Mirza Hasanuzzaman *Editor*

Agronomic Crops

Volume 2: Management Practices

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This book is dedicated to
Sher-e-Bangla A.K. Fazlul Huq
(26 October 1873—27 April 1962)

Founder of "The Bengal Agricultural Institute"
(Now, Sher-e-Bangla Agricultural University)

Preface

The history of agriculture has played a major role in human development, as agricultural progress has been a crucial factor in worldwide socioeconomic change. Since the ancient civilizations, human being has been trying to explore new food crops. In the course of time, the demands for foods are increasing, and people are trying to rely on formal cropping practices. Agronomic crops fulfill most of the basic demands of human life such as food, fuel, fiber, medicine, etc. Based on the uses of crops, agronomic crops have been classified on different types such as cereals, pulses, oil crops, fodder crops, green manuring crops, sugar crops, narcotic crops, beverage crops, etc. Plant breeders have been developing many improved varieties of such crops every year to boost up the global production. However, in most of the cases, yield gaps exist in the farmers' fields due to lack of proper agronomic management.

Crop management, therefore, becomes an integral part of food production. "Agronomy" is such a solution to make the crop field capable of securing the potential yield. Literally, it means the art of managing fields, and technically, it means the science and economics of crop production by the management of farmland. On the other hand, it is the art and science in production and improvement of field crops with the proper use of soil fertility, water, labor, and other factors related to crop production. Agronomy is the management of land for the cultivation of crop plants. The central theme of agronomy is the soil-plant-environment interrelationship. Both soil resources and climate have been changing globally, which makes crop production challenging. The basic agronomic principles can ensure the maximum yield from a crop variety, such as proper land preparation, selection of quality seeds and suitable varieties, proper water management, nutrient management, accurate pest management, proper harvesting, and postharvest operations. However, these activities should be chosen based on several factors like crop varieties, land types, agroclimate, etc. Choosing suitable cropping patterns and practicing crop rotation and multiple cropping also play an important role in enhancing land-use efficiency and crop stands.

Agricultural practices such as irrigation, crop rotation, fertilizers, and pesticides were developed long ago but have made great strides in the past century. Due to the global climate change, agronomic crops have been suffering from various abiotic and biotic stresses like salinity, drought, floods, toxic metals/metalloids, extreme temperatures, atmospheric pollutants, UV radiations, pests, etc. A substantial portion of crop yield is being declined every year due to the adverse effect of stresses. Therefore, researchers are trying to address these problems, working to explore the stress tolerance mechanisms, and manipulating adaptive features.

The knowledge of agronomic crops is essential for all agricultural graduates and scientists, not only with a view to understanding their cultivation practices but also with the objectives to know many academic and scientific details of each crop. This book covers comprehensive information on the advanced production of agronomic crops. Attempts have been made to cover all important field crops. Latest aspects about the cultivation practices, varieties, resource management, plant protection, along with quality aspects and postharvest practices are discussed in a crisp manner. The book must be immensely useful to all graduate students, faculty, and researchers in the field of agronomy and crop science.

This is the second volume (*Management Practices*) of the three-volume book *Agronomic Crops*. In this volume, different management practices and the basic principles and practices of field crop production as well as the advancement in research are presented.

I would like to give special thanks to the authors for their outstanding and timely work in producing such fine chapters. We are highly thankful to Dr. Mamta Kapila (Senior Editor, Life Science) and Ms. Raman Shukla (Senior Editorial Assistant) Springer, India, for their prompt responses during the acquisition. We are also thankful to Daniel Ignatius Jagadisan, Project Coordinator of this book, and all other editorial staff for their precious help in formatting and incorporating editorial changes in the manuscripts. Special thanks to Prof. Dr. Md. Fazlul Karim, Taufika Islam Anee, Dr. Md. Mahabub Alam, Mr. Abdul Awal Chowdhury Masud, Naznin Ahmed, and Tonusree Saha, Department of Agronomy, Sher-e-Bangla Agricultural University, Bangladesh, for their generous help in formatting the manuscripts. The editors and contributing authors hope that this book will include a practical update on our knowledge for the role of plant nutrients in abiotic stress tolerance.

Dhaka, Bangladesh Mirza Hasanuzzaman

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About the Editor

Dr. Mirza Hasanuzzaman is a Professor of Agronomy at Sher-e-Bangla Agricultural University in Dhaka. He received his Ph.D. on "Plant Stress Physiology and Antioxidant Metabolism" from Ehime University, Japan. Later, he completed his postdoctoral research at the Center of Molecular Biosciences, University of the Ryukyus, Japan. He was also the Recipient of the Australian Government's Endeavour Research Fellowship for postdoctoral research as an Adjunct Senior Researcher at the University of Tasmania, Australia. Dr. Hasanuzzaman's current work is focused on the physiological and molecular mechanisms of environmental stress tolerance. He has published over 80 articles in peer-reviewed journals, edited 6 books, and written 30 book chapters. According to Scopus®, his publications have received roughly 4000 citations with an *h*-index of 33. He is an Editor and Reviewer for more than 50 peer-reviewed international journals and was a Recipient of the "Publons Peer Review Award 2017, 2018 and 2019." He has been honored by different authorities for his outstanding performance in different fields, like research and education, and has received The World Academy of Sciences Young Scientist Award (2014).

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Crop Rotation: Principles and Practices

1

Asif Tanveer, Rao Muhammad Ikram, and Hafiz Haider Ali

Abstract

Crop rotation has been practiced from the time immemorial, and every farmer is quite familiar with it. If only one crop is sown in a particular field year after year, the roots of the crop extract nutrients from the same depth of soil every year, exhausting the rhizosphere and thus causing reduction in the crop yield. In order to maintain the achievable yield potential, it is therefore necessary to take measures to improve soil fertility and productivity. It can be done by leaving field fallow and by adding nutrients in the form of organic manures and chemical fertilizers. In view of rapidly growing population of world fallowing a large area for a long period of time is not practicable. Crop rotation may be defined as a system of raising crops in a regular order one after the other on the same piece of land keeping in view that fertility of land may not be adversely affected and farmers profit out of land may not be reduced. We classify the crops according to the residual effect on the soil, i.e., Exhaustive rotation: It includes more number of exhaustive crops which take up the plant food nutrients and leave the soil poor in fertility, e.g., wheat, cotton, field mustard, and maize. Restorative rotation: It includes those crops which improve the soil fertility. These include leguminous crops and exhaustive crops. Managing croplands according to nature's principles will reduce weed problems in all crops, and crop rotation has long been recognized for its ability to prevent weeds from developing to serious levels. Crop rotation limits the build-up of weed populations and prevents major weed species shifts. In a crop rotation, the timing of cultivation, fertilization, herbicide application, and harvesting changes from year to year. Rotation thus changes the

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growing conditions year to year, a situation to which few weed species easily adapt. Rotations that include clean-cultivated annual crops, tightly spaced grain crops, and grazed perennial sod crops create an unstable environment for weeds. Additional weed control may be obtained by including short-season weeds smothering crops such as sorghum sudan grass.

Keywords
Rotation · Cultivation · Soil · Crop

1.1 Introduction: Concept of Crop Rotation

Crop rotation has been practiced in the world from the time immemorial, and every farmer is quite familiar with it. If only one crop is sown in a particular field year after year, the roots of the crop extract nutrients from the same depth of soil every year, exhausting the rhizosphere and thus cause reduction in the crop yield. Monoculture also tends to upset the nutrient balance at different soil depths by drawing heavily on certain crop nutrients and leaving excessive amount of other nutrients unused. Thus the yield of the crops decreases continuously, and crop cultivation becomes unprofitable.

In order to maintain the achievable yield potential, it is, therefore, necessary to take measures to improve soil fertility and productivity. It can be done by leaving field fallow and by adding nutrients in the form of organic manures and the chemical fertilizers. In view of rapidly growing population of the world, fallowing a large area for a long period of time is not practicable. The fertilizers are not available everywhere at all the time of the year particularly in remote areas. Small land holders cannot afford to apply various costly fertilizers at the proper time and thus get low crop yield. Crop rotation is a technique which avoids the soil depletion, the problem associated with fallowing and the use of chemical fertilizers.

Crop rotation may be defined as a system of raising crops in a regular order one after the other on the same piece of land keeping in view that fertility of land may not be adversely affected, and farmers profit out of land may not be reduced.

The practice of crop rotation is ancient in its use and is widely recognized as a foundation stone of good agricultural practices.

1.2 Principles of Setting Different Crop Rotations

1. Crops belonging to the same natural order (family) should not follow one another.
2. The deep-rooted crop should be followed by shallow-rooted crop and vice versa.
3. Exhaustive crops (e.g., cereals which take more nutrients from soil and do not add anything to it) should be followed by restorative crops (e.g., legume crops

which not only take nutrients from the soil but at the same time also add nutrients to soil).

4. Green manure preferably legume crops should be included in the rotation.
5. The fodder crops should also be included in the rotation.
6. Diseases susceptible crops should be followed by disease-resistant crops.
7. Alternating crops with different peak requirements of labor, water and fertilizer, etc. should be included in crop rotation.
8. Long duration crops should be followed by short duration crops.
9. Crops with problematic weeds should be followed by clean crops/multicut crops (fodders) and other dissimilar crops.
10. Broadleaved crops should be rotated by narrow-leaved crops.
11. The crops with taproot should be followed by the crops with fibrous root system. This helps in proper and uniform use of soil nutrients from different depths.
12. Both wide spaced crops and thickly planted crops should be included in rotation for control of weeds. Wide spaced crops control weeds due to frequent interculturing and dense forage or legume crops controls weeds by suppressing weeds.
13. Effect of previous crop on succeeding crop should be considered for obtaining maximum yield and good quality of produce.
14. The selection of crops should be problem based, e.g., on sloppy lands, an alternate cropping of erosion-promoting (erect growing crops like millet, etc.) and erosion-resisting crops (spreading types like legumes) should be adopted.
15. Selection of crops should suit the farmer’s financial conditions.
16. In case of rainfed farming, some minor winter crops requiring less moisture like pulses may be grown on moisture retentive soils after harvest of summer crops.
17. Crops with minimum water requirements should be grown in periods of water deficiency in canal irrigated areas.
18. The rotation should be flexible enough to allow the farmers to make changes in the selection of crops with fluctuation in the economic condition of farmer and market demand and price.

1.3 Factors Affecting Rotation

1.3.1 Natural Environmental Conditions

Climate is the one of most important factors which affects the crop rotation either by wind, precipitation, humidity, light, or temperature. Climate is the dominant factor in determining which crops will grow. We should consider the annual rainfall of a region and water requirements of crops during the different crop rotations. In the high temperature region, we should keep the heat-tolerant crops in our crop rotation.

1.3.2 Availability of Labor

While setting a rotation, the type of manual labor, power, and its availability for working different tillage operations affects the crops in rotation. The labor is required at the critical stages of crop if the labor is not available at that time the crop may cause loss. Some farms require more labor than others, e.g., a market garden will employ more laborers than a sheep farm. Growing crops in a polytunnel (plastic tunnel greenhouse) to protect them from frosts and improve plant growth require extra inputs in the form of labor and work.

1.3.3 Irrigation Facilities

The types of crop will be different for rotation in irrigated areas as compared to rotation in arid or rainfed areas. As per availability of irrigation water, two or three crops are taken in a year on same land under irrigated conditions. However a dry crop should be included in the rotation to avoid damage to the soil due to continuous irrigation. We should consider total water discharge (canal and tube well water) while setting a rotation.

