damping-off	*Phytophthora capsici* and *P. sojae*	Oxysterol binding protein-related protein 1 (in fungi)	Miao et al. (2018)
Vitis vinifera	Powdery mildew	*Erysiphe necator*	VvMLO-7 (calmodulin binding of plant)	Malnoy et al. (2016)
Vitis vinifera	Gray mold	*Botrytis cinerea*	WRKY52 (TF of plant)	Wang et al. (2018c)
Zea mays	Corn smut	*Ustilago maydis*	bW2 and bE1 (in fungi)	Schuster et al. (2016)

factors and gaining insights into the plant-microbe interactions. CRISPR/Cas system has revolutionised designing of germplasm in a variety of crops worldwide. CRISPR/Cas based editing being simple, accurate, affordable, precise, cost-effective, robust, reproducible, efficient generates inheritable mutations in specific loci of genome, with minimal off-target effects and increased grain quantity and quality under various abiotic and biotic stress conditions. CRISPR/Cas-mediated genome engineering of crop plants is legalized in various countries, and it is a key goldmine to feed the extra hungry mouths under alarming scenarios of abiotic and biotic stresses due to climate change.

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Chapter 40
Biochemical, Physiological, and Molecular Mechanisms of Plant Adaptation to Salinity

Deepu Pandita

Abstract Salt stress is a detrimental abiotic stressor which limits growth, development, and productivity of plants. Plant tolerance to salinity includes interactions of the metabolic pathways and gene networks at the morphological, biochemical, and physiological levels. The crosstalk of plants with different factors of salinity and combined strategies of molecular toolboxes are domineering for the development of plants resilient to salinity. The plants adapt to salinity at levels of molecules, cell, metabolism, and physiology. The reaction of plants to stress brings about reduced or no growth of roots and shoots, and seedling development, stomata closure, slow seed germination, and decline in photosynthesis. However, the basic mechanisms of tolerance to salinity are not comprehended entirely. In this chapter, how the plants respond to salinity and advance in research on the mechanisms regulating morphological, biochemical, physiological, and molecular tolerance mechanisms for the plant survival under salinity conditions will be deliberated.

Keywords Salt stress · Plant responses · Cellular metabolism · Biochemical levels · Physiological and molecular adaptations · Tolerance mechanisms

1 Introduction

Soil salinity is one of the leading dangers to agriculture. Globally, about one-third of the arable land or 20% (1125 million hectares) of the world's cultivated land cope with salinization (Munns and Gilliham 2015; Arora 2019). In other words, one out of five irrigated lands face salt stress, and annually, 1.5 million hectares of agricultural land lose their fittingness for agriculture (Hasanuzzaman et al. 2014; Hossain 2019). The increase in salt-disposed areas is nonstop because of events caused by natural and human sources (Arora 2019), and about 76 million hectares of agricultural lands will face human-induced salinity and sodicity (Wicke et al. 2011). By

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2050, 50% of the cultivated lands will lose their suitability for agriculture (Hasanuzzaman et al. 2014; Hossain 2019).

The soil is said to be salty if Electrical Conductivity of a saturated soil Extract (ECe) value is 4 dS m^{-1} and more (Munns and Tester 2008). Salinity intensifies osmotic pressure intracellularly and leads to accumulation of high concentration of soluble salts to toxic levels (Zhao et al. 2021). Soil salinity causes two-way stress, i.e., osmotic and ionic in plants. The salts with higher concentration in soil or outside of plant roots decrease the soil water potential and osmotic potential of soil–plant relationship, which leads to the decline in water uptake by plant root cells. The osmotic phase is rapid (Parihar et al. 2015; Negrão et al. 2017). Instead, salts with high concentrations or excessive absorption and signaling of sodium ($Na^{+)}$ and chlorine (Cl^-) ions in cells lead to plant toxicity or nutritional disorders (Munns and Tester 2008; Negrão et al. 2017; Ibrahimova et al. 2021). Both the osmotic and ionic toxicities generate secondary stresses which incontrovertibly impair mechanism of seed germination, photosynthetic activity, leaf development and plant growth and development (Hasegawa et al. 2000; Munns 2002; Munns and Tester 2008).

Salinity affects physiological, biochemical, and metabolic cell functions by causing ion toxicity, membrane irregularity, growth and expansion of cells, and growth and development of shoot and root systems in plants and significantly limits agricultural production and crop yields (Munns and Tester 2008; Munns and Gilliham 2015; Parihar et al. 2015; Zhao et al. 2021). Some plant species develop different adaptation mechanisms to regulate salt accumulation inside their cells (Munns 2005). Halophytes grow in soil with high salinity, whereas the glycophytes have no tolerance to high salinity (Garthwaite et al. 2005). To face salinity, plants trigger and develop various morphological, anatomical, physiological, and biochemical adaptations (Ashraf and Harris 2013; Motos et al. 2017). Salinity tolerance can trigger differential expression profiling of various genes involved with photosynthesis and transport the vacuoles, osmolytes, membrane channels, and ROS protectors (Hassan et al. 2020), making these candidates for genetic engineering to design salt-tolerant crops. This chapter deliberates on the response of plants to salinity at their morphological, biochemical, and physiological levels and molecular advances in research on the regulation of tolerance mechanisms in plants for survival under the salinity conditions.

2 Soil Salinity

The salinity of soil leads to stress and toxicity in plants and obscure water absorption by roots and accumulate higher salt concentrations in plant body (Munns and Tester 2008). Plants surviving under salinity complete their life cycle by adapting morphologically, biochemically and physiologically. Salinity can be primary and secondary. Primary salinity in soil takes place by natural factors such as oceans and rock corrosion, and secondary salinity has mainly human-induced nature and takes place by extreme irrigation in agricultural lands and structure deterioration of lands for agriculture (Munns and Tester 2008). Salinity effects increase continuously. Sodium chloride and sodium sulfate mainly affect salinity of agricultural lands (Pessarakli and Szabolcs 2010). The nature of salt-tolerant plants can be judged during the stages of germination and early seedling when most salt-induced damages take place (Munns and Gilliham 2015). A number of factors should be considered to control salinity (Ayers and Westcot 1985). "In addition to well-known principles such as drainage and management of irrigation resource, cultural practices and agricultural land development works are also important too. When it comes to cultural practices, fertilization, planting method, irrigation treatment, land levelling factors come to mind. Agricultural land developments are development of drainage, land levelling, breeding irrigations" (Ayers and Westcot 1985). The most significant factor which influences salinity is absence of drainage. This factor destroys millions of productive agricultural lands.

3 Morphological Effects of Salinity on Plants

The most sensitive growth stages in plant life cycle are the complex multistage developmental processes of seed germination and seedling establishment. During germination and seedling stages in plants, salinity causes decline in water uptake during imbibition, decreases seed germination rates, and increases germination time (Munns 2002; Munns and Tester 2008; Ahmad et al. 2013a, b). Salinity affects development of male and female reproductive organs (Mahmoodzedah and Bemani 2008), area of plant leaves and photosynthetic rates (Kauser et al. 2006), and growth and development of plants (Ahmad et al. 2013a, b); declines shoot/root ratio (Jamil et al. 2005); and reduces plant height, size, yield, and seed quality and seed oil production (Kumar 1995; Ashraf and McNeilly 2004) (Fig. 40.1).

The halophytes adapt to the environment (Munns and Tester 2008). Halophytes develop adaptation strategies to survive in saline soils of absorption of high-concentration ions and their storage in vacuoles inside the cell, get rid of high-concentration absorbed salt ions through special cells, and control uptake of salt ions by stem cells (Acosta-Motos et al. 2017). The glycophytes are salinity-sensitive plants affected by the environment, exposure time to salt stress and concentrations of salt in water which affect their growth and have thus diverse mechanisms for negative effects (Munns and Tester 2008). Glycophytes accumulate negligible amounts of Na^+ and Cl^- in plant cells and have inappropriate compartmentation of salt ions which harms their growth and productivity (Huan et al. 2020).

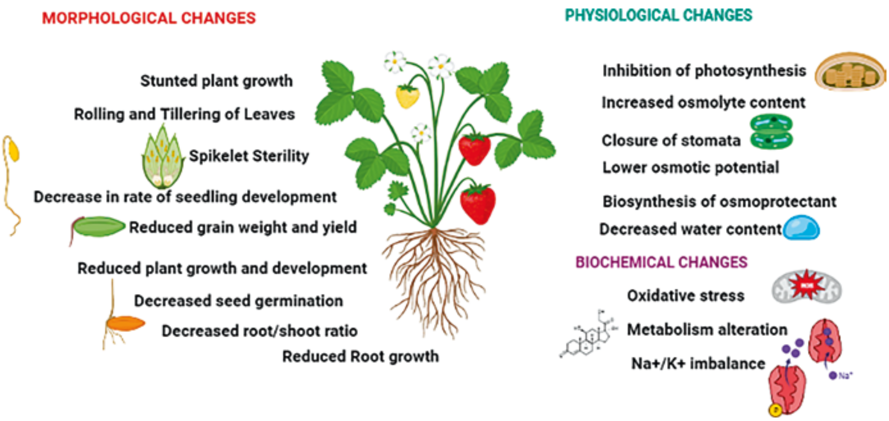

Fig. 40.1 Salinity-induced morphological, physiological, and biochemical changes in plants

3.1 Germination

The germination of seeds is one of essential stages in the plant life cycle. Salinity can prevent or decrease germination, and negatively affects plant imbibition and root growth by toxicity of salt ion and osmotic stress (Katembe et al. 1998; Shahzad et al. 2019). In wheat seeds, germination shows severe decrease in rate and delays time by salinity (Lin et al. 2012).

3.2 Seedling Development

The development of plant seedlings affects by salinity. The accumulation of biomass, leaf area expansion and stunted growth of plants result due to salinity (Shahzad et al. 2019). Salt-resilient plants show increase in biomass under high salt stress conditions, but the seedling development, fresh and dry weight of seedlings, length of the plants, and underground surface area of roots show negative effect (Shahzad et al. 2019).

3.3 Roots

The roots are initial sensors of signaling on exposure to salinity (Li et al. 2021b). The salinity affects the formation and development of root hairs (Wang et al. 2008) and root hair population density (Ali et al. 1999). Roots are susceptible to salinity in soil and root architecture modifications under salinity include root length reduction due to crackdown of cell division, initiation, elongation, or growth redirection and non-use or nonavailability of existing water caused by osmotic stress formation. This leads to negative effects on growth of both the roots and shoots of plants (Munns and Tester 2008; Pierik and Testerink 2014). Salinity stress increased elongation of the third-order lateral root system in *Brassica napus* (Arif et al. 2019), *Arabidopsis thaliana* (Wang et al. 2009), and *Silene vulgaris* (Franco et al. 2008), and decreased rate of elongation in *Triticum aestivum* (Zhu et al. 1998) and another study on *Arabidopsis thaliana* (Jbir et al. 2001).

3.4 Stomata

The plants show first response to salinity by the closure of stomata. This response limits transpiration rate, and in turn, stomatal conductivity declines (Munns and Tester 2008). The stomata close through hydroactive closure by chemical signal molecules and hydropassive closure (Mahajan et al. 2008). Abscisic acid (ABA) is one such signal molecule active in growth of plants and water balance in plants. During low down water potential sensed by root tips, ABA synthesized in roots transports via xylem into the stomata. ABA synthesis ensures regulation of stomatal conductivity under lower water potential and decrease in water content of leaves (Çulha and Çakırlar 2011).

4 Biochemical and Physiological Adaptation Mechanisms and Effects of Salinity on Plants

4.1 Reactive Oxygen Species

ROS signaling is critical to modulate stress responses in plants (Pilarska et al. 2021). At the subcellular levels in plants, salinity induces oxidative stress (Hernández et al. 2000; Acosta-Motos et al. 2017). ROS formation takes place by oxygen reduction through reducing molecules. The concentration of reducing molecules increases under stress conditions, and stomata closure decreases water loss. The leaf CO_2 reduces to reduce power of NADPH or ferredoxin. Then, oxygen reduces to radical forms of superoxide ($O_2^{\bullet-}$), hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), and hydroxyl radicals (HO•) (Sgherri et al. 2018; Hasanuzzaman et al. 2021). Salt-induced ROS overgeneration causes oxidative damage to cell plasma membrane lipids, proteins, DNA, and RNA in plant tissues and hampers morphophysiological and biochemical activities of plants (AbdElgawad et al. 2016; Hasanuzzaman et al. 2021). The disturbed morphology, physiology, and biochemistry of plants (Fig. 40.1) can be reinstated by increasing the nonenzymatic and enzymatic antioxidant defense machinery to detoxify and scavenge the accumulated toxic ROS (Gill and Tuteja 2010; Hasanuzzaman et al. 2021). Nonenzymatic antioxidants consist of glutathione (GSH), reduced ascorbate (ASC), flavonoids, phenolics, and tocopherols (Rakhmankulova et al. 2015). Enzymatic antioxidants comprise superoxide dismutase (SOD), peroxidase (POX), catalase (CAT), and GSH reductase (GR), ASC peroxidase (APX), dehydroascorbate reductase (DHAR), and monodehydroascorbate dehydrogenase (MDHAR) (AbdElgawad et al. 2016; Giordano et al. 2021).

4.2 Ion Homeostasis

Ions inside of cells increase plant growth. Nitrogen, potassium, and calcium ions effective for plant development cannot enter inside the root cells due to struggle with other salt ions of high concentration in soil. Plants respond mainly by proteins, channel proteins, and semptomers of cell membrane to ensure entry of low concentration ions inside of cells which is vital for their growth and development (Blumwald 2000; Sairam and Tyagi 2004; Shahzad et al. 2019). Antiporters located in vacuolar membranes also aid in transportation of these ions. V-ATPase channels continue plants under salinity (Dietz et al. 2001). Na^+ ion accumulation in soil leads to entry of this ion into root cell cytoplasm of plant. From cytoplasm, Na^+/H^+ antiporters transport these Na^+ ions inside the vacuoles. Under salinity, cytoplasmic K^+ homeostasis disturbs in cell metabolism due to decrease in K^+ concentration (Abbasi et al. 2014). The extracellular potassium (K^+) ions move inside the symplast of cells by K^+ transporters and channels like tandem-pore (TPK), two-pore channels (TPC), carrier-like families KT/HAK/KUP, HKT uniporters and symporters, and NHX, CHX, and KEA antiporters (Munns and Tester 2008; Hedrich 2012; Nieves-Cordones et al. 2016; Hamamoto et al. 2015; Li et al. 2018; Sze and Chanroj 2018; Shahzad et al. 2019) present inside the plasma membranes of epidermal and cortical cells of roots. Na^+ ion concentration increases under salinity, and Na^+ overaccumulation interferes with K^+ homeostasis and cytosolic Na^+/K^+ ratio, induces cytosolic K^+ efflux and reduces K^+ uptake into the cell (Tester and Davenport 2003; Munns and Tester 2008; Shahzad et al. 2019). Na^+ overaccumulation disproportions cellular homeostasis, leads to oxidative stress and deficiency of nutrients, interferes functions of Ca^{2+} and K^+, retards plant growth, and can cause cell death (Tester and Davenport 2003; Munns and Tester 2008; Craig Plett and Møller 2010; Cabot et al. 2014). K^+ ions accumulation and retention inside root cells lead to survival of wheat, maize, and beans under salinity (Katembe et al. 1998; Parida and Das 2005; Lin et al. 2012; Abbasi et al. 2014; Chakraborty et al. 2016; Shahzad et al. 2019).

4.3 Biosynthesis of Osmoprotectants

Osmoprotectants are compatible solutes or soluble organic compounds (McNeil et al. 1999; Nadeem et al. 2020; Ejaz et al. 2020). These organic compounds, such as sugars and sugar alcohols (fructan, trehalose, mannitol, D-ononitol and sorbitol), amino acids (proline and ectoine), and ammonium compounds (polyamines, glycinebetaine, *b*-alanine betaine, dimethyl-sulfonio propionate, and choline-*O*-sulfate), are interchangeable compounds synthesized by plants in low concentration under normal conditions and induced under salinity to alleviate stress (Nadeem et al. 2020). Most of these osmolytes, e.g., proline, glycine, glycine betaine, β-alanine, and raffinose, provide adaptation to plants against salinity by maintenance of osmotic balance by detoxification of reactive oxygen species and protection of intracellular membranes and protein structure (McNeil et al. 1999; Hasegawa et al. 2000; dos Santos et al. 2011; Nadeem et al. 2020). Betanin is synthesized by only a few species of family plumbaginaceae (Hanson et al. 1994).

4.3.1 Amino Acids

Free amino acids reduce osmotic stress induced by salinity (Ashrafijou et al. 2010). Accumulation of arginine, alanine, glycine, leucine, proline, valine, and serine regulates cells (Mansour 2000) under salt stress. Methionine and arginine concentrations decrease and proline increases under salinity stress (Shahzad et al. 2019). In different plants, proline amino acids are the most studied common and abundant osmolyte (Jantaro et al. 2003; Saxena et al. 2013; Shahzad et al. 2019). Under salt stress, content of proline upsurges in cells for acclimation process to evade salinity-induced negative effects (Ahmed et al. 2010; Doğan et al. 2010; Saxena et al. 2013). The proline content accumulation facilities better plant growth rate (Saxena et al. 2013) in *Zea mays* (Molazem and Azimi 2015). The proline accumulation in cell wall of *Glycine max* L. reduces negative effects and increases tolerance to salinity (Phang et al. 2008).

4.3.2 Glycine Betaine

Glycine betaine (N, N, N-trimethylglycine) is the most widely distributed compatible solute, key osmoprotectant and quaternary ammonium compound (QAC) in plants to handle osmotic stress (Rhodes and Hanson 1993; Turkan and Demiral 2009; Slama et al. 2015). The glycine betaine (GB) protects plant membrane from damages of stress and regulates intracellular osmotic adjustment and cascade of signal transduction in the plant cells under salinity stress (Rhodes and Hanson 1993; Sakamoto and Murata 1998; Gadallah 1999; Ashraf and Foolad 2007; Ahmed et al. 2010; Ranganayakulu et al. 2013; Saxena et al. 2013;

Slama et al. 2015), stabilizes proteins (Makela et al. 2000), and provides protection to photosynthetic thylakoid apparatus, thereby maintaining photosynthetic efficiency (Cha-Um and Kirdmanee 2010; Ashraf and Fooland 2007; Ranganayakulu et al. 2013) and reduces ROS (Ashraf and Fooland 2007; Ranganayakulu et al. 2013; Saxena et al. 2013). The accumulation of GB in chloroplasts effectively protects plants than in cytosol (Sakamoto and Murata 1998). In rice seedling ultrastructure, grana and intergranal lamellae disintegration and fragmentation, thylakoid swelling, and mitochondrial disruption take place under 150 mM salt stress treatment. However, on pretreatment of seedlings with glycine betaine, these damages disappear and accumulation of exogenous glycine betaine makes plants stronger against stress (Rahman et al. 2002; Saxena et al. 2013). The ultrastructure of *Oryza sativa* seedlings reported positive effect of glycine betaine under salt stress (Rahman et al. 2002). GB treatment as foliar spray stabilized pigments and increased photosynthetic rate and growth in a stressed plant and induced tolerance to abiotic stress in maize and other species (Cha-Um and Kirdmanee 2010; Ahmad et al. 2013a, b; Ashraf and Fooland 2007; Pei et al. 2020).

5 Photosynthesis

Salt stress affects the leaf physiology, mainly the process of photosynthesis (Fig. 40.1), and thus reduces plant productivity (Mbarki et al. 2018). The salt stress leads to closure of stomata. The stomatal closure decreases photosynthesis ratio because of decline in conductance of stomata restricting access of carbon dioxide (CO_2) for the Calvin–Benson cycle (Hnilickova et al. 2017). Further, electron transport chain (ETC) inhibition and inactivation of photosystem II (PSII) reaction centers (Mehta et al. 2010) take place. This destroys water-splitting complex of photosystem II and impairs capacity of the electron transfer (Kalaji et al. 2018). The salt stress declines rates of photosynthesis and electron transport, osmotic potential of leaves and CO_2 concentrations in chloroplasts of leaves in rice plant (Wang et al. 2018). PSII damages by salinity (150 mM) in wheat cultivars, and in these plants, chlorophyll content and quantum yield of PSII declined (Hussain et al. 2021). Decline in chlorophyll content is common under salinity. The concentration of chlorophyll can be a probable indicator of metabolic state at cellular level (Chutipaijit et al. 2011). In rice plant, chlorophyll a (33%) and chlorophyll b (41%) content reduce after treatment with 200 mM NaCl (Amirjani 2011). Salinity-induced water scarcity reduces conductance of stomata, which in turn reduces photosynthetic activity of plants and fast-tracks ROS accumulation by H_2O_2, $^1O_2$, $O_2^{\bullet-}$, and $OH^{\bullet}$. These agents disrupt various cellular components and structural integrity of plant (Hasanuzzaman et al. 2021).

6 Molecular Approaches to Develop Salinity Stress-Resilient Plants

The advanced technologies of CRISPR/Cas target-site genome editing help us in designing tailor-made salt-resilient plants, e.g., in rice (Zhang et al. 2019; Kumar et al. 2020). Upregulation of ROS scavenging/detoxification pathway genes reduces damage to plant cell, maintains photosynthetic efficiency, and improves growth of roots under salinity (Roy et al. 2014). The same conditions along with biomass accumulation and tolerance to salinity take place by overexpression of hydrogen (H^+) and potassium (K^+) antiport channels (Huang et al. 2017). ThNAC12 TF overexpression-based ThPIP2;5 expression regulation improved tolerance to salinity by modulating ROS removal in *Tamarix hispida* (Wang et al. 2021). SiMYB19 overexpression helps in accumulation of abscisic acid (ABA) and upregulation of *OsNCED3*, *OsPK1*, and *OsABF2* genes of ABA signal transduction pathway in rice plants (Xu et al. 2022). Ten novel QTLs were reported in *Glycine max* for tolerance to salinity. The qST6 and qST10 novel loci play role in defense against toxicity of ions and physiological damages induced by salinity, and these two novel loci induce additive consequences on tolerance to salt stress (Cho et al. 2021a). Single-nucleotide polymorphism (SNP) marker for salinity tolerance was also reported in *G. max* (Lopez et al. 2018). The overexpression technology and CRISPR/Cas9 show GmNAC06 TF leads to accumulation of GB and proline for alleviation or avoidance of ROS damages. This can also regulate sodium–potassium ion (Na^+/K^+) ratios in *G. max* hairy roots for maintaining ionic homeostasis under salt stress. GmNAC06 with a function in salinity paves way for generation of salt-tolerant crops (Li et al. 2021a). Two arms of miR166m (miR166m-5p and miR166m-3p) target chloroplastic beta-amylase 1 and calcium-dependent protein kinase 1 (CDPK1) of salinity stress, respectively, in *G. max* (Li et al. 2022). At the stages of seedling and reproductive cycle in the rice plants, 935 QTLs were identified for salt stress tolerance, out of which 63 meta-QTLs designate regions for tolerance to salinity (Singh et al. 2021). SiMYB19 improved tolerance to salinity in rice by regulation of ABA synthesis and signal transduction (Xu et al. 2022). Wheat Heat Shock Factor (TaHsfA6f) overexpression in Arabidopsis improved tolerance to heat, salinity and water deficiency (Bi et al. 2020). SlCIPK24M overexpression lines of *Solanum lycopersicum* L. showed better tolerance to salinity. SlCIPK24M in *S. lycopersicum* transgenics had higher Na^+ and K^+ contents in roots under salt stress (Cho et al. 2021b). In *S. tuberosum*, miR156 expression profiles in roots and shoots and miR398 in shoots relate to salinity stress (Çakır et al. 2021). In *Triticum aestivum*, some 5128 genes showed differential expression in salinity. The differentially expressed genes were categorized into 227 KEGG pathways. In 227 KEGG pathways, genes associated with transporters, biosynthesis of phenylpropanoid, transcription factors, glycosyltransferases, glutathione metabolism, and plant hormone signal transduction were most important for salinity responses (Amirbakhtiar et al. 2019). PsnNAC036 (NAC domain containing protein 36) overexpression stimulated growth and improved salt tolerance in *Populus simonii* × *P. nigra* (Zhang et al.

2021). MpZFP1 (zinc-finger protein) from *Millettia pinnata* positively regulates response to salinity. The *MpZFP1* activation and efficient ROS detoxification increase tolerance to salt stress and germination rate of seeds, seedling survival rate, and accumulation of Arabidopsis biomass under salinity stress (Yu et al. 2021). Acetylserotonin methyl transferase (ASMT) gene expression induced by salinity increased melatonin levels in apple and reduced salt damage symptoms, lower relative electrolyte leakage, and less total chlorophyll loss from leaves under salt stress (Tan et al. 2021). The heterologous expression of hydroxyindole-O-methyltransferase (HIOMT) improved antioxidant enzyme machinery, melatonin content, and photosynthetic capacity; maintained ion homeostasis and downregulated ABA synthesis gene (MdNCED3); and reduced ABA and ROS accumulation in Apple transgenic lines under salinity stress (Tan et al. 2021). The examples of some salinity-tolerant transgenic plants are enlisted in Table 40.1.

