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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