1.3.4 Situation of Farm

The type of crop and duration of rotation will be affected when farm is situated near the city as compared to country side.

1.3.5 Availability of Fertilizer

If fertilizer is available easily at cheaper rate, the crop rotation will be different as compared to that where fertilizer is not available and is very costly. If the fertilizer is available easily at cheaper rates, the duration of the rotation will be less and vice versa.

1.3.6 Type of Soil

While setting the rotation, nature (texture) of the soil and whether that is fertile or poor should be kept in mind. Sandy soils are less productive than silts, while soils containing clay are the most productive and use fertilizers most efficiently. Fertile and well-drained soil should be utilized for important rotation, less fertile soil for soil improving crops (legumes) and salt tolerant crops on saline or alkali soils.

1.3.7 Type of Farming

The nature of farming effects the rotation. The crops in vegetable farming will be different as compared to those in arable farming (general field crops).

1.3.8 Size of the Farm

On small farms the crops in rotation will be different in comparison to the big farms. Large farms often have rotations that include multiyear perennial crops. Farmers with limited acreage rely on short-term crops in place of multi-season crop rotations.

1.3.9 Profitability, Marketing, and Processing Facilities

The challenge of a good crop rotation system is to grow the type and quantity of crops needed to ensure the farm's profitability while continually building soil quality for long-term productivity. Most farms grow many different crops. Every crop is not equally profitable, and some crops are highly profitable but have limited markets and processing facilities. Selection of crops should be demand based, i.e., the crops, which are needed by the people or area. So that produce can be sold at a higher price. The area devoted to each crop should be constant from year to year.

1.3.10 Government Policy

Subsidies, loans, and tax reductions on different crops affect selection of crops for rotation.

1.3.11 Finance

Money is needed for farm buildings, wages, seed, animal feed, fertilizers, pesticides, and machinery. All these things affect crop rotation.

1.4 Classification of Crop Rotation

Crop rotation may be classified.

1.4.1 According to the Residual Effect on the Soil

It is further classified into two subgroups.

- *Exhaustive rotation*: It includes more number of exhaustive crops which take up the plant food nutrients and leave the soil poor in fertility, e.g., wheat-cotton-field mustard-maize.
- *Restorative rotation*: It includes those crops which improve the soil fertility. These include leguminous crops and exhaustive crops.

a. Guar bean – Wheat – Field mustard – Cotton
b. Wheat – Summer fodder – Barseem – Cotton
c. Wheat – Gram – Cotton

1.4.2 According to Their Period or Succession of Crops

It is further divided into two subgroups.

1. *Fixed Rotation*

No change is made in the sequence of crops, and the same sets of crops are grown in succession on the same piece of land year after year, e.g.:

Wheat – Field mustard – Cotton
Cotton – Wheat – Field mustard
Field mustard – Cotton – Wheat

2. *Flexible Rotation*

It can be adjusted according to the fluctuation in market rates, attach of insect, pest and diseases, and availability of irrigation water, e.g.:

Wheat – Field mustard – Cotton
Wheat – Wheat – Cotton
Wheat – Maize – Cotton

In a flexible rotation, it is not possible to grow same crop to finish within a limited period of 3 years.

3. Long Duration Crop Rotation

   These are the rotations which are generally set for a long period that is more than 2 years.

4. Short Duration Crop Rotation

These rotations are set for a short period that is generally not more than 1 year.

Depending upon duration crop rotation may be of following three types:

A. *1 year rotation*
   Potato-maize-potato
   Wheat-cotton
B. *2 years rotation*
   Wheat-cotton-wheat
   Rice-maize-rice
   Wheat-rice-winter fodder
C. *3 years rotation*
   Wheat-maize-sugarcane
   Wheat-sugarcane-sugarcane (ratoon)

1.5 Advantages of Crop Rotation

1. Crop rotation improves soil health by alternating crops with different nutrient requirements, therefore avoiding depletion of any one necessary nutrient present in the soil.
2. Crop rotation can benefit overall soil structure by alternating deep- and shallow-rooted crops, breaking up subsoil, and reducing the effects of plow pan.
3. By rotation better use of irrigation facilities is obtained.
4. It systemizes the farming system.
5. Economics of labor: Crop rotation often makes it possible to grow two or more crops with the same soil preparation.
6. Farm labor is utilized throughout the year: Crop rotation allows a more complete year work with a less period of idleness and distributing risk among several crops which helps to prevent complete failure. Usually a cropping system simplifies the farm layout and reduces the number of field on the farm by making estimate ahead of time for the amount of labor, quantity of seed, fertilizer, and power machinery necessary for the operation of the farm.
7. Nitrogen supply: Legumes generally may not only increase the supply of organic matter but also help to maintain the nitrogen supply to soil. The single cropping system will ordinary maintain the nitrogen supply of the soil unless leguminous crops are alternated with the other crops. Rotation is a low-input, soil management strategy on developing long-term soil fertility plan, preferably with less off-farm inputs. A rotation plan used in conjunction with cover cropping and compost is an ideal way for a vegetable farmer to increase fertility and organic matter while minimizing off-farm inputs.
8. Balanced removal of plant nutrients: Rotation may provide for the alternation of deep and shallow root crops, and this allows a more use of soil. Crops use the nutrients from the soil in different proportions, and when properly alternated they may reduce the different plants nutrients of the soil in a more desirable

proportion. If a single crop is grown repeatedly, that may feed heavily on one group of nutrients.

9. It allows for crop alternation or crop diversity. Different kinds of crops are grown for a similar food (e.g., paddy, wheat, potato for carbohydrates, gram, pea, lentil, soybean, cowpea, etc. for protein; rapeseed and mustard, sesamum, groundnut, sunflower, etc. for oils) as well as different varieties of same crop. Diversification can lead to more stable farm income by lowering economic risk from climate, pests, and fluctuating markets.
10. It increases the final crop yield and improves the efficiency and productivity of agricultural systems, thus contributing to improvement of farmers livelihoods.
11. The rotation helps to control weeds, insects, and diseases: Weed problems are now more serious than ever before. Farmers have to incur huge amount on weed control relative to traditional crop rotation.

This situation is the result of monoculture of selected crops leading to buildup of weeds. Buildup of *Phalaris minor* weed problem in rice-wheat system is an example of such serious problems. Because each crop has its own weeds and they thrive well when the same crop is grown successively. For example, P. minor, A. fatua with wheat, Cichorium intybus with berseem, and S. halepense with sorghum and corn. Weed tends to prosper in crops that have requirements similar to the weeds. Fields of annual crops favor short-lived annual weeds, whereas maintaining land in perennial crops favors perennial weed species. All such and several other weeds may be effectively controlled by adopting proper rotation. Lowland rice crop rotation with an upland crop is effective against moisture-loving weeds. The population of *Scirpus maritimus* and *Echinochloa* increases with continuous cropping of lowland rice but declines when rice is rotated with an upland crop.

Managing croplands according to nature’s principles will reduce weed problems in all crops, and crop rotation has long been recognized for its ability to prevent weeds from developing to serious levels. Crop rotations limit the buildup of weed populations and prevent major weed species shifts. In a crop rotation, the timing of cultivation, fertilization, herbicide application, and harvesting changes from year to year. Rotation thus changes the growing conditions from year to year, a situation to which few weed species easily adapt. Rotations that include clean-cultivated annual crops, tightly spaced grain crops, and grazed perennial sod crops create an unstable environment for weeds. Further weed control may be obtained by including short-season weed-smothering crops such as sorghum-sudan grass and sudan grass.

Incorporating crops with allelopathic effects into the rotation adds another element of weed control. Such crops include sunflowers, sorghum, and rapeseed. Weed control ability varies among crop varieties and farm management practices. For example, sweet potatoes have been shown to inhibit the growth of yellow nutsedge, velvetleaf, and pigweed. Field trials showed a 90% reduction of yellow nutsedge over 2 years following sweet potatoes.

Insect and disease problems are now more serious than ever before. This situation is the result of monoculture of selected crops leading to buildup of insects and diseases. Carryover of stem borer (pink borer) and buildup of soilborne pathogens in soil of continuous cereal system are examples of such serious problems. Many insects are troublesome for only one plant or group of plants. For example, jassid damage the cotton crop, and if the cotton crop is grown continuously, the jassid may increase rapidly; changing of crop is an effective method for checking the damage from the insects. Sometimes it is necessary to omit the crops entirely for a few years, but usually a rotation of a proper length will bring these pests within the limit of economic control. Similarly there are many diseases that injure to one crop but are not harmful to the other crops, e.g., smut of grain may increase rapidly under continuous cropping to the grain plants. Crop rotation brings about non-host plants due to which the pests are deprived of their food and the pests either die or migrate to some other location. Crop rotation helps in control of parasitic nematodes. Effective rotation is widely practiced for control of the golden nematode of potatoes. Crops like sugarcane, wheat, and chillies should be avoided in white ant-infested areas, and crops like tobacco and onion should be grown.

1. It helps in maintaining the amount of organic matter in the soil. If lands are kept constantly under tilled crops, the supply of organic matter is seriously decreased. Grasses and clover usually increase the supply of organic matter in the soil.
2. Soil can be reclaimed in a better way which is affected by water logging, alkalinity, and salinity. Barley and wheat crop appear to be a reasonably good choice for sodic soils during winter. For summer, pearl millet considered as possible alternative to rice. Rice-based cropping systems are more suitable and promising than other systems on problem soils. Rice-wheat or rice-berseem for about 3 years and diversification of cropping system afterward are ideal. Inclusion of a green manure crop in the system leads to sustainable production under several situations.
3. It protects soil against erosion. Continuous growing of one crop especially of exhaustive nature disturbs the soil structure and soil fertility which consequently results in accelerated soil erosion. Certain crops require more cultivation, and their fall period coincides with high rainfall and hence induces soil and water erosion. Whereas certain other crops require less cultivations and protect the soil during rainy season. Preference to erosion resistant crops such as legumes and other ground smothering crops whose growth coincides with heavy rains is in crop rotation.
4. Increase in soil macro- and microfauna. Biological processes are central to soil fertility and productivity and sustainability of agroecosystem. The number of organisms varies greatly depending on food supply, moisture, temperature, physical condition, and reaction of the soil. Crop rotation such as cereal-cereal or non-legume-non legume results in reduced population of soil organisms. Population and activity of soil organisms can be increased by following legume-cereal crop rotation. Biological activity can also be stimulated by simply allowing a grass cover to develop, through forestation or by adding organic material through rotation.
5. It increases the soil quality. Soil quality means the fitness of soil for use. To increase the soil quality, the use of crop rotation which improves soil function is

of immense importance. This option can increase soil organic matter and organic nitrogen, protect against soil erosion, reduce disturbance (avoid excess tillage), increase crop diversity and ground cover, and cycle water, nutrients, and energy efficiently, ultimately helpful in increasing soil quality.

1.6 How to Set Up a Rotation?

The following are the principles of setting crop rotation:

1. Economical principles
2. Agronomical principles

1.6.1 Economical Principles

These are divided into:

(a) *Selection of group of crops while forming a rotation*
  One must select the group of crops for setting a rotation, i.e., either you want to grow cereals or pulses or forage (fodder) crops or fiber crops or oilseeds or any one of these crops.
(b) *Selection of associated crops*
  In this case one must select such types of crops which will give more income as well as maintain soil fertility.
(c) *Availability of labor and capital*
  While setting a rotation, it is the duty of farmers to know that the labor is available at lower wages, so that he can earn maximum from the crops which he has included in the rotation. Similarly capital is available at lower or smaller interest, so that he may be able to purchase seeds, fertilizers, and pesticides easily and timely.