Table 40.1 Salinity-tolerant transgenic plants

Transgenic plant	Gene transferred	Transgene source	References
Arabidopsis thaliana	AtbHLH17 and AtWRKY28	*Arabidopsis thaliana*	Babitha et al. (2013)
Arabidopsis thaliana	LcMYB1 MYB	*Leymus chinensis*	Cheng et al. (2013)
Arabidopsis thaliana	HcNHX1	*Halostachys caspica*	Guan et al. (2011)
Arabidopsis thaliana	AtPP2CG1	*Arabidopsis thaliana*	Liu et al. (2012)
Arabidopsis thaliana	APXa and APXb	*Oryza sativa*	Lu et al. (2007)
Arabidopsis thaliana	ScTPS1	*Saccharomyces cerevisiae*	Miranda et al. (2007)
Arabidopsis thaliana	ALDH10A8 and ALDH10A9	*Arabidopsis thaliana*	Missihoun et al. (2015)
Arabidopsis thaliana	AtNHX1 and AtSOS1	*Arabidopsis thaliana*	Pehlivan et al. (2016)
Arabidopsis thaliana	LcDREB2	*Leymus chinensis*	Peng et al. (2013)
Arabidopsis thaliana	Glutathione *S*-transferase	*Suaeda salsa*	Qi et al. (2010)
Arabidopsis thaliana	PgNAC21 NAC	*Pennisetum glaucum*	Shinde et al. (2019)
Arabidopsis thaliana	LcERF054	*Lotus corniculatus*	Sun et al. (2014)
Arabidopsis thaliana	ZmCBL4/SOS3	*Zea mays*	Wang et al. (2007)
Arabidopsis thaliana	MaPIP1;1	*Musa acuminata*	Xu et al. (2014)
Arabidopsis thaliana	SOS1, SOS2, SOS3	*Arabidopsis thaliana*	Yang et al. (2009)
Arabidopsis thaliana	ZmSAPK8 SnRK2	*Zea mays*	Ying et al. (2011)
Arabidopsis thaliana	MdY3IP1	*Malus domestica*	Yu et al. (2018)
Arabidopsis thaliana	AtFC1	*Arabidopsis thaliana*	Zhao et al. (2017)

(continued)

Table 40.1 (continued)

Transgenic plant	Gene transferred	Transgene source	References
Arabidopsis thaliana	Cysteine protease	*Salix matsudana*	Zheng et al. (2018)
Arabidopsis thaliana	BnNAC5 NAC	*Brassica napus*	Zhong et al. (2012)
Arabidopsis thaliana	GhWRKY34	*Gossypium hirsutum*	Zhou et al. (2015)
Arachis hypogaea	AtNHX1	*Arabidopsis thaliana*	Asif et al. (2011)
Bacopa monnieri	SbVPPase	*Sorghum bicolor*	Ahire et al. (2018)
Beta vulgaris	AtNHX3	*Arabidopsis thaliana*	Liu et al. (2008)
Brassica juncea	Choline oxidase	*Arthrobacter globiformis*	Prasad et al. (2000)
Brassica oleracea var. capitata	Choline dehydrogenase	*E. coli*	Bhattacharya et al. (2004)
Cajanus cajan	P5CSF129A	*Vigna aconitifolia*	Surekha et al. (2014)
Medicago sativa	SsNHX1	*Salsola soda*	Li et al. (2010)
Nicotiana tabacum	Catalase	*E. coli*	Al-Taweel et al. (2007)
Nicotiana tabacum	GmHKT1	*Glycine max*	Chen et al. (2011)
Nicotiana tabacum	PsSEO-F1	*Pisum sativum*	Srivastava et al. (2016)
Nicotiana tabacum	CIPK6 CBL-interacting protein kinase 6	*Cicer arietinum*	Tripathi et al. (2009)
Oryza sativa	NHX	*Oryza sativa*	Amin et al. (2016)
Oryza sativa	SAPK4	*Oryza sativa*	Diédhiou et al. (2008)
Oryza sativa	PpENA1	*Physcomitrella patens*	Jacobs et al. (2011)
Oryza sativa	OsPP1a	*Oryza sativa*	Liao et al. (2016)
Oryza sativa	codA	*Arthrobacter globiformis*	Kathuria et al. (2009)
Oryza sativa	OsMYB91	*Oryza sativa*	Zhu et al. (2015)
Oryza sativa	OsMKK6	*Oryza sativa*	Kumar et al. (2013)
Populus nigra x Populus tomentosa	mt1D	*E. coli*	Lin et al. (2016)
Saccharomyces cerevisiae	SiPIP3;1 and SiSIP1;1	*Setaria italica*	Singh et al. (2019)
Saccharomyces cerevisiae	CcSOS1	*Chrysanthemum crassum*	Song et al. (2012)
Saccharomyces cerevisiae and Oryza sativa L.	HtSOS1	*Helianthus tuberosus*	Li et al. (2014)
Solanum lycopersicum	BADH	*Atriplex hortensis*	Jia et al. (2002)

(continued)

Table 40.1 (continued)

Transgenic plant	Gene transferred	Transgene source	References
Solanum lycopersicum	AtNHX1	*Arabidopsis thaliana*	Leidi et al. (2010)
Solanum lycopersicum	APX	*Pisum sativum*	Wang et al. (2005)
Solanum lycopersicum	Choline oxidase	*Arthrobacter globiformis*	Wei et al. (2017)
Solanum tuberosum	NHX2	*Hordeum vulgare*	Bayat et al. (2010)
Solanum tuberosum	SlDREB1	*Solanum tuberosum*	Bouaziz et al. (2015)
Triticum aestivum	AhBADH	*Atriplex hortensis*	Guo et al. (2000)
Triticum aestivum	TaERF3	*Triticum aestivum*	Rong et al. (2014)
Triticum aestivum	P5CS	*Vigna aconitifolia*	Sawahel and Hassan (2002)
Zea mays	BADH	*Atriplex micrantha*	Di et al. (2015)

7 Conclusion

Salinity is the leading danger to agriculture and significantly limits agricultural produce and crop yields. Salinity causes two-way stress in plants, i.e., osmotic and ionic, and leads to plant toxicity or nutritional disorders. The osmotic and ionic toxicities generate secondary stresses which impair mechanism of seed germination, photosynthetic activity, development of organs, and plant growth and development. Salinity affects morphological, physiological, biochemical, and metabolic cell functions. To face salinity, plants trigger and develop various morphological, anatomical, physiological, and biochemical adaptations. Salinity tolerance triggers expression of various genes related to photosynthesis, cell vacuolar transport, osmolytes, membrane channel proteins, ROS protectors of ROS removal pathway, and QTLs for salt tolerance (Hassan et al. 2020), making these key targets for designing tailor-made salt-resilient plants.

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Chapter 41
Managing Soil Salinity for Sustainable Agriculture

Dua Zahra Khan, Niaz Ahmad Wahocho, Muzamil Farooque Jamali, and Waqas Ahmad

Abstract To meet the food requirements of the increasing population, the world needs new resources of food and land and also needs to enhance the existing resources of land and crop production. A lot of soils are saline, which makes them unsuitable for agricultural production or minimizes production. It is the dire need of the time to enhance crop production on those lands. For this purpose, understanding of salinity effects on crop production and its management is necessary. Therefore, the main purpose of this chapter is to discuss the salinity effects on different crops and their sustainable management for enhanced agricultural production. This chapter presents salinity effects on morphological, physiological, and biochemical aspects of plants and internal plant mechanisms to survive under salinity stress along with sustainable management options.

Keywords Salinity · Crop response · Tolerance mechanism · Management

1 Introduction

Soil salinity is the measurement of salt in the soil, and salinity may occur due to water logging, inappropriate drainage and human activities. It is basically salt accumulation in soil. Millions of hectares of land are becoming nonproductive because of salt accumulation in soil. Saline soils are mostly present in the area where rainfall is not sufficient, i.e., arid and semiarid regions of the world. Saline soils are the soil containing heavy amount of salts, and more salt in soil means more salinity. Sodic soils have high concentration of exchangeable sodium salts. Due to presence of sodium in soil, the bond between soil particles breaks down. Various scientists reported differently about the sodic soil according to their research, but recent

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estimate of saline soils does not exist. According to global distribution, 954 million ha soil is salt affected (Shahid et al. 2018). In this scenario, it becomes important to produce maximum from saline soils to fulfill the world's food needs.

Sustainable agriculture is the system of farming in which farmers have to work with the natural resources, i.e., soil, water and air, to fulfill the future need of increasing population. Sustainable agriculture helps in maintaining environment and increasing economic yield. Soil salinity is a serious problem to the sustainable agriculture because the soil with the unbalanced amount of sodium, magnesium, and calcium is not suitable for the cultivation of crops, resulting in less food production. The presence of salinity in soil and water affects the growth of plants in three ways: increases osmotic potential, reduces ion absorption, and diminishes soil water permeability and soil erosion. Hence, the economic yield is reduced (Ramezani et al. 2011). The plants survive in saline conditions only through adjustment of osmotic potential and ion absorption (Ramezani et al. 2011).

Salinity reclamation is basically the addition of calcium sulfate in the soil. To address the salinity problem, the cultivation of salt-tolerant crop varieties is recommended as it is cost effective and favorable to manage by farmers. Transgenic plants having genes of halophytes can tolerate the salt stress. In order to control salinity, the transgenic plants should be developed (Türkan and Demiral 2009). Halophytes are salt-tolerant plants, and these plants grow well on the saline soils. Halophytes maintain ecological stability and are climate changing plants. But only the small quantity of the plants genotype is available which resists against the saline soils. The fewer work on saline-tolerant plant genotype is due to minor research work on the plant physiology. Leaching of salt downward in soil through water also controls the salinity. Leaching maintains the salt balance in the soil and removes excess salt from the root zone of plants. Subsurface drainage system is the only solution for the crops that are cultivated in the saline soils. Subsurface drainage system is most efficient, economic and effective system for the future. Keeping in view the abovementioned facts and problems, the major objective of this chapter is to understand the soil salinity problems for agricultural production and its sustainable management.

2 Effect of Salinity on Crop Physiology

The physiology of plants controls the water and nutrient availability to the crops. It promotes the photosynthesis and respiration in the plants, which helps in the exchange of gases in plants throughout the growing period of crops. Crops produce their food through photosynthesis in the presence of sunlight, and respiration produces energy for plant growth through photosynthesis and oxygen released as a result of photosynthesis. Crops also produce secondary metabolites, which protect them from insects and pests. Reactive oxygen species (ROS) are produced in crops because of environmental stress on crop and biochemical reactions that occur during the photosynthesis and respiration in crops. During the initial stage of salinity stress, many physiological and metabolic changes occur in crops involving accumulation of salt in root zone (in soil and plants), membrane damage, disturbance in nutrient supply, reduction in production of reactive oxygen species, less production of antioxidant enzymes and secondary metabolites, and reduction in photosynthetic activities. Thus, salt stress is considered as hyperosmotic stress (stress leads to the loss of water from plant cells with high salt concentration in soil) and hyperionic stress. Due to salinity stress, the Na^+ and Cl^- ions enter in plant tissues and discourage the consumption of K^+ ion—the most important element needed for the growth and development of plant—which causes the less production of crop and even causes death of crop. The increased production of ROS can cause more cellular damage, i.e., lipid, protein, DNA, etc., of plants. The plant biologists are trying to develop complete description of mechanism of salinity stress tolerance, but due to lack of information related to genomic, proteomic, and metabolomics studies, the process of controlling salinity stress could not be founded yet (Caverzan et al. 2019). With the help of genetic engineering techniques, the development of salt-tolerant plant species is more efficient and genes identification is possible (Tables 41.1 and 41.2).

2.1 Photosynthesis and Transpiration in Plants

Direct effect of salt on the enzyme function shows the effect of salt on respiration in crops. The respiration rate is higher in salt-sensitive crops than salt-tolerant crops; thus, the salt-sensitive crops have less chlorophyll content. Photosynthesis is prohibited by salinity. Under salinity, photosynthesis reduces by 65% due to stomatal and nonstomatal factors (Sabbagh et al. 2014). The salt stresses reduce plant growth and photosynthetic activities in plants due to accumulation of Na^+ ions in the roots of crops, which reduces the bioenergetics processes of photosynthesis, but the transpiration rate increases (Sudhir and Murthy 2004). As sodium takes the position of K^+ ions in roots, the accumulation of sodium in leaf cells and ionic imbalance take place in plants, which lower the absorption of other minerals and nutrients. Photosynthesis consists of many components, i.e., electron-transport system, photosystem, photosynthetic pigments, and carbon dioxide-reduction reaction, and any stress during any process of photosynthesis may reduce the overall photosynthetic process. Photosynthetic electron transport activities decrease due to salt stress, and plant growth rate is also decreased. The capacity of plants to protect itself can be improved by all these components through their modification, electron-transport chain between photosystems, and thylakoid membrane compositions, and photosynthetic activities of plants are the best ways to improve the salt tolerance in plants (Pan et al. 2021). In the last two decades, the transgenic lines of C3 crops were discussed having greater photosynthetic performance (Ashraf and Harris 2013). Changes in physiological activities in plants, i.e., photosynthesis and transpiration, can minimize the proteins, minerals, and nutrients uptake in crops (McGrath and Lobell 2013). At high temperature in

Table 41.1 Effect of salinity on different parameters in different crops

Crop name	Salinity level	Parameters	Effect	Reference
Mulberry	12 dS m^{-1}	Chlorophyll content	Chlorophyll and carotenoids reduced at this salinity level.	
		Photosynthesis	Decreases.	
	1.7–6.9 dS m^{-1}	Antioxidant	Above this salinity level, super oxidase dismutase, catalase, per oxidase level decreases.	
	25.4 dS m^{-1}	Germination	Seedlings survive up to this salinity level.	
Olive	66–166 mmol L^{-1}	Antioxidant	Increased activity.	
	40–160 mmol L^{-1}	Chlorophyll	Chlorophyll a and b level deceases at this level.	
		Photosynthesis	Decreases	
Guava	30 mmol L^{-1}	Chlorophyll	Leaf chlorophyll content decreases due to deficiency of N and Mg.	
	6 dS m^{-1}	Germination	At this high salinity level, seedling survival reduces above 25%.	
Rice	100 mM, 150 mM	Germination	Germination rate decreases with the increase in salinity.	
		Chlorophyll a, Chlorophyll b	Chlorophyll content decreases with the increase in NaCl level, and chlorophyll a is more affected.	
		Protein content	Reduction in protein content with the increasing concentration of salt.	
		Photosynthesis	Decreases	
Wheat	125 mM	Germination	Maximum germination at this level, but germination percentage is reduced with increasing salinity depending on verities.	Datta et al. (2009)
	125 mM	Growth	Root and shoot growth reduced below this salinity level.	
		Sugar content	Sugar content increases with increased salinity level.	
Maize	50 mM, 100 mM	Leaf water content	Decreases.	Yang and Lu (2005)
		Photosynthesis	Decreases.	
		Growth	Due to salinity, the seedling growth is reduced.	

dry areas, C_3 has high photosynthesis rate because of high CO_2 produced by the plants and high transpiration rate (Kirschbaum 2004). Stomata provide a control for both photosynthesis and respiration as they control the water losses and exchange of gasses, i.e., CO_2 (Jones 1998).

Table 41.2 List of salt-tolerant genes transferred in various species along with source species

Gene	From species	To species	Reference
TaNHX2	*Triticum sativum*	Soybean	Cao et al. (2011)
P5CS	*Vigna aconitifolia*	Chickpea	Ghanti et al. (2011)
PR10a	*Solanum tubersum*	Faba bean	Hanafy et al. (2013)
AtNHXI	*Arabidopsis thaliana*	Pea nut	Banjara et al. (2012)
WRKY58	*Zea mays*	Rice	Cai et al. (2014)

2.2 Production of Reactive Oxygen Species and Antioxidants

Organelles are the source of ROS in plant cells. Organelles, i.e., chloroplast and mitochondria, possess highly oxidizing metabolic activities and have intense rate of electron flow. A fact is discovered that ROS plays important role in cellular physiology in the life of plants. ROS acts as a second messenger in plant cells and response to any kind of stress immediately. In plant cells, change in gene expression is the function of ROS. The mechanism to generate ROS in plant cells is understood, and inactive enzymes that damage protein, lipid and nucleic acid in plant cells indirectly cause the death of plant cells (Karuppanpandian et al. 2011). Plants already contain antioxidant metabolites, enzymes and nonenzymes that purify the ROS. Antioxidants act as a defense system that helps in the maintenance between production of ROS and its destruction at toxic levels in plant cells (Caverzan et al. 2019). In plants, NADPH oxidase is involved in the production of ROS. ROS acts as a messenger that helps in activating Ca^{2+} in plants for the growth of root system (Sagi and Fluhr 2006). Salinity plays a role in damaging plant growth and development by producing heavy amount of reactive oxidases, but ROS also helps to regulate the plants metabolism. The salinity affects ROS in plants negatively. Excess amount of Na^+ and Cl^- destroy the organelles, protein synthesis, and enzyme structures in plants. When higher amount of ROS is produced, the antioxidants help to reduce the toxic effect of ROS in crops. During environmental changes, antioxidants have the ability to maintain the metabolism of plants. Salinity in plants results in imbalanced formation of ROS, which is toxic for plants. ROS damages the enzymatic and nonenzymatic compounds in plants and causes oxidative damage. As ROS contains free radicles, hydroxyl radicles, per hydroxyl radicles, alkoxy radicles, and molecular components of oxygen, these ions badly affect structure of plants and cause disturbance in plant physiology, i.e., OH^- damages the components of DNA in crops, and under these conditions, the antioxidants act as a support system for the establishment of a plant. The oxidative damage to the crops results in 50% less production of crops than previous year, and through genomic and genetic engineering techniques, the oxidative damage to the plants can be reduced, i.e., ascorbate-glutathione pathways help in the detoxification of overproduction of ROS in plant cells because it contains same compounds that help in the detoxification of ions produced by ROS, e.g., OH^- and H_2O_2 (Chakradhar et al. 2017).

2.3 Production of Secondary Metabolites

Secondary metabolites are those compounds which are not needed for plant growth but play important role between organisms and environment and protect the plants against biotic and abiotic stresses in environment. Secondary metabolites are the source of fragrance, flavor, color, and medicinal properties in plants (Pagare et al. 2015). Different technologies have been introduced to produce the secondary metabolites in plants through *in vitro* propagation techniques. Plant cell cultures, plants biotechnology, plants suspension culture, biosynthetic pathways and recombinant DNA technology are the new fields that help in the modification of genes of expressions in plants (Bourgaud et al. 2001). The presence of secondary metabolites in plants is a defense system for plants against pathogenic attacks. The secondary metabolites are synthesized from plants in cell culture or organ culture in different culture medium, i.e., MS media, kinetin, vitamins, etc. The studies showed that there are many pathways in plant systems for the generation of secondary metabolites, and the involvement of plant itself and microbes results in the formation of natural products that can also be synthesized artificially through hairy root culture, tissue culture, cell culture, organ culture, etc. Alkaloids, anthocyanin, flavonoids, glucosides, quinine, phenolic compounds, and essential oils are some of the synthesized secondary plant metabolites (Karuppusamy 2009). Safflower is a salt-tolerant crop, and hence, its seedling growth, and root-shoot growth are not affected by salinity but the rate of secondary metabolites with the increased salinity (Gengmao et al. 2015). The presence of secondary metabolites is related to salt-tolerant capacity of crops. In wheat crops, the crop is affected adversely due to salinity or other biotic factors; thus, there are compounds that work against these factors, i.e., flavonoids are plant secondary metabolites to protect the plants from microbial attacks.

3 Management of Salinity Stress

3.1 Breeding Approaches

In plant breeding, breeders must develop improved variety, but its development is not easy because of very long crop duration. Even the production of a new variety can take about 10–20 years in its development, because it involves two crops introduction for crossing, then crossing, then selection and testing of a new genetically modified variety of that crop. Different breeding approaches can be used in order to improve the traits, quality and resistance of crop against salinity; these approaches may be conventional as well as molecular techniques. By using the Cluster Regularly Interspaced Short Palindromic Repeat (CRISPR) and CRISPR-associated techniques, genomic editing is possible, which improve the crop traits as well as quality of crop.

3.2 Markers-Associated Selection

The molecular genetics and associated technologies have been made through plant breeding to improve our understandings about genetics. Marker-associated selection helps in the transfer of a single gene for the improvement of crop traits. The DNA marker is helpful in the characterization of germplasm. In marker-associated selection, the traits are controlled by quantitative trait loci (QLT). Marker-associated selection is based on PCR-based markers at a target genome (Ribaut and Hoisington 1998). The artificial selection on the trait of plants is based on the phenotype of plants. The genetic improvement of plans has become possible through the marker-associated selections with the help of different breeding approaches (Dekkers and Hospital 2002).

3.3 Transgenic Crop Genes

Nowadays, due to abnormal environmental conditions, the crop productivity is decreasing day by day. It is a need to find a proper way for increasing crop productivity for increasing population for ensuring the food security. Salinity is reducing crop yield depending upon crop type and stress level. Biotic stresses are also adversely affecting the crops. In order to improve the economic conditions, variety selection and proper use of fungicides are the two management techniques for the crop establishment under salinity stress and other biotic stresses (Haggag et al. 2015).

Crop yield is improved by developing a salt-tolerant genotype through breeding approaches and markers-associated selections. Development of salt-tolerant genotype is possible through gene transformation. Successful genotype is formed by transplanting a foreign gene into already existing crop plant by genetic engineering techniques. A new genotype will increase the survival rate of crop under salinity stress (Hussain et al. 2018).

3.4 Arbuscular Mycorrhizal Fungi Attached with Seeds

As the salt stress reduces the crop yield as well as sustainable agriculture, the arbuscular mycorrhizal fungi (AMF) act as ameliorators for salinity stress in crops. AMF are indicators that indicate the changes in plant physiology and availability of nutrients in plants under salinity stress. Studies have shown that AMF improves the crop physiology by increasing growth of crop, i.e., root and shoot growth, nutrients uptake of nitrogen, phosphorous, potassium, etc. (Chandrasekaran et al. 2014). It also increases the antioxidants' activities by increasing the peroxides, catalysis and superoxide's activation under salt stress. In mycorrhizal plants, the accumulation of Na^+ ion is reduced. Salinity can also damage the spores' formation and reduce the hyphal growth of fungus, and it may be due to the direct effect of salt on the fungi and stop the formation of AMF (Evelin et al. 2009). In saline soils, 80% of AMF spores have only single species named *Glomus geosporum* (Bothe 2012). In the grain legumes, due to the presence of growth-promoting rhizobacteria and AMF, the salt tolerance should be improved with the proper nutrient availability with the help of its proper hyphal network (Farooq et al. 2017).

3.5 Exogenous Application of Hormones

Application of hormones in plants improves vegetative and also the reproductive growth of plants. As the hormones are natural substances, they can be synthesized chemically in order to stimulate the physical activities of plants, i.e., plant height, stem diameter, and chlorophyll content in leaf. Large-scale application of hormones increases crop yield and reduces the use of chemical fertilizers and pesticides to avoid the toxicity caused due to salinity and other environmental stresses (Akter et al. 2014). The application of nutrients to the sodic soils enhances the soil nutrient status and increases the growth rate of plant with the higher yield of crop. Some hormones are growth promoters, and some are growth-retardant hormones, i.e., auxin, cytokinin, gibberellin, abscisic acid, and ethylene, respectively. In maize, the salinity affects the physiology of plants; thus, the growth hormones play a role in maintaining the crop stand under salinity. The application of cytokinins in maize increases the number or kernels per plants, while single application of auxin increases the weight of grains, and hence, harvest is increased, but the application of cytokinins with auxins gives better result in term of promoting physical structure of a crop, i.e., plant length, leaves length, stem diameter, etc. (Iqbal et al. 2020). The application of growth hormones in plants reduces the enzymatic activities in plants and antioxidant activities, improves the physiology of plants and hence gives better quality and quantity of yield.

3.6 Seed Priming

Seed germination and seedlings growth are the sensitive stages of plant growth that are adversely affected by salinity. Thus, the establishment of crop stand under salinity stress is very important. Seed priming is the most used technique that prevents the crop damage at the initial stages of crop growth. Due to salinity effect, the crop height is reduced, but the seed priming reduces the height problem in crop under salinity, and also seed priming makes the seed more resistant to stable itself under the saline soil, soil-borne diseases, etc. Seed priming regulates the pregermination metabolic processes, enhances the antioxidant system activities and also repairs the damaged cell membranes (Ibrahim 2016). Commonly, seed priming is done with calcium chloride, potassium chloride, ascorbic acid, proline, potassium silicate, spermidine, LUsw, H_2O_2, etc. Different experiments were conducted to check out the seed priming effect under salt stress in wheat. For this purpose, the wheat seeds are primed with different priming agents, i.e., spermidine (0.5 mM), proline (25 mM), K_2SiO_3 (1.5 mM), and LUsw (100 mg L^{-1}), and all these agents have shown different results under different salinity levels with the increasing growth rates. Research has proved that K_2SiO_3 is more effective for seed priming than other priming agents (Feghhenabi et al. 2020).

4 Conclusion and Prospects

Salinity is one of the major abiotic stresses that affects crop production and is also associated with the climate change. Soil salinity affects gas exchange attributes like photosynthesis, transpiration, etc.; water relations like water potential, leaf water contents, etc.; and production of primary and secondary osmolytes, which leads to poor crop growth and development. Various breeding and agronomic management strategies can be used to deal with salinity. Most sustainable management of the salinity stress is to produce crop genotype tolerant to salinity stress. Future research is needed to produce salt-tolerant gene sources from wild relative and halophytes to produce crop genotypes tolerant to salinity stress.

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Chapter 42
Climate Resilient Livestock Production System in Tropical and Subtropical Countries

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Sabiha Zarin Tasnim Bristi, Nasir Uddin, and A. H. M. Musleh Uddin**

Abstract Livestock production and human civilization are interlinked. Since the start of human civilization, livestock has been playing vital roles. Livestock serves as a source of milk and protein, an agricultural business, and a pet. Every individual requires animal proteins on a daily basis, such as meat and dairy products, the majority of which are derived from livestock animals. Industrialization of livestock production has become an important component of global GDP and a source of

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income for both industrialists and low-income marginal communities around the world. Production of livestock depends on intrinsic factors as well as environmental factors. Environmental factors such as temperature, humidity, rainfall, and so on have a significant impact on farm animal production, survivability, and disease load. The level of environmental stress differs in different climatic conditions. Therefore, a concrete understanding of environmental stress factors is required to ensure the optimum production of livestock. In this chapter, we discuss thermal stress and its detection methods, adaptive thermal stress management, the effects of temperature on bovine health, milk production, beef production, and reproductive performance, thermal effects on water availability, livestock diseases and intramammary infection, uses of small ruminants for livelihood, livestock sources of methane, and strategies to mitigate thermal stress and methane emissions.