1.6.2 Agronomical Principles

(a) The area of each crop should be nearly the same year after year unless there is deficient season for changing it.
(b) The rotation should provide fodder for the animal kept.
(c) The crops of same root system should not follow.
(d) The rotation must include tilled crops for elimination of weeds.
(e) The rotation should be such which can keep up the organic matter of soil. Crops of same natural order should not follow.

1.7 Difficulties or Limitations of Crop Rotation

1. Rotation is not always advisable, e.g., high prices which may make it advisable to grow the one of the crop for a long period. In the peri-urban areas where fruits, vegetables, and fodder crops are more remunerative than other crops, it is difficult to follow desirable crop rotation principles completely.
2. Weather conditions may be suited for only one or two crops. In rainfed areas due to scarcity of water, rotation cannot be followed in some season of the year. Same is the case in nonperennial and inundation canal areas.
3. Demand for certain crops may make it advisable to change or to substitute the existing crops by some other crops. This breaks the rotation. Crop husbandary has become so commercialized that in the vicinity of sugar, ginning mills and rice shellers sugarcane, cotton, and rice crops is grown in close succession with high inputs.
4. Crop rotation cannot be considered a complete replacement for organic and inorganic fertilizers needed for the production of crops, vegetables, and fruits.

1.8 How to Do It

Rotation may suggest that every crop should be grown on a fixed schedule on every field of farm, with each crop rotating field to field around the entire farmland. Divide the farmland into two blocks and plant the winter crops in block one, and rotate to block two next year, or divide farmland into three equal blocks, and rotate these blocks according to one of the following plans.

Plan A
- *Year 1*
    - Section 1: grain.
    - Section 2: cash crop.
    - Section 3: legume.
- Year 2
    - Section 1: legume.
    - Section 2: grain.
    - Section 3: cash crop.
- Year 3
    - Section 1: cash crop.
    - Section 2: legume.
    - Section 3: grain.

Plan B
- Year 1.
    - Sections 1 and 2: grain.
    - Section 3: legume.

Year 2.
    Section 1: legume.
    Sections 2 and 3: grain.
Year 3.
    Sections 1 and 3: grain.
    Section 2: legume.

Crop Suggestions

- Grains – maize, rice, wheat, sorghum, millet, and barley
- Legumes (cash or food crops) – soya bean, cowpea, groundnut, field bean, chickpea, lentil, green gram, black gram, or combinations of these.
- Cash crops (non-legumes) – cotton, sunflower, tobacco, sugarcane, canola, and rice

2

Improving Water Use Efficiency in Agronomic Crop Production

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Abstract

Food and agriculture are the largest consumers of water, requiring one hundred times more than we use for personal needs. Agricultural water is used to grow fresh produce and sustain livestock. Agriculture is expected to face increasing water risks that will impact production, markets, trade, and food security – risks that can be mitigated with targeted policy. Water resource management is the activity of planning, developing, distributing, and managing the optimum use of water resources. Water use efficiency (WUE) refers to the ratio of water used in plant metabolism to water lost by the plant transpiration. WUE can also be

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improved through different methods such as irrigation scheduling and on-farm water management. Irrigation scheduling is the decision of when and how much water to apply to a field. Its purpose is to maximize irrigation efficiencies by applying the exact amount of water needed to replenish the soil moisture to the desired level. It enables the farmers to schedule water rotation among the various fields to minimize crop water stress and maximize yields. It reduces the farmer's cost of water and labor through less irrigation, thereby making maximum use of soil moisture storage. This chapter reviews the main linkages between climate change, water, and agriculture as a means to identifying and discussing adaptation strategies for better use and conservation of water resources.

Keywords
Agricultural water use · Water use efficiency · Irrigation scheduling · Crop productivity · Agronomic crops

2.1 Introduction

Freshwater resources are becoming scarce and polluted, while their demands for agricultural, domestic, industrial, environmental, and recreational uses are on a continuous rise around the globe. Agriculture is the largest consumer of water, and total evapotranspiration from global agricultural land could double in the next 50 years if trends in food consumption and current practices of production continue. Traditional ways to increase yield by extending the area under cultivation, using high intensity of external inputs, and breeding for yield potential in high-input agroecosystems offer limited possibilities under limiting resource availability. Climate and weather conditions greatly affect the performance of new cultivars for yield and resource use efficiency (Mubeen et al. 2013). Improved agricultural systems should ensure high yields via an efficient and sustainable use of natural resources such as water (Gadanakis et al. 2015). Efforts are made to get higher yields by adoption of proper agronomic practices, i.e., time of sowing, integrated nutrient management, selection of varieties/hybrids adapted to the ecologies, and particularly irrigation water supplies (Nasim et al. 2017). Irrigation systems have been under pressure to produce more with lower supplies of water. Various innovative practices can gain an economic advantage while also reducing environmental burdens such as water abstraction, energy use, pollutants, etc. (Levidow et al. 2014).

Plant response to varying degrees of water regime has been a subject of considerable study and review (Khaliq et al. 2012). Irrigation scientists and engineers have used the term "water (irrigation) use efficiency" to describe how effectively water is delivered to crops and to indicate the amount of water wasted at plot, farm, command, or system level and define it as the ratio of irrigation water transpired by the crops of an irrigation farm or project during their growth period to the water diverted from a river or other natural source into the farm or project canal or canals during the same period. Making informed management of irrigation decisions is an important element of excellent irrigation management and regularly plays an important role in profitability and yield. Irrigation scheduling refers to the number of irrigations for a crop and their timing. This depends on several factors including types of crop, its stage of development, extent of the root system, rate of evapotranspiration, and the water holding capacity of the soil (Sharma et al. 2015). Subsurface trickle irrigation is currently the most advanced water-saving irrigation method. Compared with other irrigation methods, subsurface trickle irrigation can maintain and even increase the yield of more than 30 types of crops, including corn, alfalfa, cotton, tomato, sweet corn, etc. by requiring less water in most cases (Mo et al. 2017; Liu et al. 2017).

The technical basis for improving agricultural water use efficiency is illustrated in this chapter.

2.2 Use of Water in Food and Agriculture

With the world's population set to increase by 65% (3.7 billion) by 2050, the additional food required to feed future generations will put further enormous pressure on freshwater resources (Fig. 2.1). This is because agriculture is the largest single user of freshwater, accounting for 75% of current human water use. At present, 7% of the world's population lives in areas where water is scarce. This is predicted to rise to a staggering 67% of the world's population by 2050 (Turral et al. 2011). Because of this water scarcity and because new arable land is also limited, future increases in production will have to come mainly by growing more food on existing land and water. This looks at how this might be achieved by examining the efficiency with which water is used in agriculture. Globally, in both irrigated and rainfed agriculture, only about 10–30% of the available water (as rainfall, surface, or groundwater) is used by plants as transpiration. In arid and semiarid areas, where water is scarce and population growth is high, this figure is nearer 5% in rainfed crops. There is, therefore, great potential for improving water use efficiency in agriculture, particularly, in those areas where the need is greatest (Viala 2008). This may be achieved by:

I. Increasing the total amount of the water resource that is made available to plants for transpiration.
II. Increasing the efficiency with which transpired water produces biomass. It is concluded that there is much scope for improvement, particularly, in the latter and that future global research should shift its emphasis to address this real and immediate challenge (Levidow et al. 2014).

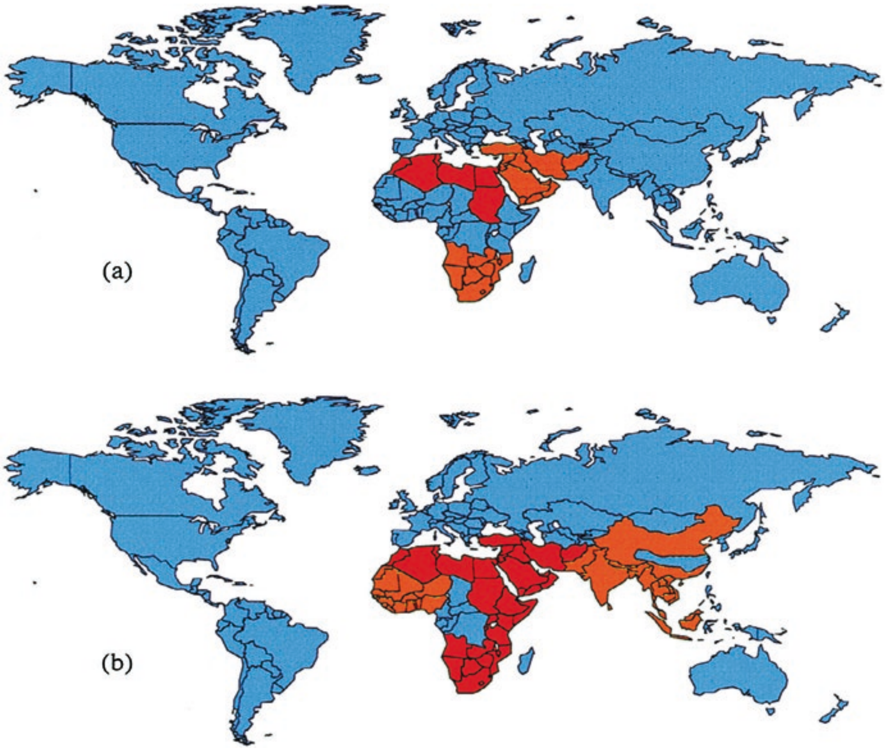

Fig. 2.1 Global water scarcity (**a**) now and (**b**) in 2050. Regions are coded according to their per capita annual renewable freshwater resource. Red, less than 1000 m^3 per person per year; orange, between 1000 and 2000 m^3 per person per year; and blue, greater than 2000 m^3 per person per year

2.2.1 Water Use by Rainfed Agriculture

The term “rainfed agriculture” is used to describe farming practices that rely on rainfall for water. It provides much of the food consumed by poor communities in developing countries. For example, rainfed agriculture accounts for more than 95% of farmed land in sub-Saharan Africa, 90% in Latin America, 75% in the Near East and North Africa, 65% in East Asia, and 60% in South Asia (Rockström 2010). At global level, this area includes temperate areas where rainfed yields are relatively high. In semiarid developing countries, therefore, the proportion of food which comes from rainfed agriculture can be even higher and over 90% in some countries. Managing water resources for crop production in these circumstances becomes a matter of making optimal use of rainfall. When rainfall reaches the soil surface, some of it may infiltrate the soil, some may evaporate from the soil surface, and the rest will run off. Ignoring, for the moment, downstream uses of runoff water, agricultural practices that maximize the amount of rainfall which infiltrate into the soil are the starting point for good water management (Molden et al. 2010; Charlton et al. 2010).

2.3 Scarcity of Water in Agriculture

To estimate the inevitable increased demand for water resources to grow the food requirement of the future population, we first need to estimate how much water is required to grow our basic per capita food requirement (Solangi 2018).

If we combine this information with the UN population statistics and estimates of total annual renewable freshwater resources, we can estimate the global and regional picture of future water scarcity. This assumes a basic dietary requirement of 2700 kcal which is mostly (85%) plant based. Using figures for the water requirement per kcal of food could estimate the annual per capita water requirement as 1570m^3 water. In a semiarid climate, Falkenmark (2017) assumes that 50% of food would come from rainfed so the annual per capita freshwater demand from irrigated agriculture would be 785m^3. This is a critical assumption in this analysis, which may be a reasonable "first estimate" for all semiarid areas. However, it will clearly vary widely between different parts of the semiarid zone (Falkenmark 2017).

Some picture of worldwide distribution of water resources is given in Table 2.1. Similarly, freshwater distribution around the globe is depicted in Table 2.2.

Table 2.1 Worldwide distribution of water

S. no.	Water type	Volume (1000 km^3)	Percentage of total global volume
1	Ocean	1,370,323	94.200
2	Groundwater (fresh and saline)	60,000	4.100
3	Glaciers	24,000	1.650
4	Lakes and reservoirs	280	0.019
5	Soil moisture	85	0.006
6	Atmospheric water	14	0.001
7	River water	1.2	0.001
	Total	1,454,703.2	100.00

Source: Adewumi (2017)

Table 2.2 Worldwide distribution of freshwater

S. no.	Water type	Volume (1000 km^3)	Percentage of total fresh volume
1	Glaciers	24,000	85
2	Groundwater	4000	14
3	Lakes and reservoirs	155	0.600
4	Soil moisture	83	0.300
5	Atmospheric water	14	0.050
6	River water	1.2	0.004
	Total	28,253.2	100.00

Source: Adewumi (2017)

2.4 Effect of Climate Change on Water Resources

Climate change has adverse impacts on health, water, biodiversity, and natural resources cited and accepted all over the globe (Nasim et al. 2018). In 1995, nearly 1400 million people lived in water-stressed watersheds (runoff less than 1000 m^3/capita/year). River runoff was simulated at a spatial resolution of 0.5 m under current and future climates using a macroscale hydrological model and aggregated to the watershed scale to estimate current and future water resource availability for 1300 watersheds and small islands under the SRES population projections. The A2 storyline has the largest population, followed by B2, then A1 and B1 (which have the same population). In the absence of climate change, the future population in water-stressed watersheds depends on population scenario and by 2025 ranges from 2.9 to 3.3 billion people (36–40% of the world's population). By 2055, 5.6 billion people would live in water-stressed watersheds under the A2 population future and "only" 3.4 billion under A1/B1. Climate change increases water resource stresses in some parts of the world where runoff decreases, including around the Mediterranean and in parts of Europe, Central and Southern America, and Southern Africa. In other water-stressed parts of the world particularly in Southern and Eastern Asia—climate change increases runoff, but this may not be very beneficial in practice because the increases tend to come during the wet season and the extra water may not be available during the dry season (Bos and Markert 2006).

2.5 Water Resource Management

The adoption of a comprehensive framework for analyzing policies and options would help guide decisions about managing water resources in countries where significant problems exist, or are emerging, concerning the scarcity of water, the efficiency of service, the allocation of water, or environmental damage (Giardino 2010).

Many of the countries with limited renewable water resources are in the Middle East, North Africa, Central Asia, and sub-Saharan Africa, where populations are growing fastest. Elsewhere, water scarcity may be less of a problem at the national level but is nevertheless severe in many areas such as in northern China, western and southern India, western South America, and large parts of Pakistan and Mexico. For some countries, such as those in Eastern Europe, pollution is the largest problem affecting water resources. In much of Africa, implementation capacity is a critical issue exacerbated by the frequency of prolonged droughts. In some countries, water resource management is not yet a significant problem. These differences among regions and countries will shape the design of strategies and programs for a given country (Winz et al. 2009).

Water resource management that follows the principles of comprehensive analysis, opportunity cost pricing, decentralization, stakeholder participation, and environmental protection can yield more coherent policies and investments across sectors, promote conservation, and move the efficiency of water allocation.

For the environment and poverty alleviation, more rigorous attention to minimizing resettlement, maintaining biodiversity, and protecting ecosystems in the design and implementation of water projects. Water and energy supplies gained through conservation and improved efficiency can be used instead of developing new supplies to extend service to the poor and maintain water-dependent ecosystems (Winz et al. 2009).

2.6 Water Use Efficiency (WUE)

Effective use of water (EUW) and not water use efficiency (WUE) is the target of crop yield improvement under drought stress.

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) could be defined in different ways. WUE is calculated as the ratio yields of crop water consumption:

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET}}$$

where Y is yields (dry weight, kg ha^{-1}) of a crop (Zhao et al. 2014).

Water use efficiency (WUE) is often considered an important determinant of yield under stress and even as a component of crop drought resistance. It has been used to imply that rainfed plant production can be increased per unit water used, resulting in “more crop per drop.” This opinionated review argues that selection for high WUE in breeding for water-limited conditions will most likely lead, under most conditions, to reduced yield and reduced drought resistance. If the biochemistry of photosynthesis cannot be improved genetically, greater genotypic transpiration efficiency (TE) and WUE are driven mainly by plant traits that reduce transpiration and crop water use, processes which are crucially important for plant production. Since biomass production is tightly linked to transpiration, breeding for maximized soil moisture capture for transpiration is the most important target for yield improvement under drought stress (Knauer 2017).

Effective use of water (EUW) implies maximal soil moisture capture for transpiration which also involves reduced non-stomata transpiration and minimal water loss by soil evaporation. Even osmotic adjustment which is a major stress adaptive trait in crop plants is recognized as enhancing soil moisture capture and transpiration. High harvest index (HI) expresses successful plant reproduction and yield in terms of reproductive functions and assimilate partitioning toward reproduction. In most rainfed environments, crop water deficit develops during the reproductive growth stage, thus reducing HI. EUW by way of improving plant water status helps sustain assimilate partitions and reproductive success. It is concluded that EUW is a major target for yield improvement in water-limited environments. It is not a coincidence that EUW is an inverse acronym of WUE because very often high WUE is achieved at the expense of reduced EUW. Water use efficiency (WUE) is often considered an important determinant of yield under stress and even as a component of crop drought resistance. It has been used to imply that rainfed plant production can be increased per unit water used, resulting in “more crop per drop” (Fig. 2.2) (Sharma et al. 2015).

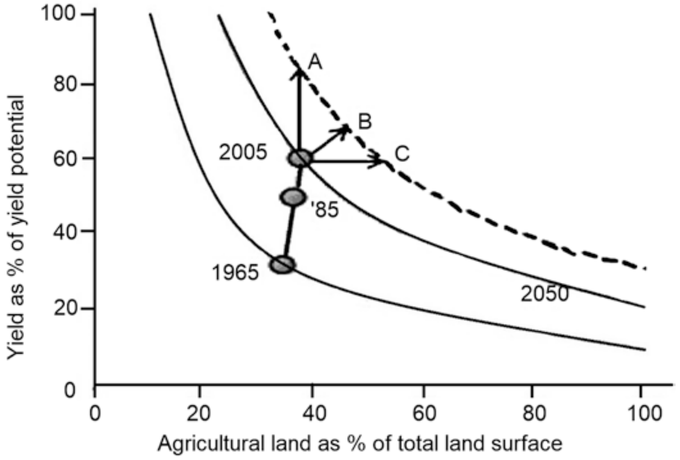

Fig. 2.2 Water use efficiency

2.7 Integrated Land-Water Management Practices

There are a number of operations which can enhance water use efficiency in agriculture and in turn come under the scope of integrated land-water management practices.

2.7.1 Adequate Soil Fertility

Adequate soil fertility refers to the ability of a soil to sustain agricultural plant growth, i.e., the ability to supply essential plant nutrients and water in adequate amounts and proportions for plant growth and reproduction and the absence of toxic substances which may inhibit plant growth (Valença 2017). Recently, scientific and public concerns have increased and thus have emphasized on the protection of water bodies from pollution caused by N leaching from agricultural systems (Hammad et al. 2017).

The following properties contribute to soil fertility in most situations:

- Sufficient soil depth for adequate root growth and water retention.
- Good internal drainage, allowing sufficient aeration for optimal root growth (although some plants, such as rice, tolerate water logging).
- Topsoil with sufficient soil organic matter for healthy soil structure and soil moisture retention.
- Soil pH in the range 5.5–7.0 (suitable for most plants).
- Adequate concentrations of essential plant nutrients in plant-available forms.
- Presence of a range of microorganisms that support plant growth.

2.7.2 Efficient Recycling of Agricultural Wastewater

Wastewater reuse in agriculture involves the further use of “treated” wastewater for crop irrigation. This type of reuse is considered an efficient tool for managing water resources, stemming from the need for a regulated supply that compensates for water shortages caused by seasonality or the irregular availability of other water sources for crop irrigation throughout the hydrological year. Although the use of wastewater is an ancient practice, it has not always been properly managed or met quality standards according to use. Accordingly, the knowledge pertaining to wastewater use has evolved with the history of mankind. In the nineteenth century, the transportation and final disposal of untreated wastewater onto open peri-urban fields triggered catastrophic epidemics of waterborne diseases such as cholera and typhoid fever. Such epidemics prompted several milestones in sanitation, such as Great Britain’s Public Health Act, establishing the “discharge of rainwater in the river and of wastewater on the soil” as the primary principle. Additionally, the international sanitary movement promoted by leading European powers led to a series of sanitary conferences on hygiene and demography. Furthermore, the International Office of Public Hygiene was established, with the purpose of performing sanitary (Khalid 2018).

The Food and Agriculture Organization of the United Nations (FAO) has also developed several guidelines relevant to the use of wastewater in agriculture. In 1987, the wastewater quality guidelines for agricultural use were published. These guidelines related the degree of restriction of water use to salinity, infiltration, and toxicity parameters of specific ions. In 1999, the FAO published the suggested guidelines for the “agricultural reuse of treated waters and treatment requirements.” In these guidelines, the type of agricultural reuse was classified based on the type of irrigated crop (Huang and Logan 2008).

2.7.3 Crop Residue Incorporation

Soil organic matter (SOM) improves soil physical (e.g., increased aggregate stability), chemical (e.g., cation-exchange capacity), and biological (e.g., biodiversity, earthworms) properties, and it mitigates climate change by sequestering carbon in soils; all these improvements in turn increase better utilization of water in the soil for growing crops. Currently, as much as 25–75% of the soil organic carbon (SOC) in the world’s agricultural soils may have been lost due to intensive agricultural practices, and about 45% of European soils exhibit low organic matter contents. The decline of OM is one of the major threats to soils described by the European Commission. Globally, approximately 4 billion tons of crop residues are produced. Incorporation of crop residues may be a sustainable and cost-effective management practice to maintain the ecosystem services provided by soils, the SOC levels and to increase soil fertility in agricultural soils.

2.7.4 Rainwater Harvesting

For our water requirement, we entirely depend upon rivers, lakes, and groundwater. However, rain is the ultimate source that feeds all these sources. Rainwater harvesting means to make optimum use of rainwater at the place where it falls, i.e., conserve it and not allow it to drain away and cause floods elsewhere. The rainwater harvesting may be defined as the technique of collection and storage of rainwater at surface or in subsurface aquifer before it is lost as surface runoff. The augmented resources can be harvested whenever needed (Abdulla and Al-Shareef 2009).

The advantages of rainwater harvesting are the following:

(a) It promotes adequacy of underground water.
(b) It mitigates the effect of drought.
(c) It reduces soil erosion as surface runoff is reduced.
(d) It decreases load on storm water disposal system.
(e) It reduces flood hazards.
(f) It improves groundwater quality/decreases salinity (by dilution).
(g) It prevents ingress of seawater in subsurface aquifers in coastal areas.
(h) It improves groundwater table, thus saving energy (to lift water).
(i) The cost of recharging subsurface aquifer is lower than surface reservoirs.
(j) The subsurface aquifer also serves as storage and distribution system.
(k) No land is wasted for storage purpose, and no population displacement is involved.
(l) Storing water underground is environment friendly.