Keywords Climate change · Thermal stress · Livestock · Production · Diseases · Mitigation

1 Introduction

Human civilization relates to the development of livestock production (Thornton et al. 2009). In the ancient era, when people used to live in the jungle, they were dependent on bushmeat and used to hunt animals from the forest to support their daily protein requirement (Lees et al. 2019a). Modern societal development and economic advancement are inextricably tied with the advancement of livestock farming and pet ownership (Moore 1988; Alkire and Deneulin 2009; Franklin 1999). Livestock rearing was linked to the evolution of human society and became a vital aspect of economic development and the backbone of an agrarian human society in the modern era (Suberu et al. 2015; Azam and Shafique 2017). With the advancements in human lifestyle, bovine animal rearing, in particular, has emerged as one of the major economic drivers. The livestock industry contributes a significant percentage of the global GDP. Human civilization gradually started with domestication of animals, and the modern era started with the development and industrialization of livestock production for meat, milk, skin, and by-products of livestock. Every day, a healthy person requires at least 732 ml of milk (Ninonuevo et al. 2006; Mullie et al. 2016; Macheka et al. 2021) and 0.8 grams of protein per kilogram of body weight (Pellet 1990; Wu 2016). Currently, the world produces around 340 million tons of beef and 800 million tons of milk every year, but to fulfill the demands of the current population, production demands for both milk and meat are higher than the present production (Kovács and Szűcs 2020). Therefore, the production of livestock becomes one of the major components not only for economic purposes but also for a healthy generation in the world.

However, livestock productivity is influenced by both genetic and environmental factors. Animals' performance traits are mainly designated as phenotypic traits. For example, the heritability of milk letdown is 0.33 (Schneider and Van Vleck 1986), which indicates 33% of the prosecution of milk letdown by cattle is dependent on the genetic combinations of the parents of cattle and the rest, 67% of the production amount, is controlled by the environment where the animals are reared. As a result, consideration of environmental stressors and management of a suitable environment for cattle is required for successful breeding and product development. Temperature is one of the major factors that influence the survivability, production performance, and health status of the bovine animals (Das et al. 2016; Lees et al. 2019a). So, the physiology, production capacity, survivability, and health status of animals as well as their diurnal behavior pattern are highly controlled by ambient temperature. Optimum production from animals requires ensuring proper temperature and climatic conditions (Sejian et al. 2017, 2021a, b; Ahamed et al. 2022). This book chapter discusses the major thermal stress factors and methods of assessing heat stress in various climatic conditions, as well as adaptive measures to reduce heat load and limit thermal stress to maintain optimal performance in bovine animals. This chapter also discusses climate variability and its impact on bovine health, including dry matter intake, growth performance, mortality, and physiology. One of the major expectations of livestock production is dairy and beef production; this chapter describes the influence of temperature on performance indicators, as well as the influence of beef and milk production and the influence of temperature on that as well. In addition, this section presents livestock reproductive performance, feed intake, water availability, disease, and intramammary infection. Finally, we highlighted how small ruminant production and rearing are related to improved livelihoods, as well as livestock sources of methane and measures to reduce methane emissions. By the end of the chapter, readers will understand the concepts of thermal regulation of bovine bodies, heat stress measuring indices, adaptive thermal stress measurement, and other heat stress-related concerns under various climatic settings. Thus, this chapter will provide a holistic idea of how optimum production could be achieved by keeping heat stress under control and optimal.

2 Thermal Stress

Thermal stress is one of the major obstacles to an effective production system in tropical and subtropical regions, which can affect livestock animals in a variety of ways (Pankaj et al. 2013; Ribeiro et al. 2020; Chen et al. 2021). Thermal stress is responsible for rising core body temperature and stimulates activation of the hypothalamus-pituitary axis, which leads to increased water intake and consequently a reduction in dry matter intake (DMI), resulting in delayed weight gain and decreased milk production. It is also responsible for the death of livestock animals in severe conditions (Kamal et al. 2018). Animals exposed to direct solar heat may suffer detrimental impacts from climate factors such as temperature, precipitation, wind speed, and relative humidity (Abdelnour et al. 2019).

During cold or heat stress, animals stimulate thermoregulation systems to maintain the internal temperature of the body within normal physiologic ranges (Kadzere

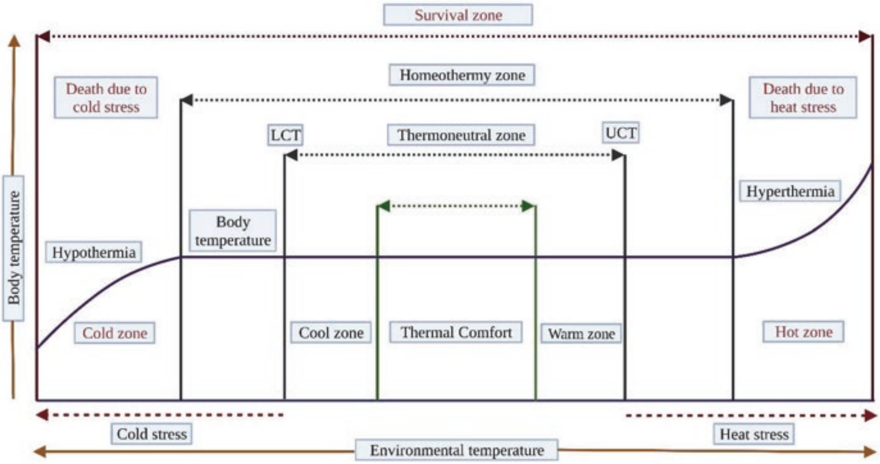


Fig. 42.1 Different thermal zones in homeothermy chart indicating lower and upper critical temperature with animal response. Abbreviations used in the figure: lower critical temperature (LCT) and upper critical temperature (UCT). (The figure was adapted and modified from Santos et al. (2021))

et al. 2002; Santos et al. 2021). Thermal zones are classified into thermoneutral, homeothermy, and survival zones. The zone between lower critical temperature (LCT) and upper critical temperature (UCT) is known as the thermoneutral zone, where the animals are kept in the thermal comfort zone but their metabolic rates are at the lowest level (Godyn et al. 2019). In this circumstance, the animal does not stimulate thermoregulatory systems to generate internal heat or emit heat into the air (Fig. 42.1). A normal body temperature is maintained during the condition, while all the energy available in the body is utilized to optimize animal reproductive and productive performances (Collier et al. 2006; Renaudeau et al. 2012).

The homeothermy zone is initiated when the atmospheric temperature rises and exceeds the UCT or LCT (Adair and Black 2003; Mitchell et al. 2018). Under this condition, animals are activating evaporative thermolysis mechanisms and modifying physiological behavior, for instance, seeking shade, increasing water intake, decreasing DMI, and so on (Sejian et al. 2018; Madhusoodan et al. 2019). When the LCT is reached, the animals' thermogenesis systems are activated in order to maintain core body temperature and/or generate internal heat. This is performed by increasing DMI to produce heat through the enhanced metabolism of nutrients in the gastrointestinal tract and by altering behaviors, for example, grouping together, avoiding lying on cold surfaces, and exposing themselves to direct sunlight. Furthermore, animals will develop hyperthermia and hypothermia if the ambient temperature rises or falls, respectively. Under the condition, denaturation of bodily proteins occurs which affects physiological processes. Animals will die if the ambient temperature is not altered to give them thermal comfort (Bettaieb and Averill-Bates 2015). Therefore, maintaining a comfort zone is important for animals to enhance performance and provide an environment that mitigates thermal stress (Collier et al. 2006; Renaudeau et al. 2012; Mannuthy 2017).

3 Methods for Assessing Heat Stress in Climatic Conditions

3.1 Temperature-Humidity Index (THI)

The temperature-humidity index (THI) is the most popular method to assess the severity of heat stress in livestock animals (Marai et al. 2001; Collier et al. 2011). THI is a distinct figure that summarizes the combined effects of ambient temperature and relative humidity on the severity of thermal stress (Marciniak 2014). THI predicts core temperature of the body in heat-stressed livestock more accurately than other environmental variables.

Several heat stress classes were created using the THI value by Thom (1959) and Armstrong (1994). Thom (1959) described discomfort as being $70 \leq \text{THI} \leq 74$ uncomfortable, $75 \leq \text{THI} \leq 79$ very uncomfortable, and $\text{THI} \geq 80$ serious. Armstrong (1994) classified THI values less than 71 as being in the comfort range, between 72 and 79 as being in a mildly stressful range, 80 and 89 as being in a moderately stressful range, and THI values beyond 90 as being in a severe stress range with a risk of animal mortality.

3.1.1 Calculation of THI

THI was developed as a method to estimate animal comfort, and this metric is frequently used to describe an animal's heat burden. The following formula is used to compute the THI:

$$\text{THI} = 0.8\text{DBT} + \text{RH} \times (\text{DBT} - 14.4) + 46.4$$

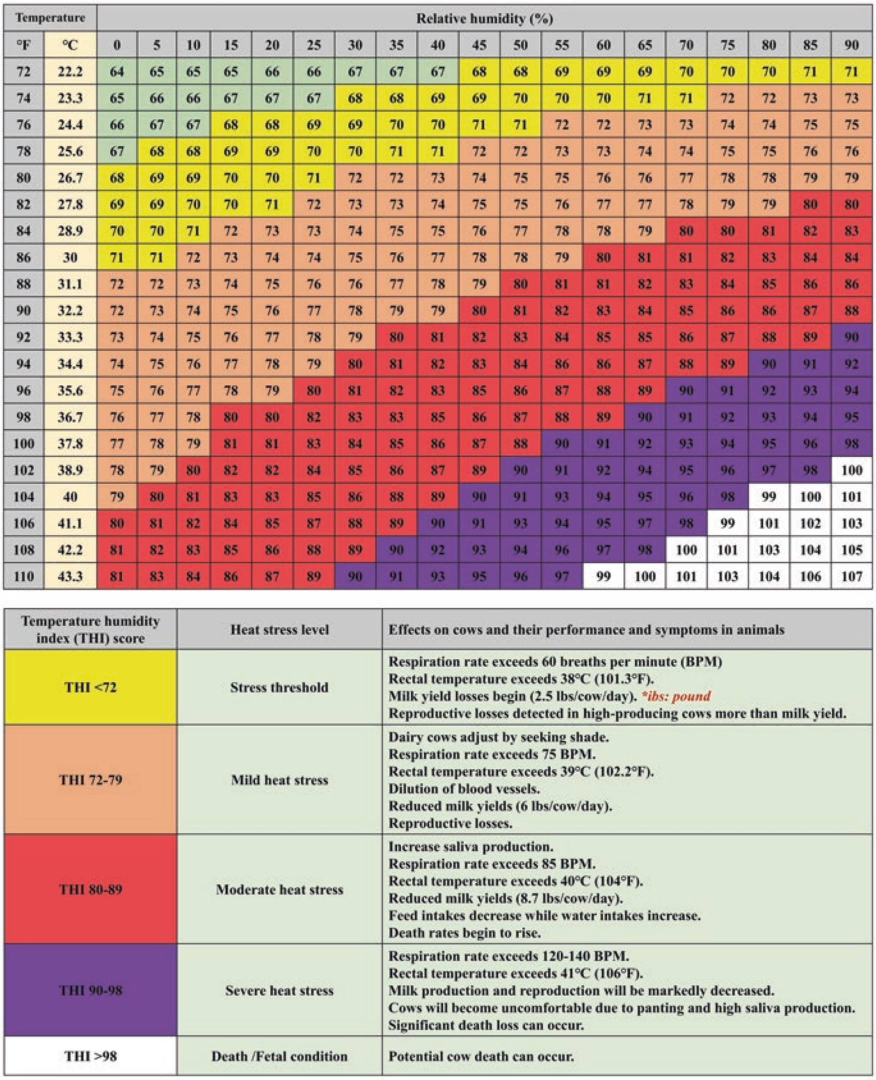
where DBT = dry-bulb temperature (°C) and RH = relative humidity in decimal form.

The wet and dry-bulb ambient temperatures in Fahrenheit for a specific day are combined to determine the THI, which is calculated using the following formula:

$$\text{THI} = 0.72(\text{W°C} + \text{D°C}) + 40.6$$

where W°C = wet bulb and D°C = dry-bulb.

In accordance with rising temperature and humidity, a THI chart can be used to determine THI (Fig. 42.2). If the temperature and humidity are known, this chart, which is typically color-coded to reveal the various levels of heat stress on cattle, helps to determine the level of heat stress being experienced by animals.



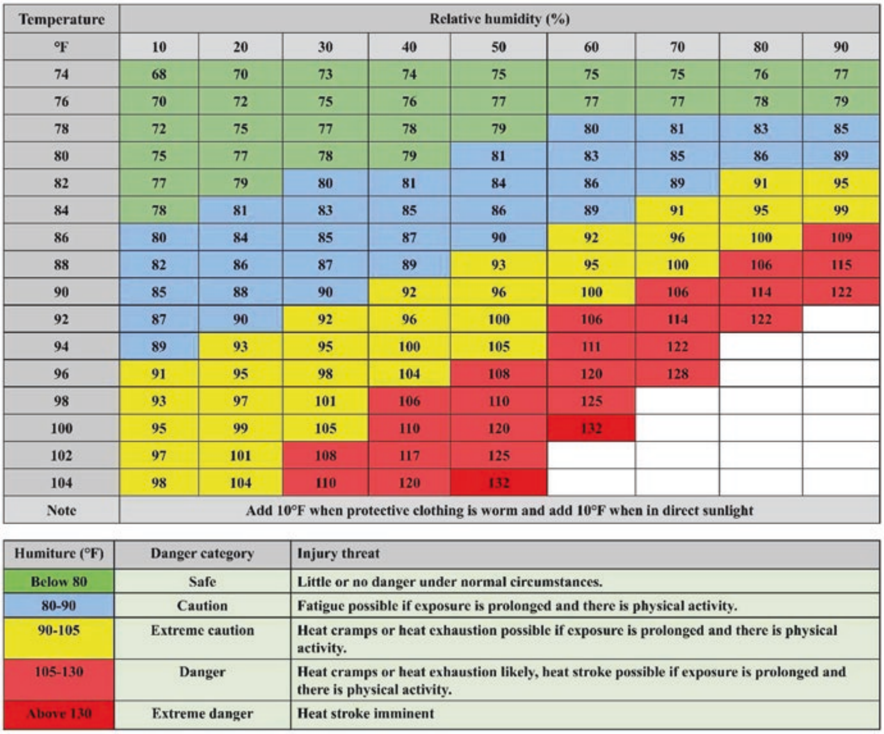
Temperature		Relative humidity (%)																		
°F	°C	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
72	22.2	64	65	65	65	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71
74	23.3	65	66	66	67	67	67	68	68	69	69	70	70	70	71	71	72	72	73	73
76	24.4	66	67	67	68	68	69	69	70	70	71	71	72	72	73	73	74	74	75	75
78	25.6	67	68	68	69	69	70	70	71	71	72	72	73	73	74	74	75	75	76	76
80	26.7	68	69	69	70	70	71	72	72	73	74	75	75	76	76	77	78	78	79	79
82	27.8	69	69	70	70	71	72	73	73	74	75	75	76	77	77	78	79	79	80	80
84	28.9	70	70	71	72	73	73	74	75	75	76	77	78	78	79	80	80	81	82	83
86	30	71	71	72	73	74	74	75	76	77	78	78	79	80	81	81	82	83	84	84
88	31.1	72	72	73	74	75	76	76	77	78	79	80	81	81	82	83	84	85	86	86
90	32.2	72	73	74	75	76	77	78	79	79	80	81	82	83	84	85	86	86	87	88
92	33.3	73	74	75	76	77	78	79	80	81	82	83	84	85	85	86	87	88	89	90
94	34.4	74	75	76	77	78	79	80	81	82	83	84	86	86	87	88	89	90	91	92
96	35.6	75	76	77	78	79	80	81	82	83	85	86	87	88	89	90	91	92	93	94
98	36.7	76	77	78	80	80	82	83	83	85	86	87	88	89	90	91	92	93	94	95
100	37.8	77	78	79	81	81	83	84	85	86	87	88	90	91	92	93	94	95	96	98
102	38.9	78	79	80	82	82	84	85	86	87	89	90	91	92	94	95	96	97	98	100
104	40	79	80	81	83	83	85	86	88	89	90	91	93	94	95	96	98	99	100	101
106	41.1	80	81	82	84	85	87	88	89	90	91	93	94	95	97	98	99	101	102	103
108	42.2	81	82	83	85	86	88	89	90	92	93	94	96	97	98	100	101	103	104	105
110	43.3	81	83	84	86	87	89	90	91	93	95	96	97	99	100	101	103	104	106	107

Temperature humidity index (THI) score	Heat stress level	Effects on cows and their performance and symptoms in animals
THI <72	Stress threshold	Respiration rate exceeds 60 breaths per minute (BPM) Rectal temperature exceeds 38°C (101.3°F). Milk yield losses begin (2.5 lbs/cow/day). *ibs: pound Reproductive losses detected in high-producing cows more than milk yield.
THI 72-79	Mild heat stress	Dairy cows adjust by seeking shade. Respiration rate exceeds 75 BPM. Rectal temperature exceeds 39°C (102.2°F). Dilution of blood vessels. Reduced milk yields (6 lbs/cow/day). Reproductive losses.
THI 80-89	Moderate heat stress	Increase saliva production. Respiration rate exceeds 85 BPM. Rectal temperature exceeds 40°C (104°F). Reduced milk yields (8.7 lbs/cow/day). Feed intakes decrease while water intakes increase. Death rates begin to rise.
THI 90-98	Severe heat stress	Respiration rate exceeds 120-140 BPM. Rectal temperature exceeds 41°C (106°F). Milk production and reproduction will be markedly decreased. Cows will become uncomfortable due to panting and high saliva production. Significant death loss can occur.
THI >98	Death /Fetal condition	Potential cow death can occur.

Fig. 42.2 Temperature-humidity index (THI) chart to calculate THI value with effects on cows and their performances

3.2 Heat Stress Index (HSI)

The permissible exposure duration to different environmental conditions is estimated mathematically using the heat stress index (HSI), also known as the Belding and Hatch Index (BHI) (Beshir and Ramsey 1988; Budd 2001). Considerations for the HSI computation include temperature, humidity, and activity level (Fig. 42.3)



Temperature	Relative humidity (%)								
°F	10	20	30	40	50	60	70	80	90
74	68	70	73	74	75	75	75	76	77
76	70	72	75	76	77	77	77	78	79
78	72	75	77	78	79	80	81	83	85
80	75	77	78	79	81	83	85	86	89
82	77	79	80	81	84	86	89	91	95
84	78	81	83	85	86	89	91	95	99
86	80	84	85	87	90	92	96	100	109
88	82	86	87	89	93	95	100	106	115
90	85	88	90	92	96	100	106	114	122
92	87	90	92	96	100	106	114	122	
94	89	93	95	100	105	111	122		
96	91	95	98	104	108	120	128		
98	93	97	101	106	110	125			
100	95	99	105	110	120	132			
102	97	101	108	117	125				
104	98	104	110	120	132				
Note	Add 10°F when protective clothing is worm and add 10°F when in direct sunlight								

Humiture (°F)	Danger category	Injury threat
Below 80	Safe	Little or no danger under normal circumstances.
80-90	Caution	Fatigue possible if exposure is prolonged and there is physical activity.
90-105	Extreme caution	Heat cramps or heat exhaustion possible if exposure is prolonged and there is physical activity.
105-130	Danger	Heat cramps or heat exhaustion likely, heat stroke possible if exposure is prolonged and there is physical activity.
Above 130	Extreme danger	Heat stroke imminent

Fig. 42.3 Heat stress index (HSI) and its features. (This table is modified from Monteiro and Alucci (2006) and Mehrotra et al. (2019))

(West 2003). The relationship between the quantity of evaporation needed and the maximum tolerance for wetness of the average animal is known as the heat stress index. At high heat stress index, animals may experience heat stress. This can result in very risky situations where animals may actually pass away from overheating and inadequate cooling. During high heat stress index, overexposure to heat can cause serious dehydration and even death (Blackshaw and Blackshaw 1994; Wagoner et al. 2020).

3.2.1 Calculation of HSI

HSI was established by Belding and Hatch in 1955. The following equation is used to determine HSI:

$$\mathrm{HSI} = \left(E_{\mathrm{req}} / E_{\mathrm{max}}\right) \times 100$$

where E_{req} = required evaporative heat loss to maintain thermal equilibrium in the body (i.e., $S = 0$) and

$E_{\max}$ = maximum evaporative capacity of heat of the environment.

3.3 Black Globe Humidity Index (BGHI)

The black globe humidity index (BGHI) is the association of net radiation, relative humidity, dry-bulb temperature, and airflow into one number (Cao et al. 2021; Harikumar 2021). When the dry-bulb temperature is substituted for the black globe temperature in the THI equation, BGHI is produced. Both BGHI and THI are almost equally useful as indices of physical comfort in situations with low to moderate thermal radiation intensity. BGHI has a direct relationship with respiration rates and the rectal temperatures of dairy cows (Dalcin et al. 2016; Li et al. 2020), although milk production and reproductive effectiveness have an opposite relationship (Buffington et al. 1981).

3.3.1 Calculation of BGHI

BGHI is a measure of dairy cow comfort based on the interactions among air movement, net radiation, humidity, and dry-bulb temperature. BGHI is determined using the following formula (Buffington et al. 1981):

$$\mathrm{BGHI} = t_{\mathrm{bg}} + 0.36.t_{\mathrm{dP}} + 41.5$$

where t_{bg} = Black globe temperature (°C) and T_{dP} = dew point temperature (°C).

A thermometer is introduced into a standard hollow darkened province (15 cm in diameter) that has been tinted with lusterless dark toner to determine the temperature of the black globe. The air temperature and black globe temperature variables are used to calculate the THI and BGHI (Fonsêca et al. 2016).

3.4 Heat Load Index (HLI)

The heat load index (HLI) is a measure that simplifies the interpretation of the atmosphere's cooling capacity by combining all the weather variables into a single value (Rashamol et al. 2019). After more than 10 years of research into evaluating heat events in Australian pasture settings for Australian cattle, the HLI has been technologically advanced in Australia.

The likelihood of heat stress in pasture cattle cannot be determined just by the HLI. The accumulated heat cargo unit (AHLU) is used to calculate this. The only circumstance in which heat stress may be detected solely by the HLI is when there is a rapid shift in the HLI over a brief period of time.

3.4.1 Calculation of HLI

The HLI, which is discussed in Tips and Tools, is a perfect illustration (Li et al. 2009). Black globe temperature, relative humidity, and wind speed must all be measured for the HLI, which uses two formulas:

(i) If black globe temperature is greater than or equal to 25 °C

$$\text{HLI} = 8.62 + (0.38 \times \text{RH}) + (1.55 \times \text{BG}) + \exp(-\text{WS} + 2.4) - (0.5 \times \text{WS})$$

(ii) If black globe temperature is less than 25 °C

$$\text{HLI} = 10.66 + (0.208 \times \text{RH}) + (1.3 \times \text{RH}) - \text{WS}$$

where HLI = heat load index

RH = relative humidity expressed as a percentage, i.e., 45 and not 0.45
BG = black globe temperature
WS = wind speed
exp = exponential

The HLI's defined reference animal is a black, healthy (BCS ≥4) *Bos taurus* bull kept in sunlight shade. The reference animal would start to warm up when the HLI reaches a threshold of 86. The reference animal could become cooler if the HLI drops below 77 (Fournel et al. 2017).

3.5 Comprehensive Climate Index (CCI)

The comprehensive climate index (CCI), also called the cattle comfort index or the climate comfort index, was established by animal scientists linked with the Universities of Nebraska and Queensland in Gatton, Australia, to measure environmental stress (Mader et al. 2010a, b; Gaughan et al. 2012; Rashamol et al. 2019).

The CCI is a more contemporary multi-seasonal measure that alters ambient temperature based on wind speed, relative humidity, and solar radiation (Arias et al. 2021). It was found that cattle might adjust their behavior to manage heat stress when the CCI is equal to or below 25 °C (Mader et al. 2010b). When compared to "no stress conditions" (CCI ≤25), dairy cow behavior changed at CCI ≥25 °C and at greater tympanic temperatures for "mild" (CCI >25 and ≤30) and "moderate" (CCI >30 and ≤35) CCI categories (Jara et al. 2016). Similarly, Arias et al. (2018) reported that cows used shade for a greater percentage of the time in the "mild" and "moderate" CCI categories and that their tympanic temperatures were higher.

3.5.1 Calculation of CCI

CCI is calculated from several meteorological conditions such as air temperature, humidity, wind speed, and solar radiation (Arias et al. 2021).

CCI adjusts the surrounding temperature using the following equation based on three elements (Arias et al. 2021):

$$\mathrm{CCI} = \mathrm{AT} + \mathrm{FRH} + \mathrm{FWS} + \mathrm{FSR}$$

where AT = ambient temperature

FRH = the adjusting factor of relative humidity
FWS = wind speed
FSR = solar radiation

3.6 Infrared Thermometer

Body temperature is measured using an infrared (IR) thermometer, a noncontact instrument (Ishimwe et al. 2014; Zhang et al. 2019; Jeyakumar et al. 2022). Infrared radiation interacts with the surface of thermopile, which is connected in either series or parallel, leading to absorption and subsequent conversion of the energy into heat. As the infrared energy from the event increases, so does the voltage output. The temperature is calculated by the detector using this output and is then shown on the screen.