2.7.5 Conservation Tillage

Existing strategies, like conservation tillage, can help producers minimize the risks associated with climate variability and change as well as improve resource use efficiency (Fig. 2.3).

The USDA-NRCS (United States Department of Agriculture, Natural Resources Conservation Service) defines conservation tillage as a system that leaves enough crop residues from cover crops and/or cash crops on the soil surface after planting to provide at least 30% soil cover. Research has identified 30% soil cover as the minimal amount of residue needed to avoid significant soil loss, but greater residue amounts are preferred. Together with cover crops, conservation tillage has the potential to reduce erosion, increase rainfall infiltration, reduce subsurface compaction, and maximize soil organic carbon (SOC) accumulation, which positively affects many soil physical and chemical properties (Kaurin 2018).

Conservation tillage includes the following practices:

- No tillage or direct seeding: In this system, the only soil disturbance is from the coulters or disk openers of direct seeding equipment.

Jeffrey P. Mitchell

With conservation tillage a crop is seeded directly into wheat stubble, shown in Five Points, 2009.

Fig. 2.3 Conservation tillage for improving water use efficiency

- Strip tillage: A narrow seedbed is tilled prior to planting, exposing some soil. This can result in the beneficial warming and drying of a seedbed.
- Ridge tillage: Soil is mostly undisturbed, and planting is done on established ridges. Some residues on the ridge tops are removed at planting by equipment sweeps or shoes to prepare the seedbed.

2.7.6 Irrigation Scheduling

Improving the efficient use of irrigation is becoming a key issue in many arid regions including most areas of developing areas (Mubeen et al. 2016).

Irrigation scheduling has conventionally aimed to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity. Nevertheless, in recent years, there has been a wide range of proposed novel approaches to irrigation scheduling which have not yet been widely adopted; many of these are based on sensing the plant response to water deficits rather than sensing the soil moisture status directly (Erdem 2010). The choice of irrigation scheduling method depends to a large degree on the objectives of the irrigator and the irrigation system available. The more sophisticated scheduling methods generally require higher-precision application systems (Chebil and Frija 2016).

2.7.7 Advantages and Disadvantages of Various Irrigation Scheduling Approaches

2.7.7.1 Soil Water Measurement

(a) Soil water potential (densitometers, psychrometers, etc.)
  Easy to apply in practice.
  Can be quite precise.
  At least water content measures indicate "how much" water to apply.
  Many commercial systems available.
  Some sensors (especially capacitance and time domain sensors).
  Readily automated soil heterogeneity requires many sensors (often expensive) or extensive monitoring programmer (e.g., neutron probe).
  Selecting position that is representative of the root zone is difficult.
  Sensors do not generally measure water status at root surface (which depends on evaporative demand).
(b) Soil water content (gravimetric; capacitance/TDR; neutron probe).

2.7.7.2 Soil Water Balance Calculations

Require estimate of evaporation and rainfall.
Easy to apply in principle.
Indicate "how much" water to apply.
Not as accurate as direct measurement.
Need accurate local estimates of precipitation/runoff.
Evapotranspiration estimates require good estimates of crop coefficients (which depend on crop development, rooting depth, etc.).
Errors are cumulative, so regular recalibration is needed.

2.7.7.3 Plant "Stress" Sensing

Includes both water status measurement and plant response measurement.
Measures the plant stress response directly.
Integrates environmental effects.
Potentially very sensitive in general.
Does not indicate "how much" water to apply.
Calibration required to determine "control thresholds".
Still largely at research development stage and little used yet for routine agronomy (except for thermal sensing in some situations).

2.7.7.4 Tissue Water Status

It has often been argued that leaf water status is the most appropriate measure for many physiological processes (e.g., photosynthesis), but this argument is generally erroneous (as it ignores root-shoot signaling). All measures are subject to homeostatic regulation (especially leaf water status), therefore not sensitive (is hydric plants); sensitive to environmental conditions which can lead to short-term fluctuations greater than treatment differences (Jones 2004).

2.7.7.5 Visible Wilting

Easy to detect.

Not precise.

Yield reduction often occurs before visible symptoms.

Hard to automate.

2.7.7.6 Pressure Chamber

(w) Widely accepted reference technique

Most useful if estimating stem water potential (SWP), using either bagged leaves or suckers.

Slow and labor-intensive (therefore expensive, especially for predawn measurements).

Unsuitable for automation.

2.7.7.7 Psychomotor (W)

Valuable thermodynamically based measure of water status.

Can be automated.

Requires sophisticated equipment and high level of technical skill, yet still unreliable in the long term.

2.7.7.8 Tissue Water Content

RWC, leaf thickness [c- or b-ray thickness sensors], fruit or stem diameter.

Changes in tissue water content are easier to measure and automate than water potential measurements.

RWC more directly related to physiological function than is total water potential in many cases.

Commercial micromorphometric sensors available.

2.7.7.9 Pressure Probe

Can measure the pressure component of water potential which is the driving force for xylem flow and much cell function (e.g., growth).

Only suitable for experimental or laboratory systems.

2.7.7.10 Xylem Cavitation

Can be sensitive to increasing water stress.

Cavitation frequency depends on stress prehistory.

Cavitation water status curve shows hysteresis, with most cavitation's occurring during drying, so it cannot indicate successful rehydration (Gong et al. 2017).

2.7.7.11 Lining of Water Courses

The comparison of water losses between the unlined and lined watercourses indicates that for the tested unlined watercourses, water losses ranged from 64% to 68%. On the other hand, the lined watercourses showed water losses ranging from 35% to 52%. Comparing the average water loss of 66% from unlined to the average water loss of 43.5% from lined watercourses, it can be assessed that the lining

Table 2.3 Comparison of water losses between unlined and lined watercourses

	Average loss (%)		
Watercourse no.	Unlined	Lined	Average loss difference (%)
26680/R	68	–	
28000/R	64	–	
25373/R	–	52	
28915/R	–	35	
Average	66	43.5	22.5

Source: Rizwan (2018)

reduced water loss by 22.5% (Table 2.3). So, it is the need of the hour to line the community watercourses to increase the water use efficiency during irrigation to farmers' fields.

It is observed that different studies refer different percentage of losses from the watercourses. The reason for reporting different rates of water losses by various agencies was investigated, and the Committee found that water losses were defined differently by research workers (Arshad et al. 2009). The main sources of water losses especially in unlined watercourses have been categorized as follows:

- Seepage/infiltration.
- Evaporation.
- Vegetation (transpiration).
- Spillage.
- Rodent holes.
- Breaches/cuts.
- Dead storage.

2.8 Trickle Irrigation Systems

Trickle irrigation is a system where water and fertilizer are applied directly to individual plants, instead of irrigating the entire area with sprinkler and surface irrigation systems. With trickle irrigation, water may be provided to the crop on a low-tension, high-frequency basis, thereby creating a near-optimal soil moisture environment. Research indicates that water use efficiency can be increased by 50% or more by using trickle irrigation as compared with surface irrigation systems. The cost of trickle irrigation system is minimized when operated continuously during the critical demand period. Thus, these systems tend to favor conditions where available. Applications tend to be smaller than surface methods which not only minimize system capacity but also reduce the consequence of shallow or badly stratified soils (Mo et al. 2017; Liu et al. 2017).

2.8.1 Advantages

In addition to reduced irrigation water requirements and minimization of return flows, trickle irrigation has other positive advantages which are as follows:

- The portion of the soil with active roots needs to be irrigated, and soil evaporation losses can be reduced to a minimum. The low rate of water application reduces deep percolation losses.
- High temporal soil water level can be maintained with trickle systems. This results in a favorable response by most crops in increasing yield and quality.
- Trickle systems are generally permanent and have low labor requirements.
- Fertilizer can be applied through trickle irrigation systems using fertilizer injectors. Effective control of water results in control over fertilizer application. However, the small amount of water lost through deep percolation results in minimum loss of fertilizer through leaching.
- The wetted surface is only a fraction of the total soil surface. Consequently, there is a reduced potential for weed growth.
- The plant canopy is completely dry under trickle systems. It reduces fungus and other pests' incidence which depend upon a moist environment.

2.8.2 Disadvantages

There are a number of problems and disadvantages with trickle irrigation systems.

- The most important one is that the small flows through emitters require small openings that have historically been plagued by clogging. With the smaller emitter orifices, more filtering and biological controls are needed. Great advances have been made to rectify this problem, but it will always require the attention of the designer.
- Point or strip wetting is not always an advantage even though water savings and weed control are significant benefits.
- Salinity tends to accumulate a short distance from the emitter and can be transported into the root zone in case of heavy rainfall.
- The root zone tends to be smaller and more densely distributed. This can result in anchorage and aeration problems for some crops.
- Interestingly, some of the predatory insects breed in the weeds around a field, and some evidence has been reported that trickle irrigation may cause somewhat higher pesticide demand. In windy areas, the dry regions between emitters can yield dust problem (Yang et al. 2017).

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Carbon Dioxide Enrichment and Crop Productivity

3

Mukhtar Ahmed and Shakeel Ahmad

Abstract
Photorespiration (oxidative photosynthetic carbon cycle) is a process in which photosynthates burn down due to oxidative action of RUBISCO. This led to 25% reduction in photosynthetic output. However, e[CO_2] can inhibit this reaction resulting to the minimum loss of carbon also known as CO_2 fertilization.

Keywords
Carbon dioxide (CO_2) · Free-Air Carbon dioxide Enrichment (FACE) · Photorespiration · CO_2 fertilization

3.1 Introduction

Carbon dioxide (CO_2) is one of the important components of life on planet earth as it helps in the process of photosynthesis. Human activities in the form of deforestation, urbanization, industrialization, fossil fuel burning, and mechanization in agricultural practices resulted to the increased level of CO_2. Mauna Loa Observatory (MLO) which is a premier research facility at Hawaii, USA, monitors and collects data related to atmospheric changes in CO_2. The data in Fig. 3.1 shows that

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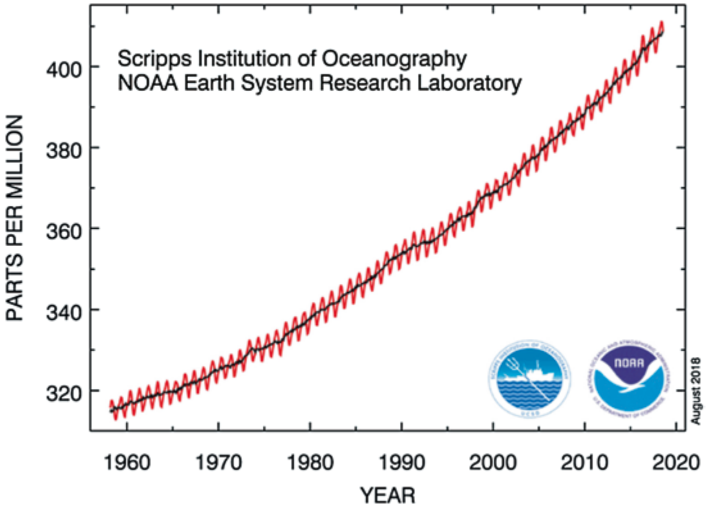

Fig. 3.1 Concentration of carbon dioxide (CO_2) from 1960 to 2020. (Source: Mauna Loa Observatory)

concentration of CO_2 is increasing at faster rate since after 1960. This situation is alarming for the world as CO_2 is main greenhouse gas. Forster et al. (2007) stated that elevated CO_2 is major driving factor of global warming and climate change. According to A1B emissions scenario of Intergovernmental Panel on Climate Change (IPCC) the carbon dioxide concentration (CO_2) might reach to 550 μLL^{-1} till 2050 (50% increase from 370 μLL^{-1} at the turn of century and 75% increase from 315 μLL^{-1} measured in 1960) (Carter et al. 2007). Such a big change in the substrate of photosynthesis and fundamental resource of plant life will have direct impacts on plant metabolism and ultimately on all agriculture and natural ecosystem (Tausz et al. 2013). Many studies have been conducted earlier in enclosure system, but after the advent of Free-Air Carbon dioxide Enrichment (FACE) technology, now elevated atmospheric [CO_2] (e[CO_2]) can be studied easily without constraints (Nösberger et al. 2006). Since managed ecosystem provide most of our food, wood, fiber, and source of renewable energy. Increased temperature and decreased soil moisture will lower the crop yield in future but that can be offset by e[CO_2] could be called as CO_2 fertilization. However, this impact will be different across the globe. FACE is a technique which can be used effectively to study the impact of e[CO_2] on crop parameters without altering the environment. FACE experiments have been effectively going on at Maricopa, Arizona, USA, since 1989. Ainsworth et al. (2008a, b) stated that FACE experiments provide good platform to do genetic screening and explain the genetic differences in crop productivity under e[CO_2]. They proposed new generation of large-scale, low-cost per unit area FACE experiments to identify CO_2-responsive genotypes which can be a starting line for future breeding program. In previous studies, it has been concluded that e[CO_2] could be easily capitalized by C3 crops by increasing photosynthesis rate, growth,

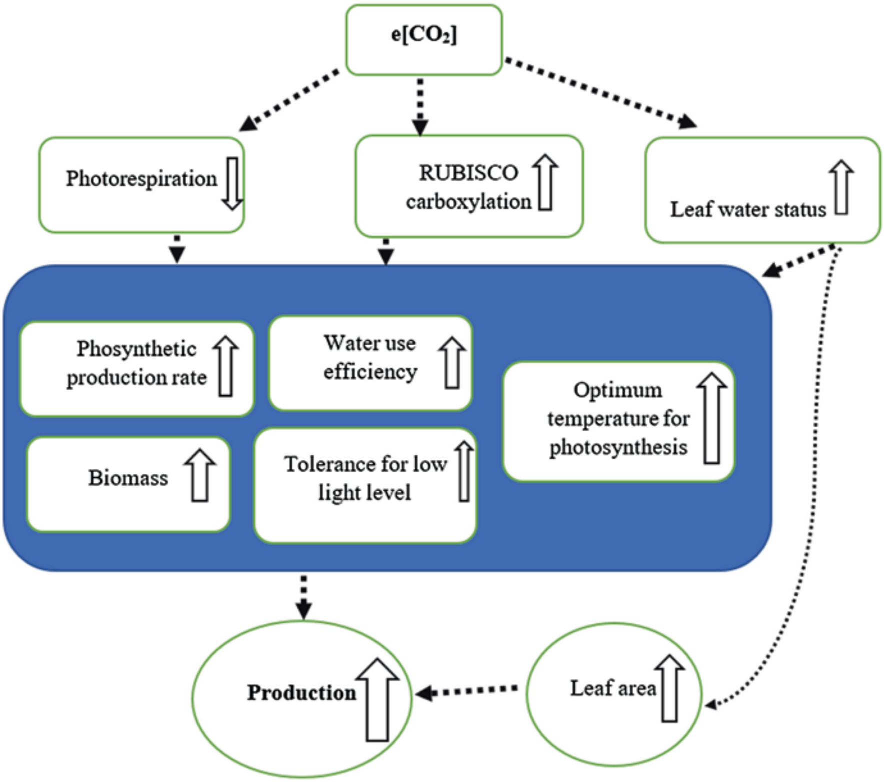

Fig. 3.2 Conceptual diagram of the direct initial effects of e[CO_2] on C3 crop production

and yield (Ainsworth and Long 2005; Long et al. 2006; Ainsworth and Rogers 2007; Ainsworth et al. 2008a, b; Leakey et al. 2009). Since e[CO_2] resulted to the increase rate of carboxylation at RuBisCO while inhibiting the oxygenation reaction. This resulted to the minimum loss of carbon due to photorespiration. Higher leaf water status and leaf area resulted to the maximum production (Fig. 3.2).

CO_2 fertilization effect is getting more attention as compared to secondary climate change factors (increasing temperatures or drought) as it is obvious that increase in CO_2 will continue to affect the planet (Ziska 2008). Therefore, to feed billions across the globe, positive effects of e[CO_2] should be harvested to offset the negative effect of drought and high temperature. Different agronomic and breeding efforts could be used to achieve this goal. Different crop traits need to be given attention through biotechnological means as they can optimize crop responses to e[CO_2]. The traits could be divided into two categories, vegetative growth traits (VGT) and regenerative growth traits (RGT). The VGT includes stress tolerance traits (thermal energy dissipation, antioxidant defense), nutrient use efficiency traits (nutrient (N,P) uptake, nutrient assimilation, stem nutrient storage), source traits (photosynthesis, RuBP regeneration, electron transport), and sink traits (tillering, root traits, stem carbohydrate storage). RGT includes stress tolerance traits (thermal energy dissipation and antioxidant defense traits in heads, nutrient use efficiency traits (nutrient (N,S) remobilization from leaf and stem and translocation, nutrient assimilation), source traits (photosynthetic traits in heads, remobilization of carbohydrates from stem and electron transport), and sink traits (seed numbers and seed weight potentials). Similarly, application of FACE facilities on major crop species needs time to have better future planning. Some of the FACE facilities are already going on soybeans (SoyFACE) (Rogers et al. 2006), rice (Rice FACE) (Okada et al. 2001), and wheat (AGFACE) (Mollah et al. 2009). These experiments have identified traits which potentially governs the growth and yield response under e[CO_2]. However, still they have to look for traits particularly for nutrient and water-use efficiency, stress tolerance, and grain quality.

IPCC (Intergovernmental Panel on Climate Change) projections reported continuous rise of CO_2 from 500 to 1000 ppm by the end of the century (IPCC 2007). This elevated level of CO_2 has direct effect on growth, physiology, and chemistry of plants. Photosynthesis which is heart of nutritional metabolism of plants has been directly affected due to elevated level of CO_2. However, ability of plants to responds to elevated level of CO_2 have interactions with mineral availability and it has been well documented in case of nitrogen (Ainsworth and Long 2005). Cure and Acock (1986) in their findings identified strengths and weakness for modeling plant responses to CO_2. They have collected published data of ten leading crops and studied response of net carbon exchange rate (NCER), net assimilation rate (NAR), biomass accumulation (BA), root-shoot ratio (RSR), harvest index (HI), conductance (C), transpiration rate (TR), and yield (Y) to elevated CO_2. There results depicted that doubling of CO_2 resulted to 52% increase in NCER and 41% increase in grain yield. However, TR decreased 23% on average. Similarly, it has been reported by Pandey et al. (2018) that hexaploid wheat is more responsive to e[CO_2] than tetraploid. Further details of overall crop responses to CO_2 doubling, CO_2 doubling and water stress interactions, CO_2 doubling and nutrient stress interactions, and CO_2 doubling and light interactions have been presented in Table 3.1.

3.2 Elevated CO_2 and Nutrients

Nutrient availability is linked with plant photosynthetic rates. CO_2 is the main substrate for carbon (C) assimilation in photoautotrophic organisms. Therefore, its higher concentration will significantly affect the nutrients availability and uptake by the plants. Nitrogen (N) is the nutrient required in largest quantities, and plant generally takes N as nitrate (NO_3^-) and ammonium (NH_4^+) form. Root N uptake affects plant productivity, but root N uptake to elevated CO_2 depends on N source (Cohen et al. 2018). Rhizosphere priming (RP) was used to enhance plant nitrogen uptake under elevated CO_2 and results showed that RP effects on soil organic matter (SOM) decomposition and N availability (Nie and Pendall 2016). Phosphorus (P) is a major macronutrient of plant. Mechanism of P-acquisition in C3 plants under changing climate needs to be studied to have crop adaptability to future climate change. Since P-reserves are declining, thus it might limit crop growth, while on the other hand

Table 3.1 Impact of elevated CO_2 on different crop parameters

Crop species	M	STCER	ACER	INAR	LTNAR	BA	RSR	HI	C	Tr	Y
Overall crop CO_2 doubling response to different plant parameters											
Wheat (*Triticum aestivum* L.)	C3	41	27	11	6	31	1.4	2.4	−22	−17	35
Barley (*Hordeum vulgare* L.)	C3	50	14	14	11	30	6.4	1.3	−52	−19	70
Rice (*Oryza sativa*)	C3	42	46	26	_-	27	−4	1.9	−33	−16	15
Corn (*Zea mays*)	C4	26	4	9	3	9	3.1	4.3	−37	−26	29
Sorghum (*Sorghum bicolor*)	C4	−3	6	–	20	9	−8.5	–	−27	−27	–
Soybean (*Glycine max* L.)	C3	78	42	35	23	39	1.1	−5	−31	−23	29
Alfalfa (*Medicago sativa* L.)	C3	139	–	–	–	57	−5	–	–	–	–
Cotton (*Solanum hirsutum* L.)	C3	60	13	-_	40	84	3.2	-_	−15	−18	209
Potato (*Solanum tuberosum* L.)	C3	105	–	–	54	−15	−2.1	1.9	−59	−51	51
Sweet potato (*Ipomoea batatas*)	C3	–	–	–	11	59	34.9	–	–	–	83
CO_2 doubling and water stress interactions											
Wheat (*Triticum aestivum* L.)	C3	–	–	–	–	35	−4.1	2.8	–	–	25
Barley (*Hordeum vulgare* L.)	C3	–	–	–	–	107	1	–	–	–	–
Rice (*Oryza sativa*)	C3	–	–	–	–	51	−3	–	–	–	–
Corn (*Zea mays*)	C4	–	–	–	–	0	−26	–	–	–	–
Sorghum (*Sorghum bicolor*)	C4	–	–	–	–	26	−8	–	–	–	–
Soybean (*Glycine max* L.)	C3	–	65	–	–	–	–	1.6	−23	−14	60
Alfalfa (*Medicago sativa* L.)	C3	–	–	–	–	130	2	–	–	–	–
Cotton (*Gossypium hirsutum* L)	C3	–	–	–	–	0	10	-_	–	–	–
Potato (*Solanum tuberosum* L.)	C3	–	–	–	–	–	–	–	–	–	–
Sweet potato (*Ipomoea batatas*)	C3	–	–	–	–	–	–	–	–	–	–
CO_2 doubling and nutrient stress interactions											
Wheat (*Triticum aestivum* L.)	C3	–	–	–	25	39	1	2.7	–	–	–
Barley (*Hordeum vulgare* L.)	C3	–	–	–	–	–	–	–	–	–	–

(continued)

Table 3.1 (continued)