3.6.1 Operational Process of Infrared Thermometer

In order to measure temperature in a variety of artificial and clinical environments, IR thermometers are useful. When the object is faint and the tactic is dangerous, this noncontact temperature element bias works well, though other kinds of thermometers are unrealistic in this situation. IR thermometers employ the knowledge of infrared radiation to determine the surface temperature of an object when the thermometer does not encounter the surface (Kunkle et al. 2004; Rhoads et al. 2009).

An infrared thermometer concentrates radiation onto an infrared sensor, which then transforms the absorbed energy into an electrical signal using a lens system (Fig. 42.4). The emissivity of the source is adjusted into the temperature derived from the electrical indication. Infrared thermometers possibly will use an optically induced small series of wavelengths, while supplementary methods may use a broad series of wavelengths. Planck's law can be used in both scenarios to connect the energy absorbed to temperature. However, as emissivity depends on wavelength, making corrections delicate, broadband infrared spectrometers suffer from being relatively expensive and simple to use. This restriction does not apply to

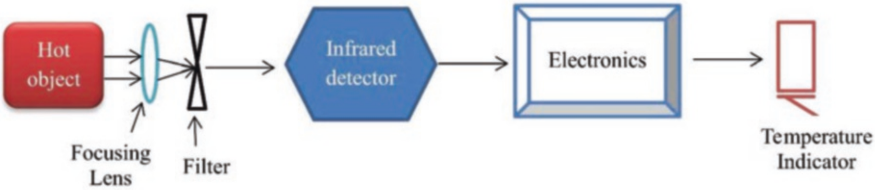


Fig. 42.4 Schematic diagram of an infrared thermometer (Priest 2004)

narrowband infrared thermometers because the emission value does not change significantly with the wavelength used (Priest 2004).

3.7 Rumen Temperature Measurement

It is becoming more common to use rumen temperature as a measure of body temperature in research, particularly long-term studies of how cattle body temperature responds to heat load (Lees et al. 2019b). Rumen temperature is thought to be 1 to 2 °C higher than rectal cavity temperature and stabilizes at 38 to 42 °C, providing a constant atmosphere for the microbial community (Bitman et al. 1984; Bewley et al. 2008a; Schutz and Bewley 2009; Lees et al. 2019b).

The intraruminal temperature measurement is a reliable pointer of internal temperature because it is unaffected by outside variables and cannot be changed externally. Rumen temperature is around 0.5 °C higher than fundamental body temperature as a result of the action of heat-producing rumen microorganisms (Sievers et al. 2004; Bewley et al. 2008b; Bodas et al. 2014). Consequently, temperature monitoring is an appropriate and realistic method to identify potentially harmful changes in animal health in real time (Wahrmund et al. 2012). Ruminal temperature can be significantly reduced for a length of time depending on water temperature and feed intake; recovery of ruminal temperature takes between 20 minutes and 2 hours (Yamada et al. 2001; Bewley et al. 2008a).

3.7.1 Method of Rumen Temperature Measurement

The rumen temperature measurement method was described by Lees and associates (Lees et al. 2018). On the first day, customized bolus applicators were used to deliver rumen boluses (Smartstock, Pawnee, OK, USA) orally. A single bolus weighed approximately 117 gm and had a cylindrical shape (3.1 cm in diameter by 8.3 cm in length). Before administration, boluses were calibrated by spending 24 hours in a 39 °C water bath. In the 915 to 928 MHz frequency range, the boluses were active radio frequency dentification (RFID) transmitters. Up to 90 meters away, the radio signal was detectable. A Yagi antenna was used to transmit the radio waves to a base station, where they were then recorded using specialized software

(TechTrol, Inc., Pawnee, OK, USA) and added to a database. Over the course of the study's 130 days, each individual's TRUM was broadcast and recorded at 10-minute intervals (Lees et al. 2018).

4 Adaptative Measures Toward Thermal Stress

There are a number of phenotypic and genotypic traits that provide an animal with the capability to adopt and maintain homeostasis in harsh environments (Joy et al. 2020; Mcmanus et al. 2020; Rashamol et al. 2020). These adaptive thermoregulatory mechanisms basically involve the morphological, behavioral, and genetic capacity of the animal for change and arise over generations through slow modifications to cope with harsh climates (Sejian et al. 2018; Mishra 2021). The adaptive process can be expanded to include (i) morphological, (ii) behavioral, (iii) physiological, (iv) hormonal, (v) biochemical, (vi) metabolic, and (vii) cellular and molecular responses, (viii) production, (ix) reproduction, and (x) immunosuppression, which combine to promote survival in a specific environment (Medeiros Dos Santos et al. 2021). They have been highlighted in Table 42.1.

5 Impact of Temperature and Climate Variability on the Health of Bovines

5.1 Water Intake

On an average, in tropical countries like India, about 5 billion cubic meters of direct watering is needed annually for livestock animals (Kulanthaivelu et al. 2022). However, different climatic conditions affect livestock animals' water intake in various ways (Table 42.2). Several studies showed that when the environmental temperature was thermally neutral, feedlot cattle were found to drink water only in the daylight (Mader et al. 1999; Valente et al. 2015; Galan et al. 2018). Thermal stress, on the other hand, modified this pattern by increasing the frequency of drinking in the afternoon and early evening, with a noticeable increase at night. Water intake of finishing cattle was found to be significantly higher (87.3%) in the summer season than in the winter in the study of Arias and Mader (2011). Ahlberg et al. (2018) also got similar results that showed steers consumed a significantly higher amount of water (around 2.3% of body weight) in the hotter summer than in the colder winter. They showed that for every 1 °C increase in temperature, water consumption increased by 0.65 kg. Shine et al. (2018) also found an increase in water intake of 1.2 L per 1 °C increase in temperature. The reason for such enhanced water intake during hotter climates may be that the animals have to regulate their body temperatures through elevated water evaporation and peripheral vasodilation.

Table 42.1 Adaptive thermoregulatory mechanisms in animals' bodies with responsive features to maintain homeostasis in harsh environments

Adaptations in the animal body	Responsive features by animal body	References
Morphological adaptations	Coat color (as compared to dark-colored animals, light-/white-colored animals may reflect 50–60% of direct solar radiation, making them beneficial in hot tropical and subtropical climates) Pigmentation in coat (higher pigmentation on the skin can protect deeper tissue by blocking shortwave UV solar rays) Coat thickness, hair length, and hair density (thin coat, short hair, and low hair density are directly linked to higher adaptability to tropical and subtropical climates) Density of sweat gland (higher sweat gland per unit area is recognized as good adaptive features in hot tropical and subtropical climates) Body size (small sized breeds are more adaptive to tropical and subtropical environments compared to bigger body sized breeds; this is partly because smaller animals require less feed and water)	Sejian et al. (2018), Santos et al. (2021)
Behavioral response	Increased standing time Decreased lying time Increased water intake Decreased DM intake Increased drinking frequency (no. of times) Increased urination frequency (no. of times) Increased defecation frequency (no. of times) Decreased rumination rate Increased wallowing	Sejian et al. (2018), Mishra (2021)
Physiological response	Increased rectal temperature Increased skin temperature Increased scrotal temperature Increased respiration rate Increased heart rate Increased pulse rate Increased panting Increased sweating rate	Sejian et al. (2018), Mishra (2021)

(continued)

Table 42.1 (continued)

Adaptations in the animal body	Responsive features by animal body	References
Hormonal response	Decreased triiodothyronine (T_3)	Pusta et al. (2003), Aggarwal (2004)
	Decreased tetraiodothyronine/thyroxine (T_4)	Aggarwal (2004), Aggarwal and Singh (2009, 2010)
	Increased blood cortisol	Zhengkang et al. (1994), Aggarwal and Upadhyay (2013)
	Decreased plasma insulin	Sejrsen et al. (1980)
	Decreased insulin-like growth hormone 1 (IGF-1)	Ingraham et al. (1982), Hamilton et al. (1999)
	Decreased growth hormone (GH)	Mitra et al. (1972)
	Decreased luteinizing hormone (LH)	Wise et al. (1988), Wolfenson et al. (1988)
	Decreased follicle-stimulating hormone (FSH)	Wise et al. (1988), Wolfenson et al. (1988)
	Increased/decreased progesterone [low progesterone prior to AI is related to enhanced uterine PGF2α secretion, to alterations in the growth pattern of ovarian follicles, and to their steroidogenic capacity]	Wise et al. (1988), Wolfenson et al. (1988), Ronchi et al. (2001)
	Increased ACTH, endorphin, and melanocyte stimulating hormone	Engler et al. (1989)
	Increased prostaglandin	Putney et al. (1988), Malayer and Hansen (1990)
	Increased catecholamines	Allen and Bligh (1969), Alvarez and Johnson (1973)
	Increased prolactin	Collier et al. (1982)
	Rumen acidosis increases Increased synthesis of free radicals, oxidation of proteins High respiration rate Increased blood flow to skin surface, reduced metabolic rate, decreased dry matter intake Increased respiratory	Habibian et al. (2015)
	Acceleration of cellular metabolism Decrease in the mobilization of fats from adipose tissue	Baumgard and Rhoads (2013)

Biochemical response	Increase in mitochondrial size, fragmentation of the Golgi apparatus and endoplasmic reticulum Destruction of DNA proteins Increase in the creatinine concentration	Vanderwaal et al. (2009), Rivera et al. (2003)
Cellular and molecular response	Disruptions in spermatogenesis Negative effect on oocyte development, oocyte maturation, early embryonic development, fetal and placental growth, and lactation Increase of sperm primary defects Decrease of the conception rate of dairy cows Significant decrease in the first service pregnancy rate Increased embryonic mortality Decreased conception rate	Mishra et al. (2013), Singh et al. (2021)
Production	Activates the HPA axis Increases peripheral levels of glucocorticoids Release of cytokines Increased lymphocyte and neutrophil Increased IgM and IgG	Naik et al. (2013), Bagath et al. (2019)

Table 42.2 Differences in water intake by livestock animals under different climatic conditions (summer and winter seasons)

Summer season (animal^{-1}d^{-1})	Winter season (animal^{-1}d^{-1})	Reference
32.4 L	17.3 L	Arias and Mader (2011)
40.5 kg (May–August 2014) 36.4 kg (May–July 2015) 49.5 kg (June–August 2016)	28.2 kg (November 2014–January 2015) 34.9 kg (January–March 2017)	Ahlberg et al. (2018)
13 L (at 45 °C)	9 L (at 0 °C)	Sexson et al. (2012)

Abbreviation used in the table: *Animal^{-1}d^{-1}* per animal per day

Moreover, increased humidity during hot climatic temperatures reduces thermal regulation by evaporative cooling because high humidity causes decreased surface and respiratory evaporation. Therefore, to cope with the increased humidity and temperature, the animals consume more water (Silanikove 2000). Furthermore, Lees et al. (2019a) showed that there is a 25% increase in urine volume, a 54% increase in respiratory tract evaporation, and a 177% increase in sweating during the summer season, all of which contribute to the need for a higher water consumption rate. Sexson et al. (2012) also found that water intake was increased with an increasing THI.

5.2 Dry Matter and Feed Intake

Dry matter intake (DMI), like water intake, is also influenced by the climate (Lukas et al. 2008; Ammer et al. 2018; Chang-Fung-Martel et al. 2021). It has been shown that the dry matter intake by cows decreases with increasing temperature and relative humidity (West 2003). Heat stress causes a 10–20% decline in dry matter intake in lactating cows. A group of researchers found a decreasing rate of dry matter intake in a THI greater than 60 (Gorniak et al. 2014). THI and DMI have a substantial negative connection ($r = 0.82$), with DMI decreasing by 0.45 kg/day for every unit rise in THI (Chang-Fung-Martel et al. 2021). Under hot climatic conditions and high humidity, lactating cows tend to take a lower amount of dry matter to avoid excessive heat production from metabolism. This has been coined as their strategy of survival to maintain euthermia (Baumgard and Rhoads 2012).

5.3 Growth Performance

Fluctuations in temperature also take a toll on the growth performance of livestock animals (Young 1981; Nardone et al. 2010; Sheikh et al. 2017). The decreased dry matter intake in the summer results in a lack of energy. This leads to a negative energy balance (NEB). Ultimately, the animals lose a considerable amount of body weight, resulting in a decrease in body score (Nardone et al. 2010).

Protein is essential for muscle gain and development in animals (Dayton and White 2008; Wu et al. 2014). But such climatic stress encourages fat storage instead of protein synthesis, as it impairs the activities of lipolytic enzymes. It also alters the ribosomal gene transcription, resulting in even lower protein deposition. Hence, muscle protein turnover declines. The RNA content gets decreased as well (Temim et al. 2000). Furthermore, chronic heat stress has been found to lower the circulating glucose levels in cows, lambs, heifers, and bulls. The lack of fatty acid oxidation to produce energy directs those animals to use glucose as the fuel. This adds to the NEB condition. All these factors finally result in reduced growth performance in excessive hot weather (Belhadj Slimen et al. 2016).

5.4 Mortality

Dramatic climatic variations sometimes result in high mortality of livestock animals (Burek et al. 2008; Morgan and Wall 2009; Van Dijk et al. 2010). In geographical areas where the temperature is extremely low in the winter, like Mongolia, the temperature and mortality have an inverse relationship. Cold winters witness a higher rate of mortality there (Rao et al. 2015). Temperature increases of 1 to 5 °C, on the other hand, may cause substantial mortality in grazing cattle (Howden et al. 2008). Such deaths are due to hyperthermia caused by the extreme conditions (Mader and Davis 2004). A study documented an increase in mortality in Mecheri sheep during the summer season (34.5% in summer and 29.2% in winter) (Purusothaman et al. 2008). Cattle mortality has been linked to various heat waves in the United States and northern Europe between 1994 and 2006 (Rojas-Downing et al. 2017).

5.5 Effect on Physiology

Under extreme climatic conditions, livestock tend to maintain balance by using physiological variables such as respiration rate, pulse rate, sweating rate, rectal temperature, and skin temperature (Silanikove 2000; Kadzere et al. 2002; West 2003). Through these physiological responses, they dissipate the excess body heat (Table 42.3). Such physiological variables usually get intense from morning until noon (7:00 a.m. to 2:00 p.m.) when the environmental temperature goes up and physiological processes peak. However, with a decline in the temperature in the evening and into the night, the values of these variables come to a stable state (Rashamol et al. 2020). The primary mechanism of an animal experiencing heat stress is an increase in respiration rate, which results in exterior insulation (coat and fur depth, hair type and density, and subcutaneous fat) and fat accumulation in the hump or tail (Chaidanya et al. 2015). Rectal temperature is another important

Table 42.3 Impact of different climatic conditions on different physiological variables (rectal temperature, skin temperature, respiration rate, heart rate, and pulse rate)

Temperature (°C)	THI	Physiological variables					Breed	Species	Reference
		RT (°C)	ST (°C)	RR (BPM)	HR (BPM)	PR (BPM)			
36.42	89.0	98.88 ± 0.04	33.97 ± 0.14(hip region)	73.81 ± 1.94	–	104.64 ± 1.34	German Fawn × Hair	Goat	Darcan and Guney (2008)
33.2	82.2 ± 1.6	39.11 ± 0.31	33.75 ± 0.99	72.93 ± 22.69	106.70 ± 15.27	–	Saanen		De Souza et al. (2014)
33.2	82.2 ± 1.6	38.97 ± 0.26	33.92 ± 1.06	54.55 ± 18.59	90.07 ± 14.27	–	Saanen × Anglo-Nubian		
44.53	81.63	38.61 ± 0.12	–	26.60 ± 0.24	–	–	Barbari		Kumar et al. (2018)
44.53	81.63	37.80 ± 0.16	–	28.80 ± 0.58	–	–	Sirohi		
44.53	81.63	37.65 ± 0.12	–	28.80 ± 0.58	–	–	Jhakrana		
36.2 °C	–	39.6 ± 0.1	–	113 ± 27	134 ± 9	–	Santa Inês	Sheep	Gesualdi Júnior et al. (2014)
36.2 °C	–	39.7 ± 0.1	–	135 ± 27	141 ± 9	–	F1 Dorper × Santa Inês cross		
–	78.95 ± 1.58	38.31 ± 0.09	–	79.09 ± 0.50	–	77.94 ± 0.29	Chokla		Ashutosh et al. (2000)
–	78.95 ± 1.58	38.26 ± 0.09	–	57.14 ± 0.50	–	79.15 ± 0.29	Avivastra		Ashutosh et al. (2000)

35.9	69.09	39.05	32.97	36.22	66.82	–	Gir	Cattle	Cardoso et al. (2015)
35.9	69.09	38.65	32.60	39.15	57.91	–	Girol Najdiando		
35.9	69.09	38.87	31.89	41.00	64.11	–	Nelore		
35.9	69.09	38.86	32.08	36.53	56.53	–	Sindhi		
35.9	69.09	39.00	31.57	33.75	61.51	–	Indubrasil		
39.35 ± 0.94	87.28 ± 1.26	38.81 ± 0.10	–	29.818 ± 0.80	–	–	Sahiwal		Gupta et al. (2017)
39.35 ± 0.94	87.28 ± 1.26	39.19 ± 0.12	–	47.299 ± 1.14	–	–	Karan fries		
31.8 ± 0.4	81.5 ± 1.0	–	36.2 ± 0.12	104.0 ± 1.83	87.0 ± 1.21	–	Angus		Valente et al. (2015)
31.8 ± 0.4	81.5 ± 1.0	–	35.6 ± 0.12	45.2 ± 1.95	–	–	Nellore bull		
32 °C	–	–	39.3	81	–	81	Holstein Friesian		Koubkova et al. (2002)

Abbreviation used in the table: *RT* rectal temperature, *ST* skin temperature, *RR* respiration rate, *HR* heart rate, *PR* pulse rate, *THI* temperature-humidity index, *BPM* breaths per minute, *BPM* beats per minute indicator, which increases in animals that are unable to regulate their body temperature. The respiration rate and rectal temperature exceed 75 BPM (breaths per minute) and 39 °C, respectively, at a THI of 72–79. At moderate heat stress (THI 80–89), they exceed 85 BPM and 40 °C. The rate exceeds 120–140 BPM and the rectal temperature crosses 41 °C at THI 90–98 (severe heat stress), above which the animal may die (Collier et al. 2006). Under such stressful conditions, the pulse rate increases as well. Increased pulse rate increases blood flow from the core to the periphery of the body, resulting in greater heat loss via both sensible (loss by conduction, convection, and radiation) and insensible (by diffusion through the skin) means (Chaidanya et al. 2015).

5.6 Effect on Rumen Physiology

Climate change causes changes in the underlying physiology of the rumen, which has a detrimental impact on productivity (Sejian 2013; Yadav et al. 2013; Joy et al. 2020). In an adaptive reaction to heat stress, dry matter intake begins to decrease. Increased ambient temperature lowers rumination time, ruminal fermentation, rumen contractions, and appetite for food. Decreased rumination time and appetite are the direct results of the detrimental impact of heat stress on the hypothalamus (Fig. 42.5). Heat stress reduces total volatile fatty acid (VFA) production and alters ruminal pH. The lactic acid concentration increases while the pH level declines, resulting in reduced gastrointestinal motility (Hyder et al. 2017). The passage rate and retention period of digesta are also altered by the rise in ambient temperature and therefore impair digestibility (Bernabucci et al. 2009). Heat stress may alter the fermentation pattern in the rumen, resulting in variations in digestibility, VFA production, and methane (CH_4) emission. According to reports, high temperatures cause a disruption in the acetic acid-propionic acid ratio. It also has a negative impact on nutrient utilization, causing reduced productivity. Intense heat stress causes lower nutrient digestibility, more specifically at 40 °C. However, some positive aspects of high temperatures were also recorded. The dry matter digestibility of Ayrshire cattle was lower at 20 °C than at 33 °C when they were fed on moderate-quality feed (Mathers et al. 1989). Similarly, in the case of Holstein cows, the digestibility of dry matter increases at 30 °C compared to 20 °C (Gaafar et al. 2021). The digestion of dry matter is related to CH_4 emissions in livestock animals. It has been found that the amount of methane emitted is higher at 25–30 °C but it gets reduced at 35 °C (due to the comparatively higher digestibility of DM at this temperature, resulting in a scarce availability of organic matter for the ruminal microbes to convert to CH_4). However, if the temperature goes above 40 °C, CH_4 emissions go up again as the organic matter digestibility gets lower (Yadav et al. 2016).

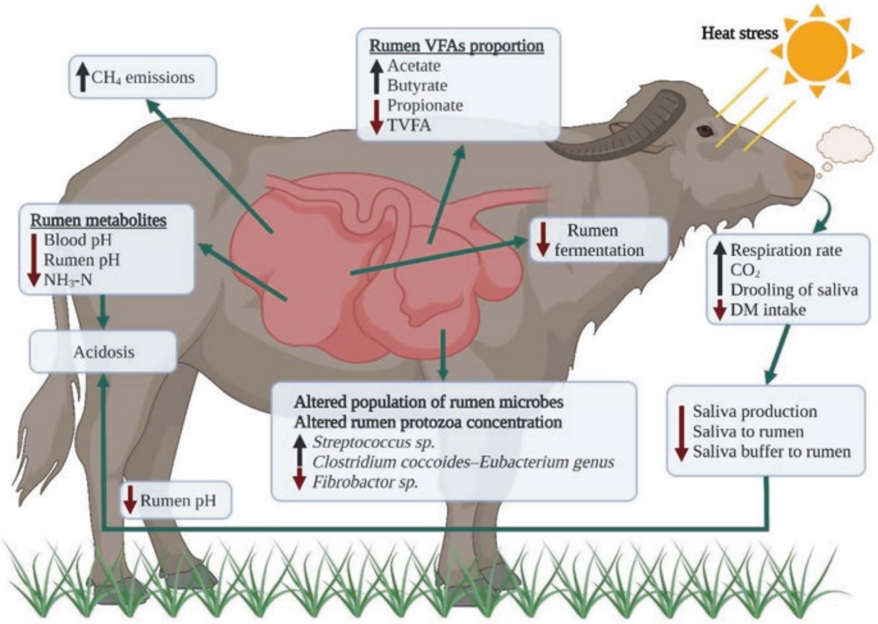


Fig. 42.5 Impact of heat stress on various rumen functions in animal. Abbreviations used in the figure: VFA volatile fatty acid; TVFA total volatile fatty acid; CH_4 methane; NH_3-N, ammonia; CO_2 carbon dioxide. (The concepts of the figure were adopted and modified from Pragna et al. (2018))

5.7 *Effect on Acid-Base Balance*

Heat stress usually leads to increased body temperature and respiration rate in order to provide a cooling effect (Blackshaw and Blackshaw 1994; Gaughan et al. 2000). This excessive rate of panting results in an excessive loss of carbon dioxide from the lungs and causes a decline in the partial pressure of carbon dioxide (CO_2) in the blood plasma of the animals. Subsequently, the hydrogen and bicarbonic acid concentrations get decreased by the bicarbonate buffer system. Ultimately, the plasma pH jumps from normal (Allahverdi et al. 2013).

5.8 *Effect on Oxidative Stress*

Ups and downs in the climatic temperature may influence oxidative stress, and then, when the amount of oxidant molecules exceeds the number of antioxidants, the animal suffers from oxidative stress. The findings of Mirzad et al. (2018) revealed that in the peri- and postpartum periods, total antioxidant concentrations in heifer serum were lower in the summer than in the winter. During the summer, plasma levels of reactive oxygen metabolite compounds rose in mid-lactating cows. At the same time, total carotene and vitamin E levels fell. Increased oxidant and reduced antioxidant molecules in the blood have been documented in both dairy and buffalo cows during the hot summer season. Finally, heat stress has been linked to an increase in antioxidant enzyme activity (e.g., superoxide dismutase, catalase, and glutathione peroxidase), which has been interpreted as an adaptation response to increasing reactive oxygen species (ROS) levels. Hozyen et al. (2014) found a significant increase in the malondialdehyde (MDA) level (indicative of escalated lipid peroxidation) in the hot summer season, while there was an increase in the total antioxidant capacity (TAC) in the spring in Egyptian buffalo.

5.9 Effect on the Immune System

There has been proof of the fact that heat stress weakens the immune systems of animals (Bernabucci et al. 2010; Tao and Dahl 2013). For example, mastitis is an inflammatory disease which is actually a response of the animal body against infection. The occurrence and reoccurrence of mastitis are most common in the summer season, implying that immunity is compromised to some extent in the summer. The activity of neutrophils, a key component that defends the mammary gland against infections, gets hindered in high humid temperatures (Lecchi et al. 2016). Maternal heat stress during fetal development influences the differentiation, migration, and formation of the highly proliferative pool of lymphoid-hematopoietic progenitor cells which are destined to become immune cells (Caroprese et al. 2021). In periparturient Holstein cows, a noticeable decline in lymphocyte activity was recorded by Lacetera et al. (2005) in the summer when the THI was 79.5 ± 2.9 in the daytime. Some studies even found a drop in immunoglobulins like Ig-A and Ig-G in the colostrum of milking cows under severe heat stress (Nardone et al. 1997). Moreover, heat stress stimulates the hypothalamic-pituitary-adrenal axis, causing a rise in the peripheral glucocorticoid levels, inhibiting cytokine production and release. Heat stress has been proven to raise blood cortisol levels, which suppresses the synthesis of cytokines such as interleukin-4 (IL-4), IL-5, IL-6, IL-12, interferon (IFN), and tumor necrosis factor (TNF) (Bagath et al. 2019) (details in Fig. 42.6).

6 Impact of Temperature and Climate Variability on Milk Productivity of Bovines

6.1 Effect on Milk Yield

Milk production is affected by sudden rises or falls in the temperature during the summer and winter (Table 42.4) (Blackshaw and Blackshaw 1994; Kadzere et al. 2002; Nardone et al. 2006; Upadhyay et al. 2007). Heat stress causes milk

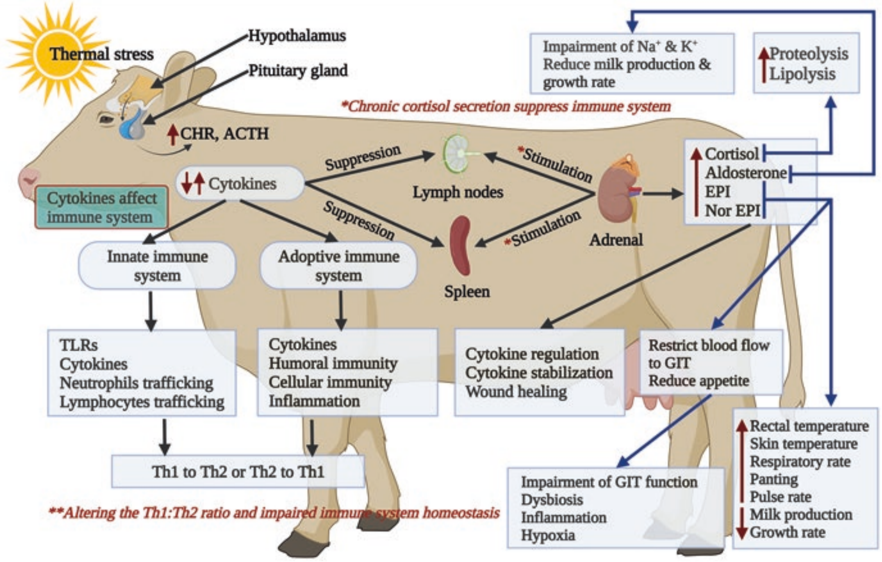


Fig. 42.6 Thermal stress impacting the immune system of dairy cattle. Abbreviations used in the figure: adrenocorticotropic hormone (ACTH), corticotropin-releasing hormone (CRH), Toll-like receptors (TLRs), T helper cell 1 (Th1), T helper cell 2 (Th2), epinephrine (EPI), Nor-epinephrine (Nor EPI). (The figure was adopted and modified from Bagath et al. (2019))

Table 42.4 The range of impact on milk production caused by the combination of temperature, humidity, and duration

Heat stress level	THI	Temperature (°C)	Relative humidity (%)	Duration (h/day)	Milk loss (kg/cow/d)
Stress threshold	<72	22	50	4	−0.28 kg; −1.1 kg
Mild	72–79	25	50	9	−0.30 kg; −2.7 kg
Moderate	80–89	30	75	12	−0.322 kg; −3.9 kg
Severe	90–98	34	85		>5 kg

production losses even in cows with excellent genetic traits (Bernabucci et al. 2014). The rise of the maximum temperature to greater than 4 °C during the summer and a drop in the minimum temperature to more than 3 °C during the winter were reported to have a detrimental influence on milk production by up to 30% on the following or consecutive days after the severe occurrence (Upadhyay et al. 2007). Several findings assumed a loss of 6.3% in the milk production of Holstein cows at the end of this century ($2.2 billion per year) due to climate change (Mauger et al. 2015). Climate variation causes such a loss because of the deviation in the response of the neuroendocrine system to changing environmental variables like temperature and humidity. Furthermore, the negative energy balance caused by decreased intake of dry matter in hot weather contributes to production losses (responsible for 50% of the milk production loss). Apart from these, the proliferation of mammary glands during the dry periods is also disrupted by high temperatures (Sheikh et al. 2017).

6.2 Effect on Milk Composition

Heat stress affects not only milk production but also milk compositions in animals (Du Preez 2000; Gorniak et al. 2014; Das et al. 2016). Bernabucci et al. (2002) found a lower level of crude protein (9.9% lower) in milk during the summer due to a decrease in casein concentration (as α_s-casein and β-casein levels drop). There was a lower casein number in the summer (72.4%) than in the spring (77.9%). The level of κ-casein did not vary between the seasons. The reduced availability of grass content, and hence the lower calorie and nitrogen content of summer diets, is attributable to the decrease in casein content in milk (Mackle et al. 1999). When cows were exposed to high temperatures during the last 3 weeks of pregnancy, milk casein in colostrum decreased (Nardone et al. 1997). Kljajevic et al. (2018) also found a lower level of protein, lactose, fat, and nonfat dry matter in Saanen goats during hot summers. Milk fat percentage was found to be the lowest in the summer and the highest in the winter (Timlin et al. 2021). The amount of total saturated fatty acids (SFA) is greater in summer, but the concentrations of total monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), and conjugated linoleic acid (CLA) are lower than in winter. Milk fat contains more linoleic acid, linolenic acid, oleic acid, and CLA in the summer than in the winter (Kumar et al. 2020).

6.3 Effect on Milk Metabolome

Heat stress can significantly alter the metabolic profile of milk (Kadzere et al. 2002; Dash et al. 2016; Liu et al. 2017). Several researchers revealed that the metabolic pathways of 25 metabolites (carbohydrate, amino acid, lipid- and gut microbiome-derived metabolites) were affected by heat stress (Tian et al. 2016). There were 119 metabolites that varied between heat-stressed and stress-free cow milk, 28 of which were identified using LC-MS in MRM (liquid chromatography mass spectrometry with multiple reaction monitoring) mode and 27 of which were lipid derivatives. This suggests that lipid metabolism is altered by heat stress. Heat stress increases the milk's citrate concentration. It can also induce apoptosis of mammary gland epithelium, leading to leakage of galactose-1-phosphate into milk and, hence, an increase of this compound (by 1.27- to 1.79-fold) in milk. Such an apoptotic index is further increased by negative energy balance due to less feed intake. Isoleucine, proline, orotate, glycine, and phosphocreatine (main precursors for gluconeogenesis) concentrations decline under high THI. The milk creatine level, butyrate, acetone, β-hydroxybutyrate (BHBA), FA, PUFA, and UFA also seem to increase under heat stress. Heat-stressed cow's milk contains more N-acetyl glycoprotein, scyllo-inositol, choline, and pyridoxamine (Yue et al. 2020).

7 Impact of Temperature and Climate Variability on Reproductive Performance of Dairy Cows/Female Bovines

7.1 Effect on Reproductive Hormones

Livestock animals lose their fertility in such temperature fluctuations due to endocrine imbalances (Krishnan et al. 2017). Steers exposed to 42 °C for 4 hours had high glucocorticoid concentrations in the plasma at around 1 hour, and they sustained these elevated levels of glucocorticoids throughout the exposure (Abilay et al. 1975). But the level seemed to plummet within the next 5 minutes of withdrawing the temperature. Testosterone level has been found to be lower in bulls under high temperatures (Gwazdauskas 1985). Alvarez and Johnson (1973) conducted research on the impact of high temperatures on non-lactating cows and found the level of the glucocorticoid to rise by 38% in just 60 minutes, which rocketed to 120% in a period of 4 hours. But the level came down to normal after 48 hours and stayed the same despite the high body temperature. The high level of glucocorticoids may be due to the fact that at high temperatures, the skin thermoreceptors activate the ACTH-releasing mechanism in the hypothalamus. But with continuous exposure to hot weather, this mechanism gets impeded by repeated glucocorticoid feedback. Such feedback is the result of a greater free-to-bound glucocorticoid ratio, as the decreased binding capacity of transcortin gives rise to free glucocorticoids in the plasma. As a result, glucocorticoids levels remain normal after a certain period of heat stress. The levels of epinephrine and norepinephrine went up by 127% and 84%, respectively, after 4.5 hours. An upward trend in the plasma catecholamine level was also confirmed. This might be due to enhanced norepinephrine release from the adrenal gland's storage vesicles (as heat stress declines the binding and inactivates norepinephrine), leading to a high level of free catecholamine in plasma without accelerating sympathetic activity. Gwazdauskas (1985) observed an increase in epinephrine and norepinephrine level in sheep kept at a cold temperature for a prolonged period. Luteinizing hormones have been documented to decrease with increased temperature by most studies (although there are some disputes). In summer, the luteinizing hormone level is usually low. However, the follicle-stimulating hormone (FSH) level seems to go up as there is a low level of inhibin in the blood due to the production of compromised follicles. Even if there is an increase in FSH, it is never sufficient to cover up the impact of a low LH level, resulting in lower availability of androgen precursors to synthesize estradiol. So, heat stress leads to a decline in estradiol (Fig. 42.7). The effect of heat stress on progesterone levels is highly debated, with some studies finding an increase, others finding a decrease, and still others finding it unchanged (De Rensis and Scaramuzzi 2003).

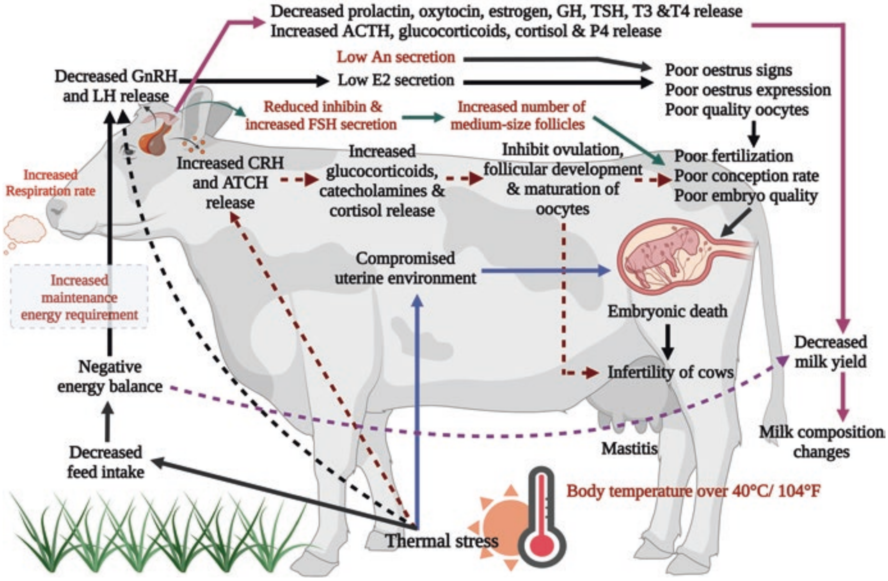


Fig. 42.7 Thermal stress impacting hormonal homeostasis, fertility, and milk production in dairy cattle. Abbreviations used in the figure: gonadotropin-releasing hormone (GnRH), adrenocorticotropic hormone (ACTH), corticotropin-releasing hormone (CRH), luteinizing hormone (LH), thyroid-stimulating hormone (TSH), triiodothyronine (T3), thyroxine (T4), growth hormone (GH), estradiol (E2), progesterone (P4), androstenedione (An), follicle-stimulating hormone (FSH)

7.2 Effect on Hypothalamic-Hypophyseal-Ovarian Axis

The hypothalamus serves as the endocrine system's coordinating center. It combines information from the upper cortex, autonomic function, environmental cues like light and temperature, and peripheral endocrine feedback. The hypothalamus then sends precise signals to the pituitary gland, which secretes hormones that affect the majority of the body's endocrine systems (Haddad et al. 2002). Heat stress can regulate the hypothalamic-hypophyseal-ovarian axis mechanism in mammals. Usually, heat stress leads to increased secretion of corticosteroids, which can inhibit the secretion of luteinizing hormone and gonadotropin-releasing hormone (De Rensis and Scaramuzzi 2003). In addition, it induces hyperprolactinemia, poor follicle development, and reduced estradiol synthesis in cattle, resulting in ovarian inactivity (Dash et al. 2016). Under extreme climatic conditions, the hypothalamic-hypophyseal-ovarian axis may not even show signs of estrus (Fig.42.7) (Sheikh et al. 2017).

7.3 Effect on Ovarian Follicles

The development of ovarian follicles is influenced by the climate. Normal fertility is usually restored after 40–60 days of an episode of heat stress, indicating a negative effect of heat stress on the early follicular development stage (Badinga et al. 1985). Under high atmospheric temperatures, the follicular development gets suppressed. Commonly, the developed follicles become smaller in size, which produce decreased amount of estradiol. This in turn delays the process of luteolysis, resulting in extended luteal phases with multiple follicular waves. Studies found that due to heat stress, the second wave dominant follicle undergoes regression. This is then replaced by a third wave dominant follicle (Wilson et al. 1998). Several findings reported that cows that were exposed to solar radiation soon after dawn for less than 45 minutes could not ovulate (De Rensis et al. 2021; López-Gatius et al. 2021).

7.4 Effects on Estrus Incidences

The onset of puberty in both male and female animals may be delayed at extremely high temperatures as well as very low temperatures. The length of estrus has been found to be shortened by high environmental temperatures. As the level of estradiol (responsible for the expression of estrus) decreases under heat stress, a cow may not show any signs of estrus. In a commercial dairy farm in Florida, 76–82% estrous period went unidentified in summer, while the percentage was 44–65% in a colder weather (Hansen and Areéchiga 1999). It was also reported that during the summer, there was a drop in estrus and a rise in anestrous and silent ovulations, with low motor activity (Fig. 42.7).

7.5 Effect on Oocytes and Oocyte Quality

Antral follicle appears prior to 40 days of ovulation. This is the follicle that ovulates. As a result of the direct effect of environmental variability on the oocytes or on the follicular dynamics during this period, the quality and number of oocytes can be affected (Hansen and Areéchiga 1999). Thermal stress has been shown to influence follicular function, as thecal cell cultures at 40.5 °C produced less androstenedione (Wolfenson et al. 1997). Several researchers showed that the composition of oocyte lipid content varies from season to season (Zeron et al. 2001) and, therefore, low quality oocytes are produced in the summer and early autumn, due to a negative energy balance (Roth et al. 2001). However, they found a slight increase in grade-1 oocytes during winter. The deterioration in the oocyte quality under high THI may be because of lower level of communication between granulosa cells, cumulus cells, and oocytes. This might also be a result of changes in follicular fluid contents like insulin-like growth factor binding proteins and steroids (Guzeloglu et al. 2001). Furthermore, heat stress inhibits the growth of the dominant follicle and creates incomplete dominance, resulting in increased proliferation of subordinate follicles. Incomplete dominance may occur in ovulation of an old follicle, which contains oocytes with diminished competence (Mihm et al. 1999). The two initial embryonic divisions were delayed in oocytes taken from Holstein cows throughout the summer. However, maternal heat damages only a subset of ovarian follicles rather than the total follicular reserve, as evidenced by spontaneous recovery of oocyte competence and conception rate throughout the autumn and ensuing winter (Wolfenson and Roth 2019). In addition, during maturation, exposing oocytes to 41 °C increased the number of oocytes with fragmented DNA. Heat stress during in vitro maturation enhanced ROS and impaired the oocyte's capacity to cleave and grow into a blastocyst (Payton et al. 2004). Various studies found reduced expression of oocyte maturation genes (FGF16, GDF9) in cows throughout the summer (Fig. 42.7) (Ferreira et al. 2016; Diaz et al. 2021; Berling et al. 2022).

7.6 Effect on Conception Rate

Hot weather has a negative impact on the conception rate. Ryan et al. (1991) reported a decreased rate of conception per insemination in hot summer. It is confirmed that the hot weather (no other environmental variables) is responsible for such decline, as the conception rate goes up when the cows are kept in a cool facility in the summer. Dunlap and Vincent (1971) reported a decline in the pregnancy rate when the body temperature was high during insemination. Wettemann and Bazer (1985) found a decrease in conception rate with reducing litter size in sows (Table 42.5).

7.7 Effect on Embryonic Growth and Fetal Development

Animals undergo some physiological changes under high temperatures to cope with heat-related stress. To dissipate the body heat, their bodies change the course of blood flow from the visceral part to the peripheral body. Although this helps in lowering the body temperature, it results in a decline in blood flow in the placental vascular bed. Hence, this alters the growth of the fetus. Hot-humid summer also reduces the number of embryos that can undergo development (Hansen and Areéchiga 1999). Rivera et al. (2005) found a deleterious impact of high temperatures on the early development of embryos. However, later developmental stages of embryos like morula and blastocyst are more resistant to heat stress. The impact of hyperthermia also depends on the breed. For instance, indigenous cattle suffer a relatively more moderate negative consequence of hyperthermia than *Bos taurus*

Table 42.5 Impact of heat stress on conception rate of dairy animals

Time frame	Maximum THI	Rate of conception (%)	References
June 1998	78	32	Roth et al. (2001)
July 1998	80	16	
August 1998	83	6	
September 1998	81	10	
October 1–15, 1998	80	13	
October 16–31, 1998	73	20	
November 1998	72	30	
December 1998	66	37	
January 1999	64	44	
2000–2012 (heifer)	72–79	73	Hagiya et al. (2017)
2000–2012 (cows in first lactation)	72–79	43	
2000–2012 (cows in second lactation)	72–79	41	

(Rodriguez-Martinez 2007). Avendaño-Reyes et al. (2006) found an increased birth weight of claves when the pregnant cows were kept in a cool temperature.

7.8 Effect on Corpus Luteum (CL)

The activity and function of corpus luteum are influenced by high temperatures due to insufficient luteinizing hormone, which may be followed by a drop in progesterone production (Roth 2020). Nanas et al. (2021) found a lower level of progesterone in the summer season compared to the winter. Moreover, their ultrasonography assessment of corpora lutea and placentomes was lower in the summer.

7.9 Effect on Pregnancy

Extreme temperature reduces placental weight (due to the altered functions of the endocrine system under heat stress) as well as uterine blood circulation in pregnant animals (Oakes et al. 1976). Placental function is also impaired under such conditions, which impacts mammary growth. Collier et al. (1982) reported a higher rectal temperature and respiration rate in pregnant cows under heat stress. Heat-stressed cows also had lower birth weight of calf and lactation performance. Estrone sulfate and plasma thyroxin (51.2 vs. 64.4 ng/ml) concentrations were lower as well. However, plasma progestin (6.0 vs. 5.1 ng/ml) and triiodothyronine (1.8 vs. 1.5 ng/ml) concentrations were found to be increased in heat-stressed cows.

7.10 Effect on Sexual Behavior

The secretion of sexual hormones is affected by variations in atmospheric temperature. Bolocan (2009) reported anestrus in cows exposed to 36–42 °C. However, when there was a high temperature in the day coupled with a moderate and tolerable temperature at night (18–21 °C), 16.7% of the heifers showed normal signs of estrus, while 33.3% expressed weak estrus, and 50% did not experience any sexual behavior. Winfield et al. (1981) found that in hot weather (40 °C), boars exhibit less courtship activity.

7.11 Effect on Maternal Recognition of Pregnancy

During the preimplantation phase, embryo-maternal contact is important for the establishment and maintenance of pregnancy. High environmental temperatures disrupt the normal mechanism of maternal recognition of pregnancy due to the high concentration of estradiol (Biggers et al. 1987). Heat stress has an adverse effect on CL and progesterone concentration, and inappropriate maternal recognition may result in pregnancy loss. This in turn results in inappropriate maternal recognition (Kasimanickam and Kasimanickam 2021).

7.12 Effect on Prepartum Period and Days Open

Prepartum period is a very crucial stage of an animal's life, which is often neglected. Many physiological processes take place during this period, such as mammary gland regeneration, colostrum production, and fetal growth, all of which affect postpartum performance (Beam and Butler 1998). But this period is often disturbed by climatic variations like extreme temperature. Feed intake decreases in this stage, resulting in a negative energy balance. The levels of placental estrogen and thyroid hormones decline. On the other hand, nonesterified fatty acid concentration keeps rising. These factors have a negative impact on the development of udder, production of milk, and growth of the placenta. Cows exposed to heat stress during the prepartum period were found to deliver calves with low body weights, according to studies. These cows also produced less milk, and the fat percentage of the milk was also altered (Moore et al. 1992). On top of that, there is usually a drop in the growth hormones, glucocorticoids, prolactin, and thyroxine in such cows (Farooq et al. 2010). However, high environmental temperatures have a positive impact on days open. Many researchers found the period of days open to be increased under heat stress (Moore et al. 1992). The reason for such an increase may be decreased fertility during the hot summers.

8 Impact of Temperature and Climate Variability on Reproductive Performance of Dairy Bulls/Male Bovines

8.1 Effect on Testis

For the growth of healthy offspring with good performance, bull fertility is equally important as dam fertility. To produce viable sperm, a bull's scrotal temperature must be 2–6 °C lower than the body temperature. However, heat stress may increase that temperature, exerting an adverse impact on the testis (Das et al. 2016). High ambient temperatures with high humidity can obstruct (as they alter the functions and structures of the pampiniform plexus, tunica dartos, cremaster muscle, scrotal superficies, and scrotal sweat glands) heat loss by evaporation from the scrotal surface. This, combined with an elevated body temperature due to interference with heat dissipation away from the body and the tissue's increased metabolic activity, results in a higher temperature inside the testicles (Alves et al. 2016). One of the most important hormones produced by the testes is testosterone. A lower level of testosterone is correlated with a lower expression of sexual behavior in male animals. This is because thermal stress affects testicular cells like Leydig, Sertoli, and germ cells (Shahat et al. 2020). Spermatogenesis was impaired in bulls exposed to 40 °C for 12 hours, as was vacuolation in spermatids (Skinner and Louw 1966). The impact of high temperatures on testis ultimately influences the quality, properties, and production of semen and sperm (Fig. 42.8).

8.2 Effects on Spermatozoa

The significance of lower testicular temperature is that it improves the quality of sperm and lowers the rate of DNA mutation. If the temperature increases, there is a possibility of the development of a hypoxic condition as there will be enhanced metabolic activities of the cells without any rise in blood flow. This results in an increased level of lipid peroxidation and enhanced production of ROS. Increased ROS further enhances lipid peroxidation, leading to loss of viability of the spermatozoa (especially the part with mitochondria). Furthermore, high ROS levels cause DNA oxidation, intracellular ATP loss, and axoneme disruption. Such a condition is deleterious for spermatocytes (Alves et al. 2016). Due to an enhanced prooxidative process in semen plasma and spermatozoa, the quantity and motility percentage of spermatozoa seem to decrease in younger calves than in older bulls in the summer. Spermatozoa are very sensitive to high temperatures because they have a very little cytoplasm in their heads and tails, and their cytoplasmic antioxidant functionality is quite low (Balic et al. 2012). Sperm motility, mitochondrial membrane function, and plasma membrane consistency are all decreased, but DNA fragmentation is more common (Garcia-Oliveros et al. 2020).

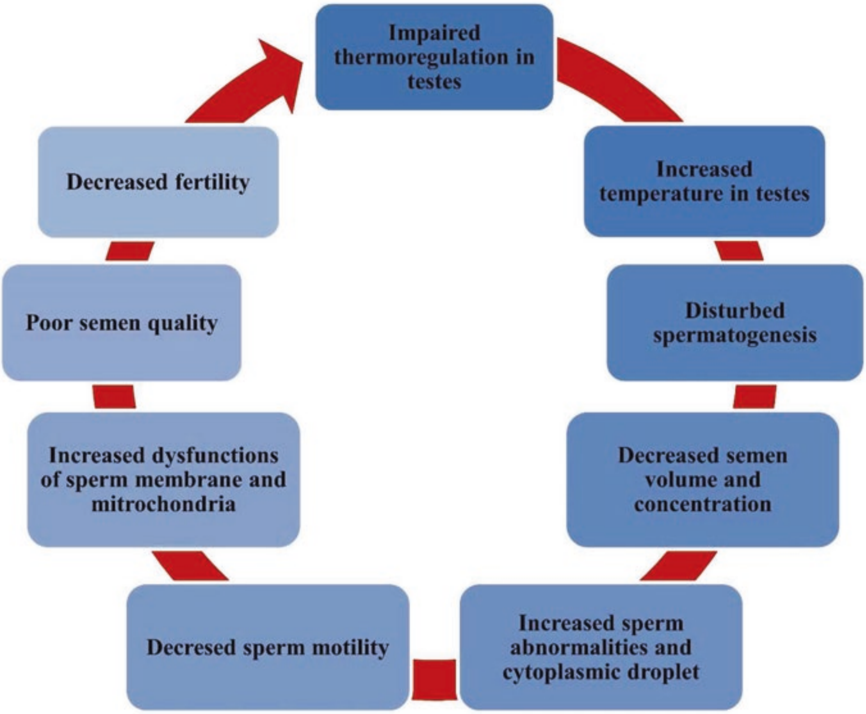


Fig. 42.8 Impacts of thermal stress on reproductive performances in breeding bull

8.3 *Effect on Semen Quality and Characteristics*

Heat stress reduces the production and quality of semen in bulls and bucks (Gholami et al. 2011). Under high THI, buffaloes have a lower volume of semen and a higher number of abnormalities (Ahirwar et al. 2018). The number of viable spermatocytes in the semen, acrosome integrity of fresh semen (AIFS), and plasma membrane integrity of fresh semen (PMIFS) are also lower at a high THI. The amount of abnormal sperm per ejaculation increases at high environmental temperatures. In the winter, the sperm count is higher because the sperm is milky or creamy (Bhakat et al. 2014). On the other hand, watery sperm is evident in the hot summer. This might be the result of apathy to feeding and a high amount of abnormal and dead sperm in the semen. More dead or abnormal sperm cells mean more resorption, which leads to a lower reserve of epididymal sperm. Ultimately, concentration declines. However, it has been discovered that high temperatures have no effect on the pH level of sperm (Fig. 42.8).