Crop species	M	STCER	ACER	INAR	LTNAR	BA	RSR	HI	C	Tr	Y
Rice (*Oryza sativa* L.)	C3	–	–	–	–	32	–	–	–	–	_-
Corn (*Zea mays* L.)	C4	–	32	5	–	14	−1.9	–	–	–	–
Sorghum (*Sorghum bicolor* L.)	C4	–	–	–	–	–	–	–	–	–	-_
Soyabean (*Glycine max* L.)	C3	–	39	35	19	52	−0.3	−5.1	−37	–	–
Alfalfa (*Medicago sativa* L.)	C3	-_	–	–	–	13	−9.6	–	–	–	–
Cotton (*Gossypium hirsutum* L.)	C3	76	35	-_	–	146	–	–	–	–	–
Potato (*Solanum tuberosum* L.)	C3	_-	–	–	–	–	–	–	–	–	–
Sweer potato (*Ipomea batatas*)	C3	_-	–	–	–	–	–	–	–	–	–
CO_2 doubling and light interaction											
Wheat (*Triticum aestivum* L.)	C3	37	–	–	–	15	–	–	–	–	–
Barley (*Hordeum vulgare* L.)	C3	_-	11	9	7	20	–	–	–	–	–
Rice (*Oryza sativa*)	C3	–	–	39	_	28	–	–	–	–	–
Corn (*Zea mays*)	C4	21	–	8	−3	16	2	–	–	–	–
Sorghum (*Sorghum bicolor*)	C4	-_	–	–	–	–	–	–	–	–	–
Soybean (*Glycine max* L.)	C3	52	84	23	–	44	−2	–	–	–	–
Alfalfa (*Medicago sativa* L.)	C3	_-	–	–	–	–	–	–	–	–	–
Cotton (*Gossypium hirsutum* L.)	C3	67	–	–	–	–	–	–	–	–	–
Potato (*Solanum tuberosum* L.)	C3	–	–	–	–	–	–	–	–	–	–
Sweet potato (*Ipomoea batatas*)	C3	_	_	_	_	_	_	_	_	_	_

Where *M* Metabolism, *STCER* short-term carbon exchange rate, *ACER* acclimatized carbon exchange rate, *INAR* initial net assimilation rate, *LTNAR* long-term net assimilation rate, *BA* biomass accumulation, *RSR* root-shoot ratio, *HI* harvest index, *C* conductance transpiration rate, *Y* yield

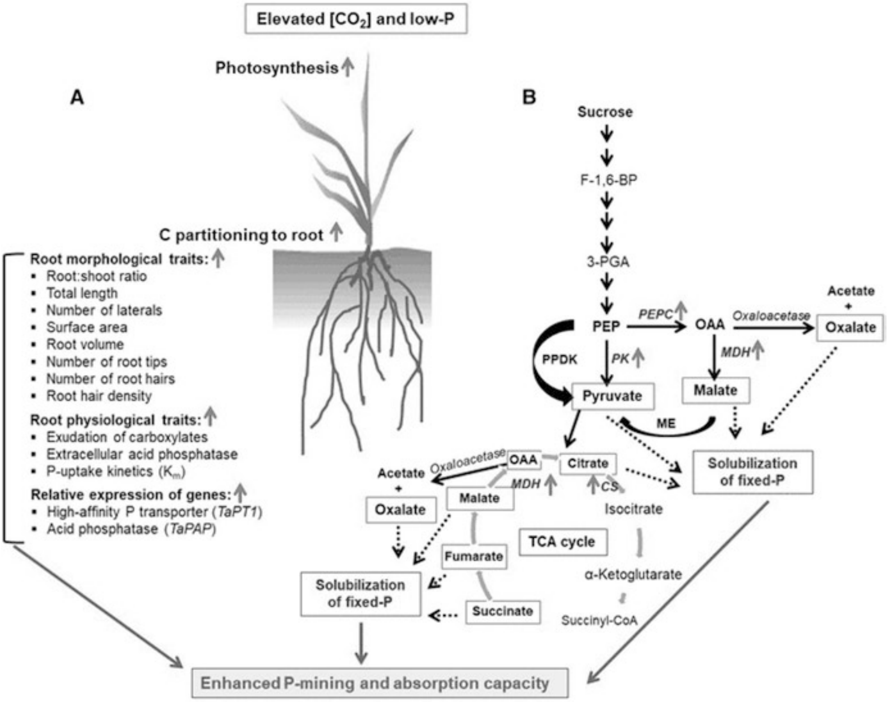

Fig. 3.3 Proposed P-model under elevated CO_2. (Source: Pandey et al. 2018)

elevated CO_2 increases growth rates by altering physiological processes. Norby et al. (2010) reported that growth stimulation under elevated CO_2 depends on the availability of nutrients and water. Interactive effect of P and e[CO_2] were studied on different plant processes. Results showed that e[CO_2] resulted to increased root biomass, volume, and surface area. e[CO_2] might also influence exudation of C compounds in the rhizosphere which is good adaptation strategy to coup with P deficiency (Krishnapriya and Pandey 2016). Model for e[CO_2] facilitated by P-mining and absorption by plants under P starvation was proposed by Pandey et al. (2018). Model depicted that e[CO_2] resulted to increased photosynthesis, high C partitioning to root, and improved root traits. This further increase extracellular acid phosphatase activity and P-absorption due to expression of phosphatase enzymes. The model also proposed bypass reaction under P starvation (Fig. 3.3).

3.3 Elevated CO_2 and Soil Microbiome

Significant effect of elevated CO_2 has been reported on soil mycorrhizae. Terrestrial ecosystems (type of ecosystem found only on biomes also known as beds) have connection with CO_2 through photosynthetic fixation of CO_2, C-sequestration, and release of CO_2 through respiration and decomposition. Previous studies depicted impact of CO_2 enrichment on terrestrial ecosystems in the form of organic C dynamics. Since majority of life in soil is heterotrophic and dependent on photosynthesis (plant-derived organic carbon), therefore, activity and functioning of soil organism have strong association with elevated CO_2. Studies showed that main effect of elevated CO_2 on soil microbiota is through plant metabolism and root secretion. Figure 3.4 illustrates that increased photosynthetic C-allocation due to elevated CO_2 is directed to mycorrhizae and root tissue. Mycorrhizae then translocate C into the soil microbial community (bacteria and fungi) which resulted to the change in the

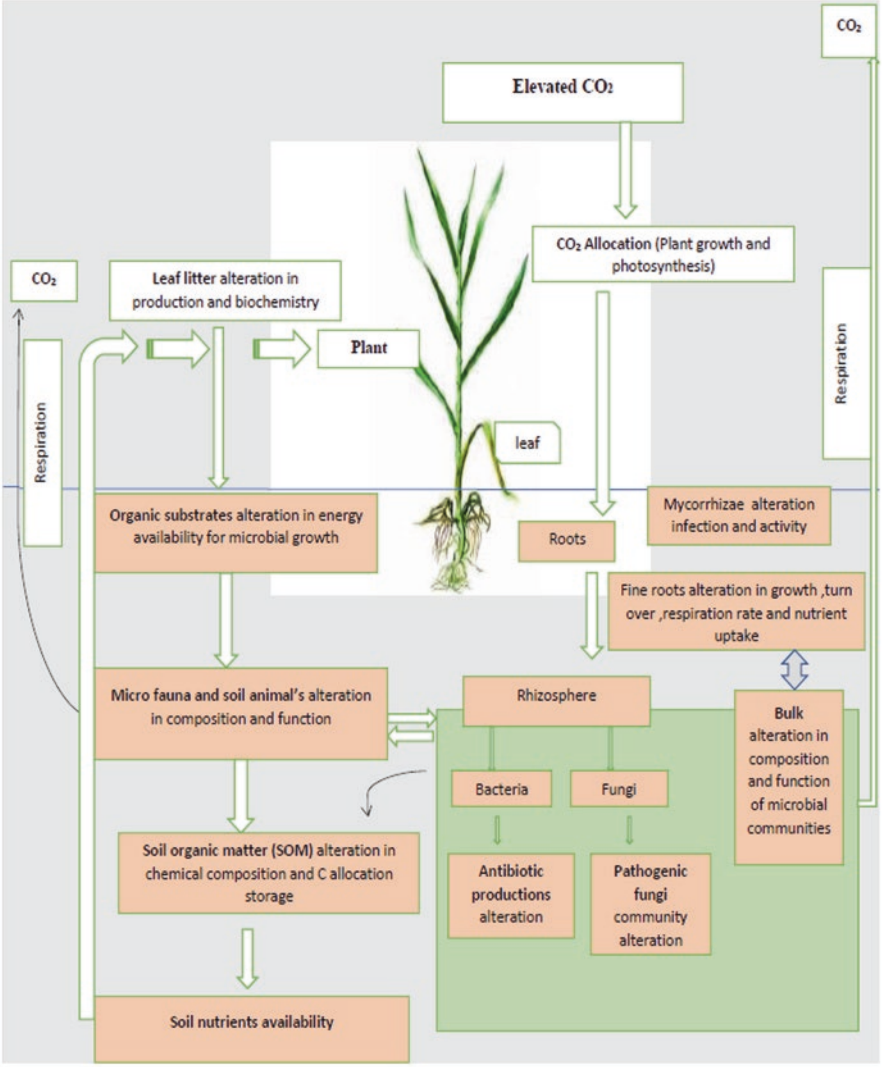

Fig. 3.4 Effects of elevated atmospheric CO_2 on microbial community

structure, size, and activity of the community. It further mediates ecosystem feedbacks that regulate the cycling of C and N (Phillips et al. 2006; Drigo et al. 2008; Nguyen et al. 2011; Xiong et al. 2015; Calvo et al. 2017). Sulieman et al. (2015) reviewed the benefits of elevated CO_2 on N_2-fixing leguminous symbioses. They concluded on the basis of previous results that elevated CO_2 have beneficial effect on symbiotic legumes. The effect will be on leaves, root, nodules, and rhizosphere as shown in Fig. 3.5. e[CO_2] affect soil nitrogen (N) cycling by altering N-losses from terrestrial ecosystems. Soil organic matter dynamics were also affected by elevated CO_2. Nevada Desert Free-Air Carbon dioxide Enrichment (FACE) Facility (NDFF) reported greater ecosystem C and N concentrations as it was exposed to elevate CO_2 for 10 years (Tfaily et al. 2018).

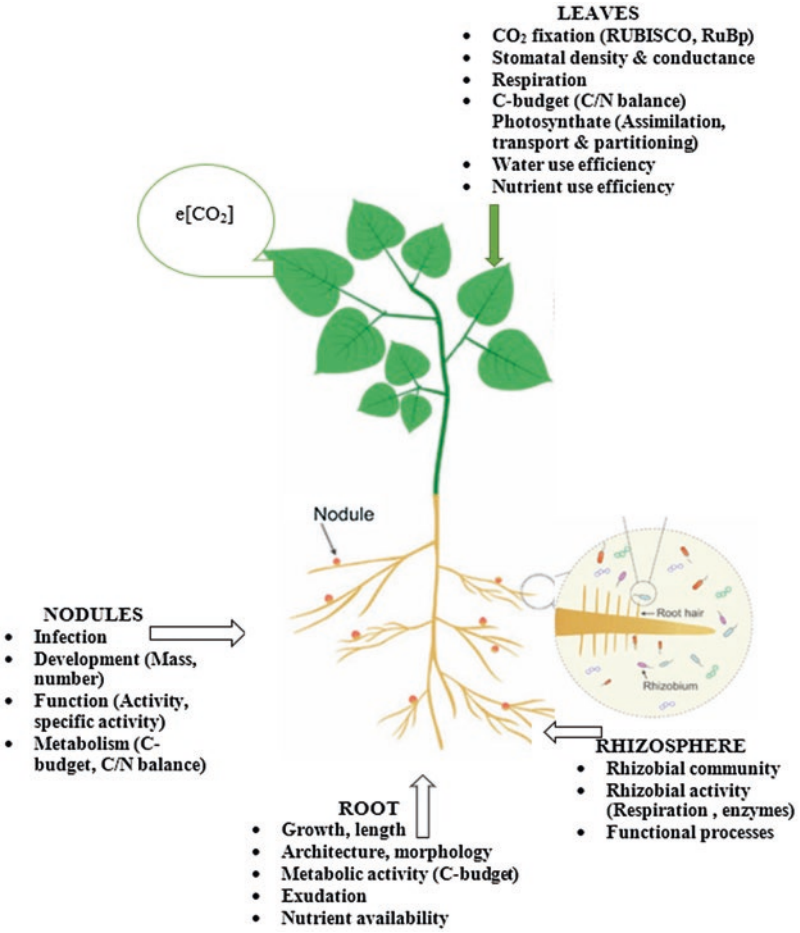

Fig. 3.5 Elevated carbon dioxide concentration and different morphological, physiological, and biochemical parameters in legume crop