9 Thermal Effect on Quantity and Quality of Feeds

Climate change triggers a modification in the types of forage feed grown for animals (for instance, high temperatures favor the cultivation of alfalfa grass). A dry and hot environment may encourage the production of plants with altered compositions, which may not be suitable for grazing (Hall et al. 1998). Higher temperatures decrease the primary production and production-period length of pastures (Hidosa and Guyo 2017). Such lower production may be due to the reduced production of biomass needed for the growth of grasses in the lowland area (Morton 2007). Low temperatures and water-rich soil usually favor the growth of more productive feedstock. The environment has a greater effect on the storage mechanism of the cultivated feedstuff. The quality and quantity of the silage or hay depend on the environmental temperature. The nutritional quality seems to decline with increased temperature (Nardone et al. 2010). In hotter and drier climates, the lignin content of the forages increases and results in low digestibility (Tubiello et al. 2007). A decrease in the digestion of the cell walls of the xylem, bundle sheath, and sclerenchyma has been found for plant leaves grown in hot climates (Wilson et al. 1991).

10 Thermal Effect on Water Availability

Recent studies have linked water contamination with chemical agents like aluminum, arsenic, lead, fluorides, pesticides, and radon (Calderon 2000). Water salinization is another concerning fact. In a hot and dry climate, livestock animals seem to drink two to three times more than in a cool environment. This results in an increased intake of those hazardous chemical compounds which not only affect the production but also affect the health of the animals. Excess nitrite concentration can harm both the pulmonary and cardiovascular systems; abundant heavy metals can harm the sanitary and hygienic quality of production as well as the excretory, skeletal, and neurological systems of animals. Moreover, the metabolic activity, along with digestion and fertility, is also disturbed by the altered pH of the water at high temperatures (Nardone et al. 2010). However, the livestock industry uses water for a variety of maintenance and product-processing purposes in addition to the water required on farms for drinking and the growth of feed crops. For instance, the water consumption of *Bos indicus* cattle increases from around 3 kg DM intake at 10 °C ambient temperature to 5 kg at 30 °C and to approximately 10 kg at 35 °C. At the same three temperatures, intake for *Bos taurus* cattle ranges between 3, 8, and 14 kg DM intake. So, with a decrease in the availability of water in hot and dry weather, there will be a negative consequence for the production and rearing of livestock.

11 Thermal Effect on Livestock Diseases and Disease Vectors

The distribution, severity, and timeframe of the livestock disease outbreaks are strangely correlated with climatic change. Climate change may have an effect on livestock diseases via plenty of direct and indirect channels. Changes in air temperature, humidity, rainfall, frequency, and the severity of extreme weather events have a negative effect on animal health and well-being (Lacetera 2019). Infectious pathogens and parasites develop more rapidly in environments with higher temperatures and more relative humidity. On the other hand, changes in wind speed can alter the spread of microbes and disease vectors that can be deadly for livestock (Prasad et al. 2022). Additionally, parasites and infections that are sensitive to dry or moist environments may be affected by changing rainfall and flooding, increasing infestation and livestock mortality rates. Vector-borne diseases like trypanosomiasis in cattle are linked with changes in precipitation (Mcdermott et al. 2002). Changes in pattern of precipitation and air temperature accelerate the spread of disease vectors and macro-parasites, as well as the introduction of new diseases in livestock. Disease-causing arthropod vectors become more active at high ambient temperatures, increasing the risk of infection transmission between hosts. These climate sensitive livestock diseases are summarized in Table 42.6.

12 Thermal Effect on Intramammary Infections

High environmental temperatures (41 °C, for 2 hours) alter the phagocytic activities of the polymorphonuclear cells (PMNs). The oxidative burst of these cells is hampered as well (Lecchi et al. 2016). In addition, the apoptotic gene expression along with miRNA gets interrupted, which results in a lower level of immunity. Less immune cattle are more susceptible to intramammary infections like mastitis. That is why mastitis is prevalent in cows at high THI (Rakib et al. 2020). There is also an increase in the somatic cell count in hot-humid seasons (SCC > 2,50,000 cells/ml in bulk tank level is indicative of subclinical mastitis) (Lievaart et al. 2007). Shock et al. (2015) reported that 50% of the herds with an increased SCC in bulk tank level were in the hot summer season. Moreover, high temperatures are favorable to many microbes which are capable of causing mammary gland infection. *Staphylococcus aureus*, *Streptococcus (S.) uberis*, non-aureus staphylococci (NAS), *Escherichia coli* (*E. coli*), and *Klebsiella* spp. are the mostly reported species isolated from intramammary infections (Rakib et al. 2020). Gao et al. (2017) found *E. coli* and *Klebsiella* spp. to be the most prevalent ones in the summer season. Other studies also found a higher incidence of mastitis in the summer (Riekerink et al. 2007; Alhussien et al. 2016). There was a significantly higher rate of adherence and internalization of *S. uberis* when it was cultured with heat-stressed bovine mammary epithelial cells, as the viability of the cells was decreased (Almeida et al. 2018). An increased incidence of *S. dysgalactiae* was found in the summer season (Dahl 2018).

Table 42.6 Climate sensitive livestock diseases with clinical features

Disease	Etiology	Transmission	Occurrences	Major signs	Major PM lesions	Control	Treatment	Reference
Papillomatosis or Warts	Bovine papillomavirus	Contaminated fomites Blood	More prevalent in hot summers	Growth on the skin that looks like cauliflower	–	Avoid contact with infected animal	Surgical removal Autohemotherapy	Saied et al. (2020)
Foot and mouth disease (FMD)	Aphthovirus	Direct contact By fomites Infected bull's semen	More prevalent in wet seasons	Vesicles in the mouth and feet Profuse salivation	Tiger striped appearance of heart of young calves	Vaccination	No specific treatment Supportive treatment with antibiotics	Kitching et al. (2005)
Lumpy skin disease (LSD)	Neethling virus	Stable flies Mosquitoes Hard ticks	More prevalent in hot summers	Raised nodules throughout the body Skin eruption	–	Vaccination	No specific treatment Supportive treatment with antibiotics, antihistamine	Abutarbush et al. (2015)
Peste des petits ruminants (PPR)	Morbillivirus	Direct contact Fomites	More prevalent in wet and cold seasons	Profuse salivation and high fever Diarrhea	Zebra striping of the colon	Vaccination	No specific treatment Supportive treatment with antibiotics	Abubakar et al. (2009)
Crimean Congo hemorrhagic fever	Orthonairovirus	Ticks and tick-borne diseases	Hot-humid conditions	Fever Muscle pains Headache Vomiting Diarrhea Bleeding into the skin		Vaccination	No specific treatment Supportive treatment with antibiotics	Grace et al. (2015)
Rift Valley fever	Rift Valley fever phlebovirus	Mosquito-borne viral disease	Hot-humid conditions	Fever Vomiting Diarrhea Respiratory disease Meningoencephalitis Abortions	–	Vaccination	No specific treatment Supportive treatment with antibiotics	

(continued)

Table 42.6 (continued)

Disease	Etiology	Transmission	Occurrences	Major signs	Major PM lesions	Control	Treatment	Reference
Bluetongue	Orbivirus	Vector-borne disease	Hot-humid conditions	Fever	Edema, congestion, hemorrhage, inflammation, and necrosis	Vaccination	No specific treatment Supportive treatment with antibiotics	Morand (2015)
Japanese encephalitis	Japanese encephalitis virus	Vector-borne disease	Hot-humid conditions	Fever Headache Malaise Neck rigidity Cachexia Hemiparesis Convulsions	–	Vaccination	No specific treatment Supportive treatment with antibiotics	
Malignant catarrhal fever	Gamma herpesvirus	Aerosol transmission Horizontal transmission Intrauterine transmission	Hot-humid conditions	High fever Swollen lymph nodes Lameness	Catarrhal inflammation; erosions and mucopurulent exudation		No specific treatment Supportive treatment with antibiotics	Kimaro et al. (2017)
Bovine viral diarrhea (BVD)	Bovine viral diarrhea virus	Vertical transmission Horizontal transmission	Hot-humid conditions	Bloody diarrhea High fever (105–107°F) Off-feed Mouth ulcers Often pneumonia	–	Vaccination	No specific treatment Supportive treatment with antibiotics	Al-Kubati et al. (2021)
Rinderpest	Rinderpest virus	Horizontal transmission	Hot-humid conditions	Fever Discharge of watery mucus from eyes and nostrils Rapid breathing	–	Vaccination	No specific treatment Supportive treatment with antibiotics	Roeder and Taylor (2002)

Botulism	*Clostridium botulinum*	Food/wound contamination	More prevalent in wet seasons	Muscular weakness and paralysis leading to collapse	Excessive pericardial fluid containing free-floating fibrin Pulmonary edema and congestion	Reduction of microbial contamination	Administration of vitamin AD3E and activated charcoal	Pandian et al. (2015)
Pinkeye/ infectious bovine keratoconjunctivitis	*Moraxella bovis*	By face flies Fomites Direct contact	More prevalent in hot summers	A clear discharge runs down from the affected eye Eye appears red Eyes bulge	–	Control of flies	Antibiotic treatment	Angelos (2015)
Mastitis	*Streptococcus* sp., *Staphylococcus* sp., and many other bacteria	Milking machine Contaminated hand/materials Direct contact	Prevalent in all seasons	Painful swelling and hardening of udder Watery milk with clots/pus	–	Proper management Avoid contamination	Antibiotic treatment	Morse et al. (1988)
Anthrax	*Bacillus anthracis*	By spores	More prevalent in hot summers	No specific signs, sudden death	Tarry blood in the natural orifices	Vaccination	Antibiotic treatment	Turner et al. (1992)
Black Quarter	*Clostridium chauvoei*	Ingestion of spore while grazing	More prevalent in wet seasons	Gangrenous lesions with crepitating sound	–	Vaccination	Antibiotic treatment	Useh et al. (2006)
Hemorrhagic septicemia	*Pasteurella multocida*	Direct contact Ingestion Inhalation	More prevalent in wet seasons	Edema and swelling of throat Septicemia Fever (104–106°F)	Widespread hemorrhages, edema Edema consists of a coagulated serofibrinous mass with blood-stained fluid	Vaccination	Antibiotic treatment	Shome et al. (2019)

(continued)

Table 42.6 (continued)

Disease	Etiology	Transmission	Occurrences	Major signs	Major PM lesions	Control	Treatment	Reference
Leptospirosis	*Leptospira* sp.	Poor management practices and environmental conditions	Flood, wet season	Blood-tinged milk Embryo losses Estrus repetition Weak offspring	–	Vaccination	Treatment with antibiotics	Bett et al. (2017)
Foot rot	*Fusobacterium necrophorum*		Flood, wet season	Swelling between the claws of the hoof Lameness	–		Treatment with antibiotics	
Brucellosis	*Brucella* sp.	Ingestion of organisms, artificial insemination by *Brucella*-contaminated semen	Hot-humid conditions	Abortion Stillborn Weak calves Retained placentas Reduced milk yield	–	Vaccination	No specific treatment Supportive treatment with antibiotics	Kimaro et al. (2017)

Coxiellosis (q-fever)	*Coxiella burnetii*	Ticks and tick-borne diseases	Hot-humid conditions	Fever Malaise Profuse perspiration	Endocarditis	Vaccination	Treatment with antibiotics	Grace et al. (2015)
Borreliosis (Lyme disease)	*Borrelia* sp.	Ticks and tick-borne diseases	Hot-humid conditions	Weakness Numbness Altered sensation		Vaccination	Treatment with antibiotics	
Ehrlichiosis	*Ehrlichia* sp.	Ticks and tick-borne diseases	Hot-humid conditions	Reticuloendothelial hyperplasia Fever Lymphadenopathy	Splenomegaly	Long-term tick control	Doxycycline Tetracycline Imidocarb diproprionate	
East Coast fever	*Theileria parva*	*Rhipicephalus appendiculatus* (brown ear tick)	Hot-humid conditions	Fever Enlarged lymphnodes	Damage in lymphoid and respiratory systems	Control of ticks	No specific treatment	
Cowdriosis	*Ehrlichia ruminantium*	Ticks and tick-borne diseases	Hot-humid conditions	Edema Hypovolemia	Hydropericardium	Vaccination	No specific treatment Supportive treatment with antibiotics	
Anaplasmosis	*Anaplasma marginale* and *Anaplasma centrale*	Ticks and tick-borne diseases	Hot-humid conditions	Fever Inappetence Loss of coordination Breathlessness	Spleen is enlarged and soft Liver is mottled and yellow-orange Gallbladder is distended and contains thick brown or green bile	Vaccination	Treatment with tetracycline drugs (tetracycline, chlortetracycline, oxytetracycline, rolitetracycline, doxycycline, minocycline)	
Dermatophilosis	*Dermatophilosis congolensis*	Flies and ticks act as mechanical vectors	Hot-humid conditions	Matted hairs Scab formation Cutaneous keratinized material	–	Control of ectoparasites	Topical and systemic antibiotics	Bett et al. (2017)

(continued)

Table 42.6 (continued)

Disease	Etiology	Transmission	Occurrences	Major signs	Major PM lesions	Control	Treatment	Reference
Contagious bovine pleuropneumonia (CBPP)	*Mycoplasma mycoides*	Inhaled infected droplets disseminated by coughing	Dry season	Fever up to 107°F (41.5 °C) Anorexia Painful and difficult breathing		Vaccination	Treatment with antibiotics	Kimaro et al. (2017)
Trypanosomiasis	*Trypanosoma* sp.	Transmitted by the tsetse fly	Hot-humid conditions	Fever Swollen lymph glands Blood in urine Aching muscles	Enlarged lymph nodes and internal organs	Reduce the the tsetse fly	Treated with pentamidine or suramin (Stage I) Treated with melarsoprol or eflornithine (Stage II)	Das (2022)
Babesiosis	*Babesia* sp.	Ticks and tick-borne diseases	Hot-humid conditions	High fever Hemoglobinemia Hemoglobinuria	Swollen liver with an enlarged gallbladder containing thick granular bile	Vaccination	Babesiacides Supportive treatment	

Haemonchosis	*Haemonchus contortus*, *Haemonchus placei*	Horizontal transmission	Hot-humid conditions	Accumulation of fluid in submandibular tissues Dehydration Diarrhea Weight loss Rough hair coat	–	Vaccination	Anthelmintics	Morand (2015)
Trichinellosis	*Trichinella* sp.	Horizontal transmission	Hot-humid conditions	Fever Cough Swelling of the face and eyes Aching joints and muscle pains Itchy skin	–	Vaccination	No specific treatment Supportive treatment with antibiotics	
Fasciolosis	*Fasciola hepatica*	Trematode, transmitted By aquatic snails	Flood, wet season, and presence of intermediate snail host	Anemia Unthriftiness Submandibular Edema Reduced milk production	–	Snail control	Anthelmintics (nitroxinil, triclabendazole, and albendazole)	
Schistosomiasis	*Schistosoma* sp.	Direct contact	Dry season followed by wet season	Diarrhea Weight loss Anemia	Granulomas in the intestines and liver	Snail control	Praziquantel	Demlew and Tessma (2020)

Abbreviation used in the table: *PM* postmortem

13 Role of Small Ruminants in Ensuring Livelihood Security in the Face of Climate Change

Small ruminants largely depend on grazing for survival. They are considerably more robust under heat stress. Even under conditions of significant hemoconcentration, they can regulate their circulation (especially small ruminants in deserts). There was not any dramatic drop in the body water reserves even when the water level went down more than three quarters of the required amount. Moreover, the crude fiber digestibility seems to increase in such stressed sheep. The rectal temperature of Merino×Nali sheep remains lower than that of the native breeds in high ambient temperatures. Goats like Beetal and Black Bengal adapt their physiological conditions like body temperature, respiration rate, and pulse rate under thermal stress. Coastal sheep breeds seem to have adapted their prolificacy to the higher THI of such regions. Most sheep breeds are adaptable to a range of climatic variations. They are capable of producing high-quality protein and wool from poor quality pastures (Patel 2013). In such climatic conditions, the productive and reproductive performances of these small ruminants can be easily improved by providing a shaded shelter and supplementing their regular diet. Thus, they can play a significant role in ensuring livelihood security in the face of climate change (Rohilla and Chand 2004).

14 Livestock Source of Methane Emission and Mitigation Strategies

14.1 Livestock-Related Greenhouse Gas (GHG) Emission Sources

Greenhouse gases (GHGs) are gases in the atmosphere that trap heat. This gas absorbs infrared light from the sun and converts it to heat that is then dispersed in the atmosphere and eventually lost to space. GHGs warm the Earth by trapping heat. Many reasons have contributed to the increase in GHGs in the atmosphere, the majority of which are attributed to human activity over the last 150 years. The main cause of GHG emissions in the United States is the burning of fossil fuels for transportation, heating, and power. There are 5981 million metric tons of carbon dioxide (CO_2) equivalent in total emissions in 2020, according to estimates (Shreyash et al. 2021).

The agricultural economy contributed 11% of all US GHG emissions in 2020, a 6% rise since 1990. Livestock like cows, agricultural soils, and rice cultivation all contribute to agriculture's GHG emissions (Fig. 42.9). Livestock sector accounts for 18% (or 7.1 billion tons of CO_2 equivalent) of the world's anthropogenic GHG emissions (O'mara 2011). Cattle, buffalo, goats, sheep, and poultry are the main

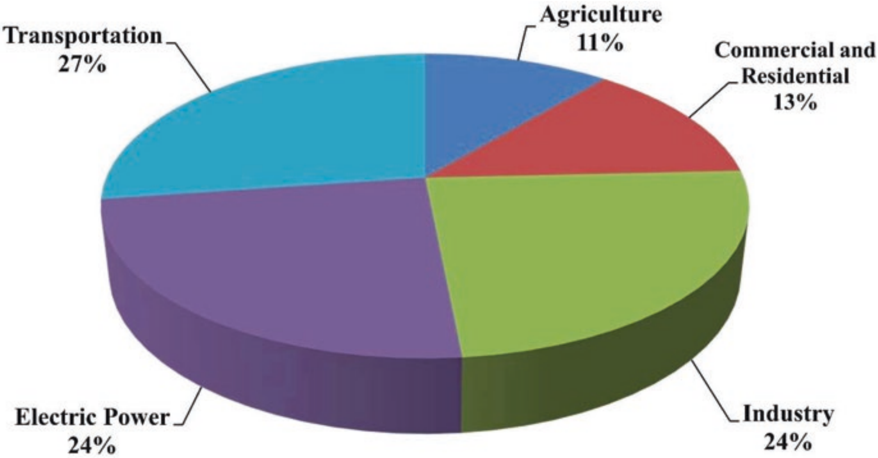


Fig. 42.9 Greenhouse gas emissions from all economic sectors in the United States in 2020 (Shreyash et al. 2021)

livestock species that emit GHGs (Zhou et al. 2007; Patra 2014; Das et al. 2020). Animal husbandry produces GHGs like methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) that have direct and indirect impacts on climate change (Cassandro et al. 2013; Bhatta et al. 2015; Sejian et al. 2016; Ceyhan et al. 2020). CH_4, CO_2, and N_2O are the main GHGs produced from livestock sources such as animals (25%), land-dwelling (32%), and manure (31%), respectively. When these gases are converted into CO_2 equivalent quantities as a common metric, they have an unknown worldwide warming potential (Moran and Wall 2011).

The two primary sources of GHG emissions from livestock are enteric fermentation, in which CH_4 is created as a by-product of digestion from certain microorganisms in the rumen, and anaerobic manure fermentation, wherein CH_4 is generated and nitrogen fixation of manure yields N_2O (Fig. 42.10) (Sejian et al. 2012a; Skinner and Louw 1966).

14.1.1 Emission of Enteric Methane

Methane (CH_4) is produced as part of regular digestive processes in ruminants like cattle, buffaloes, and other livestock, which is where enteric fermentation mostly occurs. The enteric fermentation process accounts for more than a quarter of the emissions from the agricultural economic sector. The main sources of CH_4 appear to be ruminal fermentative digestion and natural anaerobic ecology. Livestock emits CH_4 through enteric fermentation and feces, with an annual production of ~90 Tg CH_4 from enteric fermentation and ~25 Tg from feces (Sejian et al. 2016).

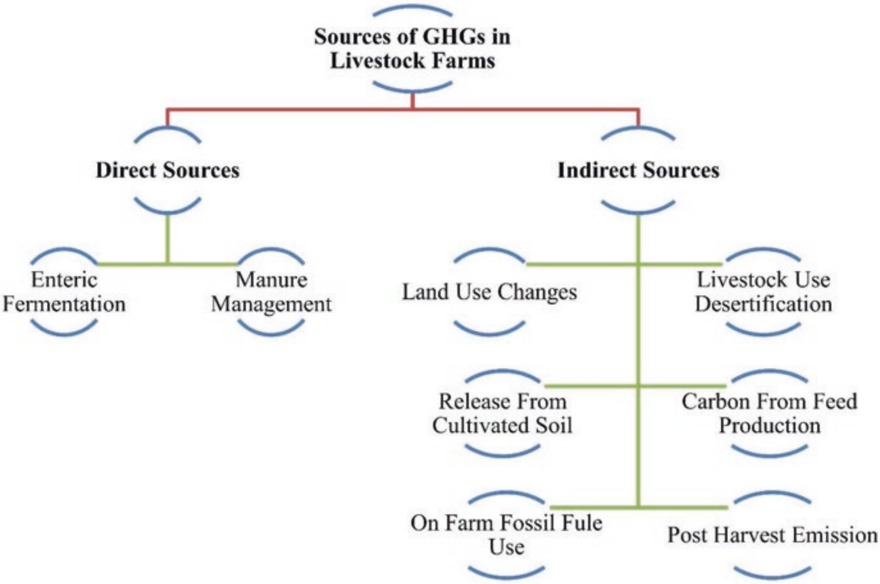


Fig. 42.10 Different sources of GHGs from livestock sector (Sejian et al. 2012a)

14.1.1.1 Enteric Fermentation

Enteric fermentation occurs during the digestive process of herbivore animals, in which carbohydrates (CHO) are broken down by bacteria into simple molecules for absorption into the bloodstream, and eventually this process generates CH_4 as a by-product (Sejian and Saumya 2011). Methanogens, a subclass of bacteria *Archaea* that is found in the phylum *Euryarchaeota*, are responsible for producing CH_4 in the rumen and intestine of ruminants. Through the regular process of feed digestion in ruminants, methanogens can freely generate CH_4. The “forestomach” or rumen, a vast, muscular organ where about 200 species and strains of microbes are present, is what gives ruminants their special ability to manufacture and emit CH_4. Plant materials consumed by animals undergo enteric fermentation by microbes. Figure 42.11 depicts the enteric CH_4 emission from various feed ingredients by diverse species of methanogens in rumen. Monogastric animals do not have rumens; therefore, inadvertent fermentation that happens during digestion results in low levels of CH_4 production, but herbivores without rumen generate CH_4 at a rate that is equivalent to ruminant animals. Despite lacking rumens, these animals’ huge intestines undergo extensive fermentation, which allows for vast amounts of plant nutrients to be digested and utilized (Sejian et al. 2011).

Methanogens generate energy by synthesizing CH_4 from a range of substrates generated during the earliest stages of fermentation (Lyu et al. 2018). Because this process is thermodynamically favorable to organisms, all methanogen species may utilize hydrogen ions (H_2) to reduce CO_2 in the production of CH_4. The abundance

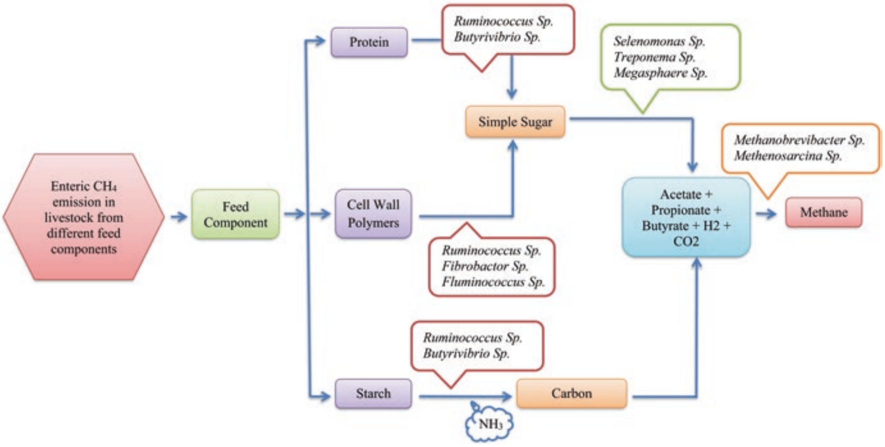


Fig. 42.11 Numerous rumen methanogen species emit enteric CH_4 from various feed ingredients

of H_2 in the rumen is determined by the percentage of final products produced by the fermentation of the consumed feed. Methylamines, formate, methylamines, dimethyl sulfide, acetate, dimethylamines, methanol, and certain alcohols are all examples of materials that methanogens can utilize. Only formate, however, has been shown to be a replacement for CH_4 within the rumen. The mechanisms of CH_4 production in the rumen following digestion are depicted in Fig. 42.12 (Sejian and Naqvi 2012).

14.1.1.2 Enteric Methane Estimation Methods

There are numerous techniques that can be used to measure CH_4 emissions from the different stages of ruminant animal production. The cost, necessary accuracy level, scale, and design of the tests all influence the choice of the most appropriate technique (Johnson et al. 2000).

14.1.1.2.1 Individual Animal Technique

Without a question, the respiration chamber, or calorimetry, is the best method for nutritionists to count individual ruminants' CH_4 levels (Bhatta and Enishi 2007; Storm et al. 2012; Garnsworthy et al. 2019). This method, which successfully gathers data on CH_4 emissions in animals, uses whole animal compartments, ventilated coverings, head boxes, and face masks. These techniques are applied in enclosures to get data on CH_4 emissions from specific cattle. In order to evaluate the energy balance, calorimeters are primarily used to measure gaseous exchange, with CH_4 being valued as a component of the monitoring process. The most popular of the several designs, the open-circuit calorimeter, circulates external air across the

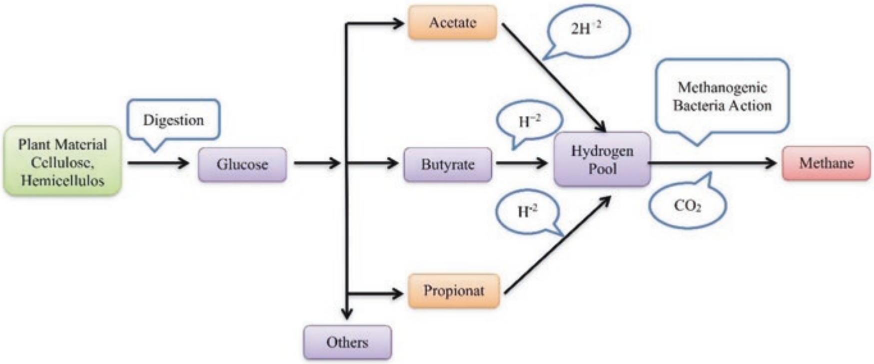


Fig. 42.12 Mechanisms of CH_4 generation in the rumen throughout the digestive process

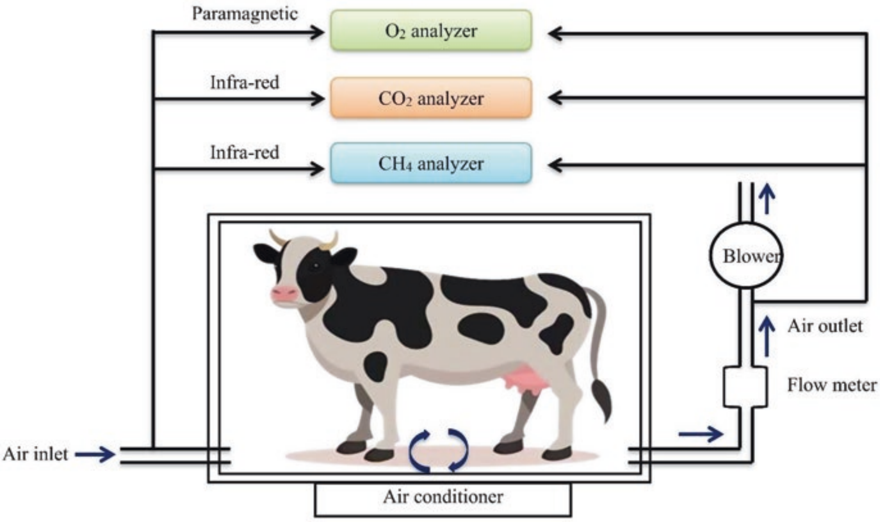


Fig. 42.13 Open-circuit indirect calorimeter

animal's nose, mouth, and head before collecting the terminated air for further examination (Fig. 42.13) (Blaxter 1962).

The animals are kept inside an open-circuit respiration chamber for a number of days, while the inputs such as oxygen, feed, and CO_2 and outputs such as oxygen, excretion, CH_4, and CO_2 are estimated. The results are used to determine the amount of released methane. The chamber needs to be tightly sealed and able to hold a modest negative pressure in order to guarantee there is no net loss of CH_4. By including dehumidification, air conditioning, waterers, feeders, and removal of feces and urine, the chamber is made to be pleasant for the animals. While the animal should be slightly restricted inside the room, it should nevertheless be given the most flexibility to wander around and behave normally. The following things should be taken into account when conducting an experiment on animals: (a) absence of environmental stresses on the animal (such as absence of heat stress), (b) dietary restriction to ensure that the experiment can be repeated, (c) duration of the experiment, (d) lack of exercise, etc. (Bhatta and Enishi 2007).

14.1.1.2.2 Tracer Gas Technique

Emissions from ruminants using a calibrated tracer (ERUCT) technique can be used to measure methane emission from ruminants (Mcginn et al. 2006; Hammond et al. 2015). It is possible for the tracer to be isotopic or non-isotopic. When using isotope tracer techniques, basic experimental designs and very simple computations are typically needed (Johnson and Johnson 1995). (3 H-) or (14C-) methane and ruminally cannulated animals are employed in the isotopic approach. The continuous infusion approach is used to sample gas in the dorsal rumen, with infusion lines delivering the tagged gas to the rumen's lower area. After establishing the radiolabeled methane gas' specific activity, the total amount of methane produced can be estimated.

The measurement of CH_4 production, which is frequently done on sheep and cattle, is also possible using non-isotopic methods. Sulfur hexafluoride (SF_6), an inert gas tracer, was used in a method described by Johnson and others in their study (Johnson et al. 2001). Calculations of the rate of CH_4 emission are performed with the formula $QCH_4 = QSF_6 \times [CH_4] / [SF_6]$, where QCH_4 is CH_4 emission rate (g/day), QSF_6 is known SF_6 release rate (g/day), and $[CH_4]$ and $[SF_6]$ are the respective absorptions in the cylinder.

14.1.1.2.3 In Vitro Technique

Though in vivo investigations with real animals are ultimately required, in vitro simulations of the rumen can frequently be useful and efficient due to their relative readiness and low operating costs. Research on in vitro gas generation tests claimed that the size of the gas can be determined by rumen microbial activity tests (Getachew et al. 1998). Solid feed ingredients are put in nylon bags in the rumen simulation technique, which is changed once a day with new bags. The ration amount is negligible (10–25 g DM/day/L of vessel) in comparison with the actual in vivo standards, and the liquid dilution rate set points are negligible (2–5%/h) (Bhatta and Enishi 2007). Other methods for measuring gas include the following: (i) manometric method, (ii) liquid displacement system (Beuvink et al. 1992), (iii) Hohenheim gas method or Menke's method (Menke et al. 1979), and (iv) pressure transducer systems including manual (Theodorou et al. 1994), computerized (Pell and Schofield 1993), and combined pressure transducer and gas release systems (Cone et al. 1996).

14.2 Emissions from Manure Management

Animal excrement is gathered, stored, processed, and used in manure management, and both dung and urine are referred to as animal manure. Manure management is important in the production and release of GHG gases (CH_4, N_2O, and CO_2) into the environment. The manure's organic matter decomposes under anaerobic conditions, resulting in GHG emissions in both the solid and liquid states of manure storage. Through the production of CH_4, liquid state manure management makes a greater contribution than solid state. Due to the ideal conditions for microbial growth, a higher amount of CH_4 is produced in liquid manure systems. The generation of CH_4 and N_2O is affected by a variety of factors, including the volume of manure produced, the control method, the presence of volatile fatty acids, the type of feed, and the surrounding temperature. 5% N_2O and 4% CH_4 from manure management make up around 10% of all animal GHG emissions, while 7% of all agricultural emissions come from this process (Sejian et al. 2016).

14.2.1 Mechanism of Methane Emission from Manure

Several bacterial groups are involved in the anaerobic digesting process of manures, including methanogenic, acetogenic, acidogenic, and hydrolytic bacteria. There are four phases in this process: (i) hydrolysis of complex organic matter into simpler low-molecular-weight compounds; (ii) acidification of simpler low-molecular-weight organic compounds into alcohol and organic acids; (iii) acetogenesis of alcohols and organic acids into CO_2, H_2, acetate, and acetic acid; and (iv) methanogenesis which produces CH_4 and CO_2 through the consumption of acids or hydrogen from methane (Sejian et al. 2016).

Manure output and the percentage of it that decomposes anaerobically determine the amount of CH_4 produced, which is aggravated when manure is kept in a liquid state under anaerobic conditions (Fig. 42.14).

14.2.2 Factors Affecting Methane Production from Manure

The production of CH_4 from manure is influenced by several factors, including microbial load, temperature, pH, moisture, type of feed, and organic matter content. However, the main factors influencing manure's CH_4 emission are as follows:

(i) Solid manure generates minimal to no CH_4; however, management practices like liquid waste disposal in ponds and tanks can produce up to 80% manure based CH_4.
(ii) Environmental factors are equally critical. Higher temperature and humidity levels will result in higher CH_4.

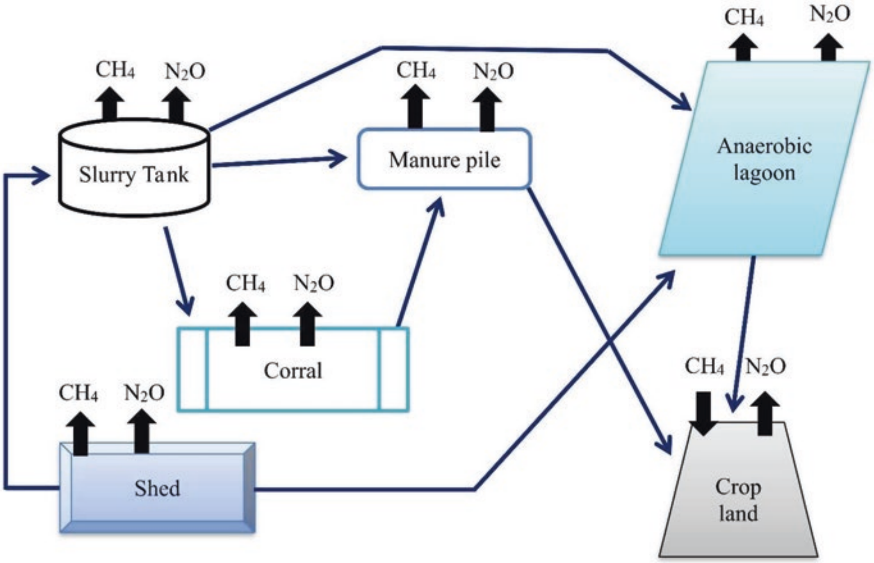


Fig. 42.14 Sources of manure management related CH_4 and N_2O emissions. Manure is shown to move between areas by long, thin arrows. The proportional emission rate is indicated by short, thick arrows

(iii) CH_4 emissions are also impacted by the amount of manure generated, which is controlled by the size of the animals, the volume of feed ingested, and the digestibility of the feed.

(iv) Manure characteristics are determined by the type of animal, the quality of the meal, and the rumen bacteria found in the rumen and digestive tract (Sejian et al. 2016).

14.3 Mitigation Strategies to Reduce Methane Emission

There are two broad mitigation strategies for CH_4: preventive and “end of pipe” options. Preventative methods, primarily nutritional management, limit carbon/nitrogen inputs into the animal husbandry system, whereas “end of pipe” alternatives reduce or block CH_4 synthesis (methanogenesis) inside the animal husbandry system (Sejian et al. 2012a, b; Sejian and Naqvi 2012). Numerous practices, such as managing various animal feeding regimens; collecting, storing, and spreading manure; managing the production of feed crops; etc., can reduce GHG emissions in the livestock sector.

Management, nutritional, and advanced biotechnological solutions are the most typical broad categories under which methane mitigation strategies can be categorized. Nowadays, enteric methane emissions from ruminants are being reduced through nutritional mitigation. There are several methods available to limit the amount of methane released by ruminants' enteric fermentation, such as raising the quality of the roughage, enhancing grazing techniques, using rotational grazing, adding legumes, and feeding forages.

14.3.1 Dietary Manipulation

Animal methane emissions and rumen fermentation are both significantly influenced by the chemical makeup of the animals' diet. The animals' methanogenesis was reduced because of the varied treatments that increased the digestibility of lignocellulose diets. Methane emissions from sheep were decreased by processing wheat straw with urea (4 kg of urea per 100 kg of DM) or urea and calcium hydroxide (3 kg of urea plus 3 kg of calcium hydroxide per 100 kg of DM) and storing it for 21 days prior to feeding. By treating straw with urea and urea molasses mineral block lick, 12–15% less methane was created, and the molar percentage of acetate decreased while propionate production increased. Methanogenesis is greatly reduced when green corn and berseem are included in the diet. When the concentrate amount in the rice straw-based diet was increased, methane production decreased but propionate concentration increased in the rumen liquor (Agrawal and Kamra 2010).

An increase in feeding control, such as grazing systems with daily rotation, can help with this mitigation. This technique only allows for supplementing during milking or specific periods of the year. Additionally, diet modification is possible for some animals whose physiological conditions necessitate the inclusion of additional nutrients, or who merely use pastures with a variety of forage crops, which can be supplied, or whose nutrient availability matches the animal's physiological condition (Rivera and Chara 2021).

14.3.2 Diet with a Higher Percentage of Concentrate

An increased amount of concentrate in the feed reduces CH_4 emissions as a fraction of calorie consumption (Yan et al. 2000). The amount of concentrate in the food and methane generation are inversely correlated, resulting in a noticeable drop in methane generation when dietary starch content is above 40%. The production of hydrogen can be decreased by substituting starch for plant fiber in the diet (Singh 2010). Others have also noted that there is a significant reaction to high concentrations of grain-enriched concentrate on methane lowering (Beauchemin and Mcginn 2005; Mcallister and Newbold 2008). By just lowering the activity and population of methanogens, hydrogen (H_2) generation can be reduced without affecting the fermentation of feed. To minimize the effects of the gas's increase, it should preferably be performed concurrently with the activation of pathways that use H_2 (Martin et al. 2008). The feed is fermented by microorganisms, and hydrogen is created during this process. Methanogens use this hydrogen as a source of energy. It is hypothesized that effective H_2 removal will accelerate fermentation by removing H_2's inhibitory influence on microbial breakdown of plant material (Mcallister and Newbold 2008). Hydrogen passing through the dissolved pool at a certain pace determines the rate of CH_4 production, and the amount of H_2 passing through the pool determines the amount of CH_4 generated. Some feed variables, such as the quantity of various diets on the feed complex, the type and quantity of feed, the degree of its breakdown, and the quantity of H_2 created from it, determined the overall amount of CH_4 formed (Singh 2010).

14.3.3 Lipid Addition to the Diet

Dietary impact appears to be a viable nutritional alternative to concentrate that does not result in a drop in ruminal pH (Sejian et al. 2011). Oils can reduce CH_4 emission in ruminant diets considerably, reaching 80% in vitro and around 25% in vivo (Iqbal et al. 2008; Alemneh and Getabalew 2019). Lipids contribute to the suppression of CH_4 emission due to their toxic effect on methanogens, the reduction in protozoa populations and concomitant decline in protozoa-associated methanogens, and decreased fiber digestion. Lauric and myristic acids are two oils that are highly harmful to methanogens. When added to the diet in amounts between 6 and 8%, the dietary lipids reduce methane output. Nevertheless, a 10 g/Kg DM increment in dietary fat will reduce methane generation by 1 g/Kg and 2.6 g/Kg DM in cattle and sheep, respectively, when provided at a rate of less than 8% in the diet. High oil meal and by-product feeds from the biodiesel sector may act as inexpensive supplies of dietary lipids with potential methane-reducing effects. Lipids, including fatty acids and oils, have been studied for their impact on methanogenesis both in vitro and in vivo as alternatives for feed supplementation. By inhibiting protozoa, increasing propionic acid synthesis, and "bio hydrogenating" unsaturated fatty acids, a higher amount of lipid in the diet is intended to reduce methane production. As a substitute for decreasing carbon dioxide, unsaturated fatty acids can act as hydrogen acceptors. Furthermore, it is believed that fatty acids directly inhibit methanogens by attaching to the cellular membranes and engaging in membrane transfer (Hook et al. 2010).

14.3.4 Ionophores

Antimicrobial ionophores, such as monensin, are frequently employed in animal production to boost productivity. Monensin, an antibiotic derived from the bacteria *Streptomyces cinnamoneus*, is used to improve feed conversion ratio, increase body weight, raise milk yield, and reduce milk fat (Sauer et al. 1998). It makes sense to employ this as a methane mitigation approach since this is incredibly effective at inhibiting gram-positive microbes providing methanogens with substrate for methanogenesis. Because of its capacity to obstruct ion flux, it has an effect on microbial cells (Russell and Strobel 1989; Russell and Houlihan 2003).

Due to a lack of molecular H, monensin directly inhibits H-producing bacteria, which lowers methane synthesis. Monensin also encourages the growth of bacteria that produce propionate. It is therefore believed that monensin limits the growth of bacteria and protozoa instead of methanogens, creating a substrate for methanogenesis rather than affecting methane generation via suppressing methanogens (Russell and Strobel 1989; Russell and Houlihan 2003).

14.3.5 Secondary Metabolites from Plants

Secondary metabolites in plants are chemical molecules present in plants that do not participate in the essential metabolic activities of plant development and reproduction (Bartwal et al. 2013; Pagare et al. 2015). These substances may serve as a source of nutrients and a defense mechanism that ensures the endurance of their structural and reproductive aspects by preventing pathogen or insect attacks or by limiting herbivore grazing. Numerous plants have been revealed to contain thousands of secondary metabolites, many of which are used in traditional Chinese and Indian medicine (Kumar et al. 2007).

14.3.5.1 Tannin

Condensed and hydrolyzable tannins are reported to reduce intestinal methane production by 6–27%. The amount of hydroxyl groups in tannins' structures is positively correlated with their action, which directly influences rumen methanogenesis and is dependent on application rate. Concentrated tannins are believed to hinder methanogens directly and indirectly by lowering the hydrogen supply during methanogenesis (Tavendale et al. 2005). Goats were fed concentrated tannin with *Lespedeza cuneata* on a daily basis, and this diet reduced methane by 57% as measured by g/kg DMI compared to goats fed *Digitaria ischaemum* and *Festuca arundinacea* (Puchala et al. 2005). Although tannin with *Flemingia macrophylla* and *Callinada calothyrsus* lowered methane by 24% in lambs, a concentrated tannin preparation from sorghum silage and *Schinopsis quebrachocolorado* administered to cattle was unable to inhibit methane production (Tiemann et al. 2008). When comparing the emission costs of extracting plant tannins (such as *Acacia mearnsii*) being used as supplements to those already present in plants and using those plants to reduce enteric CH_4 (Goel and Makkar 2012), the former may be a crucial consideration. There are several plants with high tannin contents that have the potential to prevent the rumen microbes from releasing methane both in vitro and in vivo, including *Emblica officinalis*, *Bergenia crassifolia*, *Populus deltoids*, *Peltiphyllum peltatum*, *Rheum undulatum*, *Quercus incana*, *Terminalia chebula*, *Vaccinium vitis-idaea*, and *Terminalia belerica* (Patra et al. 2006; Kumar et al. 2009).

14.3.5.2 Saponins

It has been noted that saponins may help ruminants produce less methane. It has been proven through multiple researches that plants containing saponin are harmful to protozoa. Saponins, often known as organic detergents, are glycosides with a high molecular weight that have sugars connected to a steroidal or triterpene aglycone moiety. These compounds cause cell death by building compounds with sterols in cell membranes of protozoa (Cheeke 2000). Ruminal fermentation is modified by inhibiting protozoa and certain bacteria in the rumen. It is widely known that protozoa and the bacteria that cause the rumen to produce methane are related, and selective suppression of protozoa has been proposed as a successful method to reduce methane production. Saponin-containing plants may improve the efficiency with which feed is utilized, improve rumen flux of bacterial protein, and reduce methanogenesis (Goel and Makkar 2012).

14.3.6 Bacteriocins

It is widely known that several bacteriocins can decrease methane generation in vitro (Russell and Mantovani 2002; Mcallister and Newbold 2008). Likely, the ionophore antibiotics monensin and nisin are hypothesized to work indirectly on microorganisms that produce hydrogen (Callaway et al. 1997). A bacteriocin called bovicin HC_5 that was isolated from rumen bacteria reduced methane generation in vitro by up to 50% without causing methanogens to adapt (Moumen et al. 2016; Garsa et al. 2019).

14.3.7 Organic Acids

Organic acid is typically converted to propionate in the rumen, and sinking equivalents are used in the process (Castillo et al. 2004; Carro and Ungerfeld 2015). As a result, they may act as a secondary hydrogen sink, reducing the quantity of hydrogen required for CH_4 production. In batch culture and artificial rumens, acrylate and fumarate are more productive (Newbold et al. 2005). Recently, various in vivo tests have been conducted. The reaction to fumarate in sheep was described by Newbold et al. (2002) as being dose-dependent. The cost of organic acids today makes employing them profitable, which is the largest obstacle to this procedure. This is true even though the amount of decrease in CH_4 emissions that could be accomplished is relatively questionable.

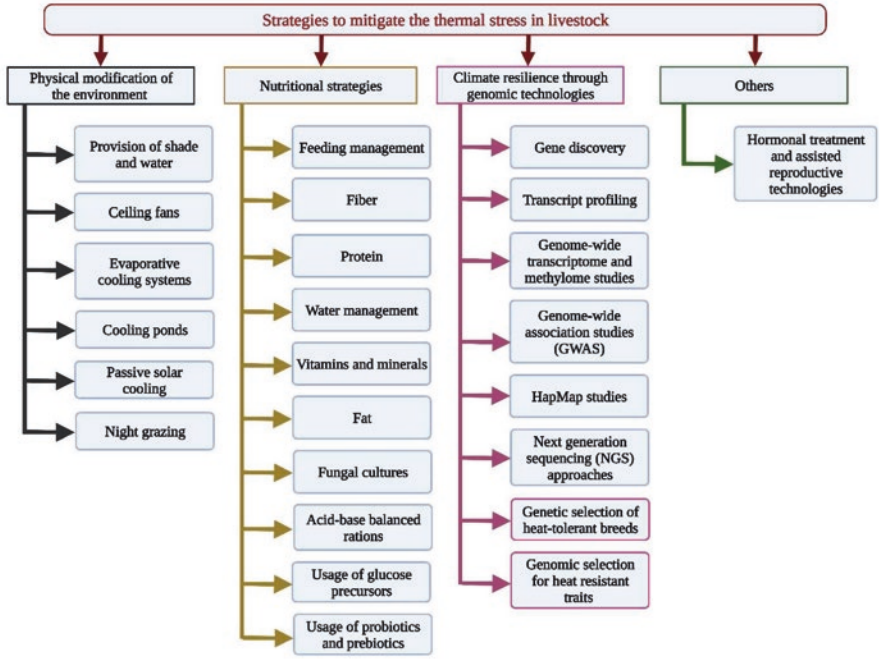


Fig. 42.15 Different fundamental management practices for alleviating effect of thermal stress on production of livestock in tropical and subtropical climatic regions

15 Strategies to Mitigate the Effect of Thermal Stress for Maximizing Production in Bovine

The effects of climate change on livestock behavior and production can be mitigated by using some techniques to help animals cope with heat stress (Nardone et al. 2010; Polsky and Von Keyserlingk 2017). There are three fundamental management practices for tropical and subtropical climates that will lessen thermal stress in animals: (i) physical modification of the environment, (ii) nutritional strategies, and (iii) climate resilience through genomic technologies for development of climate resilient livestock (Martínez et al. 2021). This section of the book chapter will discuss these methods to mitigate the effect of thermal or heat stress for maximizing production in bovines in tropical and subtropical countries (Fig. 42.15).

15.1 Physical Modification of the Environment

15.1.1 Provision of Shade and Water

Provision of shade to the animals as well as water and feed has positive impact on the mitigation of heat stress and conserving the production performance of the animals. Keeping the herd in a well-shaded place may cut down the stress by approximately 30% or even more in some cases (Armstrong 1994; Blackshaw and Blackshaw 1994). The study conducted by Mitlöhner et al. (2001) revealed that shading increased the standing time in heifers and it also reduced the respiration rate significantly. In addition, they reached their aimed body weight 20 days earlier than others (Mitlöhner et al. 2001). However, they found water misting to be not very effective to reduce heat stress. In contrast, herds fed with misters had a reduced rate of respiration, higher milk output (albeit not the same in the second summer), and higher dry matter intake (Lin et al. 1998). Vaginal temperature and time spent on grazing during the midafternoon were found to be reduced in cows having access to shade, while milk production increased (although the composition of the milk remained the same) in the study (Kendall et al. 2006).

15.1.2 Ceiling Fans

Ceiling fans are useful tools to mitigate the impacts of heat stress on beef-type cattle as they have been found to enhance the average body weight gain, rumination period, and activity (Marchesini et al. 2018). Bulls had lower respiration and panting rates while the rumination period increased; at the same time, the moisture content of the litter appeared to decrease, preventing bulls from getting dirty (Magrin et al. 2017). However, this study didn't find any improvement in the growth performance of the bulls due to the installation of ceiling fans. Similarly, Das et al. (2014) reported lower rectal temperature, respiration rate, and pulse rate and a significant rise in milk production in the herd provided with ceiling fans.

15.1.3 Evaporative Cooling Systems

To remove the heat energy needed to evaporate water, evaporative cooling systems use high pressure, a fine mist, and a lot of air, which can be done by atomizing or spraying water into the airstream, passing air over a water surface, or passing air through a wetted pad. As a result, the room's temperature is lower, which helps to lessen the effects of heat exhaustion (West 2003). Forced ventilation is very effective in this regard. However, there is debate about whether these facilities are cost-effective, despite evidence that they can reduce respiration rate and rectal temperature as well as somewhat increase feed intake (Armstrong 1994; Marai et al. 1995). According to West (2003), these installations caused the temperature to drop by 4.50 °C and 5.90 °C in the two following summers during the hottest portion of the day. Several researchers reported some evaporative cooling systems decreasing the heat stress on a farm by about 90% (Vitt et al. 2017).

15.1.4 Cooling Ponds

One of the most useful ways to lose body heat by conduction is by wetting the animal's body. This can be accomplished by the provision of a cooling pond on the farm. This not only leads to the mitigation of heat stress by the conduction method but also by evaporation when the animals get out of the water body (Aggarwal and Upadhyay 2013). Wang et al. (2020) have also recognized cooling ponds as a way of reducing heat stress.

15.1.5 Passive Solar Cooling

The use of sunlight for heating and cooling a building depends on the interaction between the building and its surroundings, which results in passive cooling. Building designs that allow natural ventilation and radiative cooling are efficient in this regard. A north-south orientation keeps the building cool by reducing solar radiation entry. An east-west direction can be taken into consideration, nevertheless, if this permits strong winds to enter the farm (Martzopoulou et al. 2020). By including overhangs for windows with a southerly orientation, a few windows facing west, shade trees, thermal mass, and cross ventilation, a building can achieve passive solar cooling (Aggarwal and Upadhyay 2013). The best way to reduce energy consumption is with an excellent insulation system in the building that maintains heat movement between indoor and outdoor settings properly. The roof absorbs some of the sun's energy in addition to reflecting some of it (Martzopoulou et al. 2020). If the roof is made of materials that can emit the bulk of the absorbed heat, heat stress might be decreased. To prevent heat from entering a farm, several expensive mechanical devices are utilized. However, this might be accomplished simply by using adequate window glassing (east and west glass to avoid low sun angle exposures) and shading such as porches, overhangs, and extrusions (Aggarwal and Upadhyay, 2013). Earth-integrated buildings are useful to avoid heat stress in warm regions. In greenhouse-style structures, wind catchers can be affixed to the roof with bolts or put in perimetrical welding at the base of the chimney. Trees can be planted in the vicinity of farms to provide effective shade (Martzopoulou et al. 2020).

15.1.6 Night Grazing

Cows kept in shades are found to have higher body temperatures at night than those kept unshaded. This is because the unshaded cows need to maximize their vasodilation mechanism to cope with high temperatures during the day, so they lose more body heat during the early evening and remain less active during the night. As cows under shade have higher body temperatures during the night, they tend to remain more active at night and were found to graze for an increased period at night. Night grazing with adequate security and lighting can help in the reduction of heat stress as the temperature-humidity index is comparatively lower during the nighttime (Lallo et al. 2018; Martínez et al. 2021).

15.2 Nutritional Strategies

15.2.1 Feeding Management

Many authors have pointed out that livestock animals reduce their feed intake during hot periods of the day to avoid the consequences of excessive heat production due to metabolism. But this puts a tool on their growth performance. This can be overcome by adjusting the frequency and time of feeding. So, they can be supplied with nutritious feed at some suitable intervals at relatively cooler times of the day (Mader and Davis 2004). The feeders and drinkers can be placed in shaded areas of the farm. Nocturnal grazing and feeding can be a nice alternative to feeding in the hotter daytime hours (Renaudeau et al. 2012).

15.2.2 Fiber

A lot of heat is produced due to the fermentation of crude fiber compared to concentrations. It also results in a loss of combustion gases. Contrary to the generation of ATP from glucose, the production of ATP from short-chain fatty acids uses more energy and increases the body temperature. Crude fiber adds to the bulkiness of the diet leading to less feed intake in hot environmental temperatures. So, in hotter climatic conditions, livestock diets should be low in crude fiber content. Low dietary fiber showed an increase in milk production and a decrease in respiration rate and body temperature in the study of West (1999), whereas Reynolds et al. (1991) reported an increase in body temperature in livestock fed with 75% alfalfa grass (fiber) compared to 75% concentrate. This might be due to the fact that fibers are rich in acetate, which produces higher levels of body heat as opposed to concentrates rich in propionate (Loholter et al. 2013). However, an adequate amount of fiber in the diet is a must to maintain rumen health (60% roughage-neutral detergent fiber has been demonstrated to be efficient for dairy cows) (Baumgard et al. 2014). Lipids can be added to the diet, which increases energy intake while reducing heat production at the same time.

15.2.3 Protein

There is usually a misconception that increasing dietary crude protein (CP) is a good idea to maintain production performance under heat stress. However, studies have shown that this not the case. Higher dietary crude protein, more specifically rumen undegradable protein, is responsible for more heat production as this causes a drop in the motility and passage rate of the rumen (Baumgard et al. 2014). At lower temperatures, protein is used for maintenance as opposed to higher temperatures, where it is also used for production. This explains why heat increments at higher temperatures are greater. Additionally, the metabolism of proteins gives rise to excessive ammonia content and other nitrogenous waste, and their expulsion requires more energy (7.2 kcal/g nitrogen during the conversion to urea for excretion) and increases heat production. More dietary protein also means more protein turnover. This typically results in a larger heat increment in hot weather and increased heat stress (Musharaf and Latshaw 1999). So, it is important to formulate a diet with an adequate amount and the appropriate type of crude protein to mitigate the effect of heat stress. A diet containing 16.1% CP with a lower level of degradability was proven to have a better effect on milk production than a diet with 18.5% CP with medium degradability (Huber et al. 1994). Under heat stress, the transcription and translation processes of RNA are impeded, resulting in impaired protein synthesis. This usually affects production and growth. To combat such situations, certain essential amino acids can be supplied through the diet, such as methionine and lysine, which improved milk yield by 11%. Methionine increases milk production along with improvements in immunity (Conte et al. 2018).

15.2.4 Water Management

During higher temperatures, livestock animals tend to regulate their body temperature in a number of ways, and the water seems to be an excellent carrier of heat in this process. This usually results in an increased demand for water under heat stress, especially for high-yielding animals (Berman 2011; Conte et al. 2018). Apart from evaporative water loss, they lose a lot of water in the form of milk, urine, and feces, which leads to increased water intake under hot climatic conditions. If the animals do not get enough water, there is a reduction in the fecal water content at first, and then gradually the serum protein and albumin content go down (although the amount rises in acute conditions). Some animals may experience slower glomerular filtration, resulting in an increase in plasma creatinine and urea in acute conditions due to enhanced urea reabsorption (Chedid et al. 2014). So, the animals under heat stress should be supplied with adequate water at regular intervals. In such cases, colder water is more efficient. Water at 10 °C appeared to lower body temperature and respiration rate while increasing dry matter intake when compared to water at room temperature. If the water's sulfate level is too high, desalination of the water may be required in some areas (Conte et al. 2018).

15.2.5 Vitamins and Minerals

Sodium bicarbonate and potassium bicarbonate in the diet mitigate the effect of heat stress as the demand for sodium and potassium ions increases due to their high rate of urinary excretion under such conditions (Sanchez et al. 1994). Vitamins and minerals like vitamin A, E, selenium, copper, and zinc are essential for the udder health and immunity of dairy cows. Vitamin A and C have an antioxidative function, combating the free radicals generated due to heat stress (Bernabucci et al. 2002). Glutathione peroxidase, an enzyme, destroys the free radicals accumulated in the cellular cytoplasm due to heat stress. Selenium is a component of that enzyme, and so selenium in the diet can mitigate the effect of heat stress, particularly when supplied at night (Tahmasbi et al. 2012; Liu et al. 2016). α-Tocopherol also acts as an antioxidant. Glucose metabolism gets increased under hot climatic conditions, and chromium supplementation can be useful in this regard as this mineral enhances the activity of insulin (Conte et al. 2018). To mitigate the effect of heat stress at a cellular level, niacin is a great option as it causes vasodilation and increases evaporative heat loss (Lundqvist et al. 2008).

15.2.6 Fat

There are some disputes regarding the efficiency of fat supplementation during heat stress. Dietary fat is usually richer in energy content while producing less body heat during metabolism, and that's what makes it a great supplement to provide during heat exhaustion. However, depending on the impact of lipids on ruminal fermentation, such supplementation might be inefficient or, in some cases, harmful (Knapp and Grummer 1991; Huber et al. 1994). Therefore, lipid supplementation should be carefully done, and treated lipids should be prioritized as they have a minor or no impact on the rumen microflora (Conte et al. 2018).

15.2.7 Fungal Cultures

Fungal cultures like *Saccharomyces cerevisiae* and *Aspergillus oryzae* have been proven to be effective for heat stress mitigation. Yeast supplementation (3–5 g/d) results in an increased digestibility of feed contents and leads to higher nutrient flow to the small intestine. Finally, it reduces the rectal temperature and respiration rate under heat stress (Shwartz et al. 2009). However, some studies did not find any positive impact of yeast cultures on heat stress mitigation (Bruno et al. 2009).

15.2.8 Feeding of Dietary Acid-Base Balanced Rations

West (1999) reported that dietary cation-anion balance did not have any significant impact on body temperature, milk production, or composition under heat stress. However, the dry matter intake increased with the increasing amount of cation-anion balanced ration.

15.2.9 Usage of Glucose Precursors

Glucose precursors can be added to the diet to mitigate the effects of heat stress. Moreover, glycerol, monensin, and propylene glycol are effective in this case as they encourage the production of propionate (Belhadj Slimen et al. 2016).

15.2.10 Usage of Probiotics and Prebiotics

Gut microflora can be modified by using probiotics and prebiotics to the animal's benefit under heat stress. They usually mitigate the adverse impact of heat stress and improve immunity (Anadón et al. 2019). Prebiotics and probiotics, along with other feed additives, reduce the body temperature, rectal temperature, respiration rate, and heart rate of animals under stress (Ayyat et al. 2018). Similar results were seen in other studies on species like poultry, rabbits, and doe (Jiang et al. 2021; Ahmad et al. 2022).

15.3 Climate Resilience Through Genomic Technologies

The future challenge for animal scientists is to increase livestock's adaptability to climate change through the formulation and implementation of better productivity and risk management systems. Heat stress, which is brought on by excessive exposure to or activity in extremely hot environments, is the most traumatic stress experienced by animals (Hochachka and Somero 2002). Thermal stress is a distinct and complex phenomenon that poses a variety of difficulties above and beyond the animal's basic homeostatic mechanisms, altering the usual physiological mechanisms and inducing a stressful reaction. Heat shock or stress begins in cells because of an abrupt environmental change. Abrupt reactions at the cell level along with diverse organs and tissues with acclimation responses are involved in changes in gene expression that are linked to a response to environmental stresses. The following examples show how genomic technology (Fig. 42.16) can be utilized to examine heat stress in dairy animals:

15.3.1 Gene Discovery

The finding of differentially expressed genes between two or more states is known as gene discovery. It is the process of finding genes that contribute to the formation of a phenotype or trait. The purpose of gene discovery is to uncover novel genomic pathways. An essential genomic strategy for identifying heat stress-related genes is based on ESTs (expressed sequence tags) derived from several cDNA (complementary DNA) libraries that reflect heat stress-treated tissues at various phases of improvement (Nayan et al. 2012).

15.3.2 Transcript Profiling

By utilizing genomic methods, including quantitative real-time PCR (qPCR), MPSS (massively parallel signature sequencing), and SAGE (serial analysis of gene expression), high-throughput gene expression analysis can be carried out

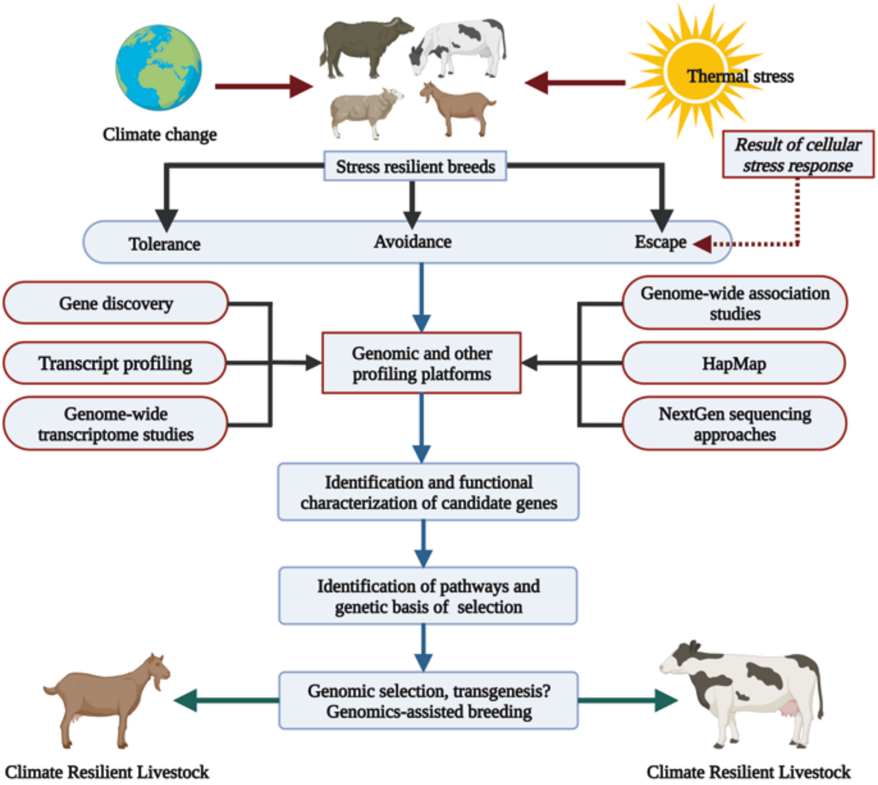


Fig. 42.16 Genomic technologies for unraveling heat and abiotic stress toward climate resilient animals

in control and stressor-treated tissues. EST-based cDNA arrays can be used to learn more about the awareness of gene expression patterns and functions as well as stress tolerance. The use of cDNA microarrays or macroarrays for gene expression profiling can also be a new method for determining the escalating number of copies of genes and the pathways leading to mechanisms for stress tolerance. Further perception can be attained by reviewing the co-regulation identification for condition-specific co-regulation of underlying sets of genes. It occurs as a result of specific species, breeds, or genotypes having effective transcriptional modifications and stress signal perception that can result in successful adaptive responses, adaptations, and finally increased tolerance (Nayan et al. 2012).

15.3.3 Genome-Wide Transcriptome and Methylome Studies

Identification of important molecules and regulators on the basis of gene expression patterns associated with the interaction of many stresses can be accomplished by genome-wide transcriptome analysis. The capacity to discover encoded gene transcription factors, which are activated or suppressed by a variety of environmental stresses, may prove to be an effective approach for identifying biomarkers for a specific heat stress. Thus, molecular interactions within the gene regulation network involved in coping with heat stress may be discovered (Nayan et al. 2012).

15.3.4 Genome-Wide Association Studies (GWAS)

It is feasible to choose animals which are genetically tolerant of heat stress in order to minimize the severity of the condition. Many livestock animals have already evolved thermotolerant breeds or strains (Oleson et al. 2015). GWAS can be used in this situation to find genetic markers that can be utilized to choose animal breeds and species that can withstand heat or are tolerant to the heat stress effects. The quantitative trait loci (QTL) and single nucleotide polymorphisms (SNPs) linked to the regulation of rectal temperature are also found using GWAS. Although the increase in reliability is lower than that of the more heritable traits, QTL can be recognized for their usage to improve consistency of genetic estimations. On the other side, GWAS can be helpful in comprehending the fundamental science of a trait by locating genetic markers near a QTL, which is well recognized for its low heritability features (Berry et al. 2012; Xiong et al. 2013).

15.3.5 HapMap Studies

A haplotype is a group of nearby genetic markers that are frequently inherited together. Improved dependability for an associated QTL region can be obtained via association analysis of heat stress haplotypes. Several species, especially farm animals, have these haplotypes stored in their HapMap projects. In Chinese Holstein cattle, an HSP70A1A haplotype has been found to be associated with greater risk when exposed to heat stress (Misztal 2017).

15.3.6 Next Generation Sequencing (NGS) Approaches

Several comparable technologies that provide massively parallel or deep-sequencing coverage for a chosen area or the whole genome of an organism are together referred to as NGS.

The quest for genes influencing features related to heat tolerance may be sped up due to NGS. Techniques like digital gene expression TAG (DGE-TAG), deep SAGE, and RNA-Seq have been developed as a result of the use of NGS technologies for gene expression analysis. Deep-sequencing methods are used in RNA-Seq, a more recent method of profiling the transcriptome. Direct high-throughput sequencing of the RNA from the tissues that have been subjected to heat stress under various circumstances may be possible with RNA-Seq based on NGS technology. Applications for NGS go beyond whole genome analysis because they have important ramifications for current developments in basic genomics and help with disease resistance, heat tolerance, and osmotic shock tolerance (Nayan et al. 2012).

15.3.7 Genetic Selection of Heat-Tolerant Breeds

Heat tolerance, which refers to an animal's capacity to continue producing and reproducing under warm and humid conditions, is a trait that is now economically significant in dairy systems all over the world as a result of global warming. Many dairy industries often use high-yielding dairy breeds. Dairy cow performance is influenced by animals with experience responding to environmental stress, and greater production is attained by cows that are best matched to the specific environment (i.e., environmental flexibility) (Sánchez et al. 2009). More specifically, adaptation shows how well cows handle environmental stress, particularly heat stress. The start of heat stress among Holstein-Friesian cows affects daily milk production differently (Hammami et al. 2015). Furthermore, a portion of the variability has a genetic basis, which may be employed in the selection of genetic programs to increase heat stress resistance (Hammami et al. 2015). The most efficient way to manage heat stress is to choose dairy cows that can withstand high temperatures, but this must be done with the assumption that good production efficiency can be linked to the capacity to withstand extreme heat (West 2003). The efficiency of the selection procedures depends on both commercial data and continuously improved management, and West (2003) also demonstrated that a mixed selection is achievable for productivity and resistance to heat stress. The fact that there is a negative relationship between production characteristics and THI shows that dairy cows with higher heat tolerance frequently have worse production performance. Dairy cattle also tend to crossbreed less frequently with heat-resistant breeds, and the heat tolerance trait is exclusively ignored when selecting cows for production, which lowers their total performance. Cows with a high tolerance for heat can be chosen to breathe during the breeding seasons using the degree and phenotypic performance records. A prospective fire that can transfer significant traits can also be chosen due to the differential in thermoregulation. Because the characteristic (tolerance to heat stress) has a low heritability, the previous study revealed that the rate of genetic improvement is modest. All things considered, genetic selection is a continual process and is anticipated to reduce the environmental impact of the cow's production for a unit of production (Sánchez et al. 2009). So, by keeping an eye on the genetic component of heat stress' trends, it is possible to prevent a drop in high heat tolerance (Carabano et al. 2016).

15.3.8 Genomic Selection for Heat-Resistant Traits

In the face of rising temperatures and the effects of climate change, it is critical to accelerate the rate of genetic gain for heat tolerance. The effectiveness of production was increased by early forms of biotechnology such as multiple ovulation embryo transfer and artificial insemination (Williams 2005). Less attention was paid to health and adaptation traits, such as the ability to withstand heat stress, in order to boost production traits (Pedersen et al. 2009). Through the application of marker-assisted selection, further genetic merit was confirmed. The accuracy of marker-assisted selection is improved by using data on the genetic makeup of individual animals, which also influences genetic advancement. The utilization of a particular genetic marker that only accounts for a small portion of the genetic differences is the only restriction on the use of marker-assisted selection (Meuwissen et al. 2001). Overall, genomic selection advances more rapidly than genetic development. Genomic selection entails employing genome-wide genetic markers to estimate the breeding value of chosen animals (Silva et al. 2014). SNPs are also used in genomic selection, as they are capable of capturing all QTL that affect a trait's variability. Genetic differentiation between qualities of economic value is based on the linkage equilibrium between polymorphisms and markers. Since genetic markers can be found throughout the entire genome, traits with poor heritability and adaptability are also available. Genetic selection can be used to increase heat stress resistance (Nguyen et al. 2017). An indicator trait for heat stress tolerance may be the extent to which milk production declines as heat stress increases (Wolfenson et al. 2000). High-density SNP data can also be used to determine the genomic estimated breeding value (GEBV) for heat stress resistance (Nguyen et al. 2016).

The compilation of reference populations of genotyped herds, however, is the fundamental issue with GEBV, and in addition, GEBV for heat stress tolerance is necessary if the trait is taken into consideration while making selection decisions (Wolfenson et al. 2000). Fortunately, by integrating climatic and performance data, lower milk production may be successfully obtained on a large scale and utilized as a trait for heat stress tolerance (Wolfenson et al. 2000). From this, a genetic prediction for heat stress tolerance can be derived (Wolfenson et al. 2000). Following the prediction of breeding value from SNP genotypes, cows (i.e., those being considered for selection) must be ordered according to GEBV so that the best can be selected (Weller et al. 2017).

15.3.9 Hormonal Treatment and Assisted Reproductive Technologies

Hormonal therapy may be able to lessen the consequences of heat stress in animals (Hansen and Areéchiga 1999; De Rensis and Scaramuzzi 2003; Bernabucci et al. 2010). Gonadotropin-releasing hormone (GnRH) treatments during the early estrus phase occur concurrently with the LH surge and help to increase conception rates. When GnRH agonist or hCG (human chorionic gonadotropin) is injected on day 5 of the estrous cycle, the first wave dominant follicle ovulates or luteinizes, and an auxiliary corpus luteum (CL) develops, which raises plasma progesterone levels to make up for the depletion from chronic heat stress (Pursley et al. 1998; Samal 2013). When paired with a GnRH injection to trigger a scheduled ovulation, a timed artificial insemination (AI) regimen boosts summer fertility. This procedure should be followed 7 days later by a PGF2 injection to regress the CL and enable the ovary's ultimate maturation. In order to assure successful conception, a second dosage of GnRH administered 48 hours after PGF2α can trigger ovulation and reproduction in cows at a 16-hour interval (Hoque et al. 2014). When used in conjunction with timely AI, the Ovsynch technique successfully synchronizes ovulation in buffalo and raises conception rates (El-Tarabany and El-Tarabany 2015). According to El-Tarabani and El-Tarabani (2015), in subtropical environmental circumstances, the CIDRsynch and Presynch protocols increased conception rates in Holstein cows. Since embryos are transferred after a period when they come more vulnerable to heat stress, embryo transfer (ET) increases the rate of pregnancy in the summer. Transfer of cryopreserved or frozen embryos created by superovulation increased conception rates in cows subjected to heat stress as compared to AI. Numerous studies are being conducted to determine whether a particular advancement in a timed AI protocol performs better for cows that have been exposed to heat stress than for cows that have not, but there is still much work to be done on optimizing timed AI protocols generally and under particular circumstances of heat stress. Ovulation failure is more common during hot weather, and this can be prevented by giving more potent GnRH analogs. Using GnRH (Ovsynch) or estradiol cypionate (Heatsynch), Shabankareh et al. (2010a) assessed variations between the summer and winter in P/AI (pregnancy per artificial insemination) at first service for cows reared in spontaneous estrus. In the summer, no variation was observed in P/AI (30, 30, and 32% for Heatsynch, spontaneous estrus, and OvSynch, respectively); however, in the winter, spontaneous estrus had the greatest P/AI (51%), OvSynch had the middle P/AI (40%), and HeatSynch had the lowest P/AI (35%) (Shabankareh et al. 2010b).

Increased circulating progesterone concentrations have been tested in a number of tests to see how they affect the fertility of heat-stressed cows (Wolfenson et al. 2004; Bridges et al. 2005; Dirandeh et al. 2015). The results were mixed and frequently reliant on the subgroup of cows treated. However, progesterone treatment for cows with low body condition or postpartum uterine abnormalities had a positive impact on their health (Zolini et al. 2019). Progesterone was administered via a CIDR device from days 5 to 18 following conception. hCG therapy at day 5 post-insemination in the study by Shabankareh et al. (2010b) enhanced P/AI in both summer (24 vs. 38% for saline and hCG) and winter (35 vs. 47%). Summer cows treated with hCG on day 5 had a higher pregnancy rate, but the impact was only evident in primiparous cows (López-Gatius et al. 2006). In a different study, there was no therapy that improved P/AI on day 0, but GnRH on day 5 or on both days 0 and 5 enhanced P/AI, but only in cows that were in their third or later lactations (Roth et al. 2001). According to the theory that early ovarian follicle development may be hindered by heat stress, fertility can be enhanced in the fall by rapidly removing damaged follicles from the ovary. Multiple follicular aspiration

(Roth et al. 2002), FSH (Friedman et al. 2011), and somatotropin (Friedman et al. 2011) are just a few of the medications that have been used to promote follicular turnover in order to improve oocyte efficiency in autumn as determined by in vitro development to the blastocyst stage. Furthermore, it has been suggested that inducing three consecutive 9-day follicular waves by administering GnRH and PGF2α has some favorable effects on fertility in summer and fall milch cows. Primiparous cows had a treatment effect (37% vs. 53% for control and treated cows), but multiparous cows did not have any treatment effect (27 vs. 29%).

16 Conclusions and Future Prospects

It is reasonable to expect climate change to cause long-term changes in the environment, which will have an impact on farm animal production. There is a very close relationship between animal energy metabolism and ambient temperature, as well as animal performance and product quality. When formulating professional animal nutrition, we should not only take into account our understanding of the energy metabolism of farm animals but also the discoveries of its relevant fields, such as microbiology, immunology, molecular biology, molecular genetics, and digestive physiology. Understanding these factors helps us to develop high-quality, safe foods that satisfy human nutrition requirements without increasing the environmental burden of production, therefore reducing the stress caused by climate change through nutrition. The establishment of climate-resistant livestock production systems is also crucial in tropical and subtropical regions where the effects of climate change are more extreme. These systems are of utmost importance as they provide food security and livelihoods to millions of people in the area and also play a key role in reducing greenhouse gas emissions and maintaining ecological stability. However, the implementation of these systems faces challenges such as limited access to resources, knowledge, and technology, necessitating increased investment in research and development to improve their sustainability and resilience. To achieve this goal, climate researchers, meteorologists, plant breeders, crop producers, animal nutritionists, biologists, geneticists, livestock producers, animal housing technicians, nutrition biologists, doctors, and others should all collaborate within the framework of a carefully structured and coordinated project. It is also necessary for governments, international organizations, and the private sector to work in collaboration to incorporate the development of these systems into national and regional strategies for climate change adaptation and mitigation, taking into account the needs of livestock farmers, the environment, and the economy. The ultimate goal is to ensure that the implementation of these systems is inclusive, sustainable, and equitable and that they contribute to the future of food security, livelihoods, and environmental sustainability in tropical and subtropical countries.

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Corrections to: Crop Improvement in the Desert

Nimra Shehzadi, Filza Ishfaq, Athar Mahmood, Muhammad Mansoor Javaid, Maria Naqve, Abdul Jabbar, and Ahsan Aziz

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