3.4 e[CO_2] and Plant Enzymes

The effect of e[CO_2] has been also seen at enzymatic level. The enzyme used in C_3 pathway is ribulose 1,5-bisphosphate carboxylase/oxygenase (RuBisCO) which is capable of performing two distinct reactions; one leads to formation of two molecules of PGA provided that CO_2 is the substrate, while the other leads to one molecule of PGA and phosphoglycolate provided O_2 is the substrate. When CO_2 is deficient, RuBP performs oxygenase reaction resulting in less CO_2 fixation and release of CO_2 in process called photorespiration. The photosynthetic activity of C3 plants decreases considerably with decrease in CO_2 because of RuBisCO sensitivity to O_2, whereas it increases under elevated CO_2 levels since RuBisCO gets saturated with CO_2 and is forced to perform carboxylation (Ainsworth and Rogers 2007). RuBisCO of C4 plants is almost 12–20 times greater than that for C3 plants. Information from IPCC suggests that CO_2 concentration will change from 6.3 to 15 mM at active site of RuBisCO of C_3 plants by the end of the century. This scenario will result in an increase in C3 photosynthesis because of increase in the rate of carboxylation reaction as RuBisCO will get substrate saturated at elevated CO_2 levels. Moreover, oxygenation reaction of RuBisCO will be inhibited reducing CO_2 loss (Long et al. 2004). To study the effect of elevated CO_2 on C3 plants photosynthesis and stomatal conductance, usually FACE experiments are used. FACE experiments help to simulate the impact of future elevated CO_2 levels by providing more realistic conditions (Ainsworth et al. 2006). Guard cells sense CO_2 because of their inherent property as they are more responsive to intercellular CO_2 as compared to CO_2 at leaf surface. Assmann (1999) reported that if the membrane potential of guard cells is made less negative or in other words is depolarized, it will result in stomatal closure. The activity of inward rectifying K+ channels is decreased under increased CO_2 levels, whereas the activity of outward rectifying K+ channels increases as observed through electrophysiological studies. The greater the depolarization of membrane potential of guard cells, the greater will be the reduction in stomatal aperture. It is yet not clear as controversies still continue whether or not photosynthetic metabolites and processes have an effect on the response of guard cells to elevated CO_2 levels. Calcium sensitive and insensitive phases may also be used as response mechanism by guard cells against elevated CO_2 levels. Zheng et al. found that long-term exposure to elevated CO_2 levels resulted in reduced stomatal conductance in soybean. They reported that reduced rate of transpiration as a result of decreased stomatal conductance (gs) was partially responsible for poor N translocation. Furthermore, CO_2-induced downregulation of leaf photosynthesis was observed by the consistently declined leaf net photosynthetic rate (An) with elevated CO_2 concentrations. This could also be due to dramatic decrease in carboxylation rate (Vcmax) and the maximum electron transport rate (Jmax). Moreover, leaf photosynthesis downregulation was also partially attributed with reduced gs due to number of features such as declined stomatal density and stomatal area and changes in the spatial patterns of stomata. Since stomatal conductance is controlled by the integration of environmental and endogenous signals, Habermann et al. (2019)

studied the combined effect of e[CO_2] and +2oC warming on stomatal properties. Their results showed that under alone effect of elevated CO_2, transpiration rate was reduced with increased leaf temperature and maintenance of soil moisture which was due to reduced stomatal density, stomatal index, and stomatal conductance (gs). However, warming alone resulted to the enhanced PSII photochemistry and photosynthesis. The combined effect of warming and elevated CO_2 revealed that leaf temperature was increased compared to alone effects. This showed that stomatal opening under elevated CO_2 was not changed by warmer environment but in combination (e[CO_2] x warming) can significantly improve the whole plant functioning. Zheng et al. (2019) reported that elevated CO_2 concentrations exceeding the optimal not only reduced the stomatal conductance but also changed the spatial distribution pattern of stomata on leaves. It was observed that the maximum photosynthetic efficiency was 4.6% for C3 photosynthesis but 6% for C4 photosynthesis. This advantage over C3 will expire as atmospheric [CO_2] reaches 700 ppm. There is 60% increase in maximum photosynthetic efficiency in C4 plants compared to C3 plants. The C4 plants can photosynthesize with ~50% greater water-use efficiency, as C4 photosynthesis has the potential to assimilate an equal amount of CO_2 with only half the stomatal conductance.

3.5 e[CO_2] and Nutritional Quality

Elevated CO_2 have significant impact on nutritional quality of crop. Dong et al. (2018) reported that e[CO_2] resulted to the increased concentration of carbohydrates (glucose (13.2%), fructose (14.2%), total soluble sugar (17.5%)), total antioxidant capacity (59.0%), phenols (8.9%), flavonoids (45.5%), ascorbic acid (9.5%), and calcium (Ca) (8.2%). However, decreased concentration of protein (9.5%), nitrate (NO_3^{-1}) (18.0%), magnesium (Mg) (9.2%), iron (Fe) (16.0%), and Zn (9.4%) have been observed (Fig. 3.6). The increased concentration of sugars and decreased N content have been observed due to elevated CO_2 in different studies (Webber et al. 1994; Sun et al. 2012). Guo et al. (2015) work on rice revealed that elevated CO_2 increases the contents of Ca (61.2%), Mg (28.9%), Fe (87.0%), Zn (36.7%), and Mn (66.0%) in panicle. However, in stem Ca, Mg, Fe, Zn, and Mn were increased by 13.2, 21.3, 47.2, 91.8, and 25.2%, respectively. Similarly, they concluded that elevated CO_2 had positive effects on the weight ratio of mineral/biomass in stem and panicle. Grain quality of rice genotypes was investigated by Jena et al. (2018) and they reported that elevated CO_2 resulted to higher yield but lower nutrient harvest index and use efficiency values. Reduction in grain protein (2–3%) and Fe (5–6%) was observed in their findings under elevated CO_2. Analysis on dietary intake of iron, zinc, and protein under elevated CO_2 concentrations revealed that future human population will be zinc and protein deficient. Therefore there would be more chances of anemia prevalence. This risk will be more in South and Southeast Asia, Africa, and the Middle East (Smith and Myers 2018).

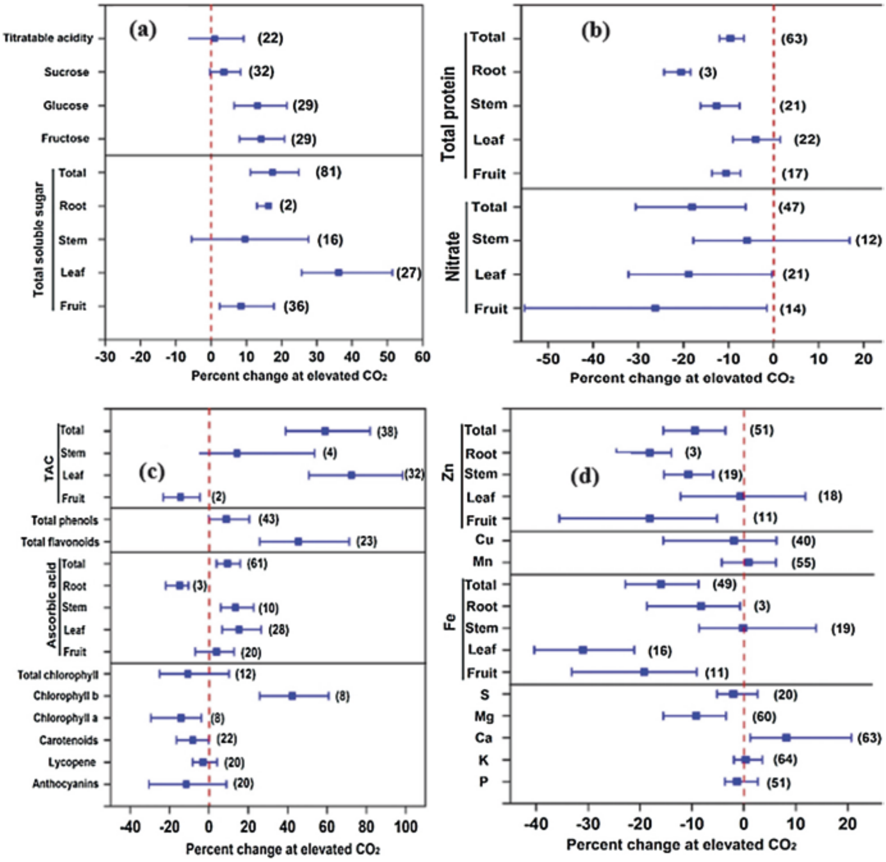

Fig. 3.6 Effect of e[CO_2] on (**a**) carbohydrates and acidity, (**b**) total protein and nitrate (NO_3^{-1}), (**c**) antioxidants, and (**d**) minerals in plants. (Source: Dong et al. 2018)

3.6 e[CO_2] and Modeling

In today's world models are the useful tools to study the impact of climate change on crop production and food security. Mechanistic eco-physiological models are being increasingly used for climate change impact on crop production (Tubiello and Ewert 2002). There is great emphasis on improvement of crop models so that climate change impact on crop production could be worked out. At first the crop models were being used for study of climate change impact on a small field. Far ahead efforts were made to evaluate the impact of climate variation on larger areas such as nations and large watersheds (Rosenzweig 1985; Hoogenboom et al. 1995; Parry et al. 2004; Rosenzweig and Tubiello 2007; Rosenzweig et al. 2013; Ruane et al. 2013). The CROPGRO model was used to stimulate the impact of increased CO_2 concentration on maize and to predict the climate change impact on maize production in the future (2080–2100). Model showed that yield of the crop reduced due to rise in temperature, but it increases at the same time due to enhanced CO_2 concentration and precipitation thus causing the counter balance. Change in CO_2 concentration greatly effects the plant growth and development, and this has been demonstrated by different scientists (Tubiello et al. 2007). The APSIM-Wheat model was used for studying the effect of elevated CO_2 on crop growth. Meanwhile, multimodel ensemble approach could be used to study the sole effect of elevated CO_2 (Ahmed et al. 2019). O'Leary and his co-workers have also used APSIM to study the impact of elevated CO_2 on crop growth and its interaction with RUE and TE (Anwar et al. 2007; O'Leary et al. 2015). This equation shows the light limited photosynthetic response to CO_2 concentration at 350 micro mol per mole.

$$\phi P = \frac{\left(CO_2 - T\right)\left(350 + 2T\right)}{\left(CO_2 + 2T\right)\left(350 - T\right)}$$

T temperature dependent CO_2 compensation point is given by

$$TE = \frac{\left(163 - T\right)}{\left(5 - 0.1T\right).}$$

The experiment showed that under elevated CO_2 the transpiration efficiency (TE) increases. The APSIM-Wheat model showed 21% increase in wheat biomass in response to elevated CO_2.

3.7 e[CO_2] and Breeding Traits

Breeder in the future should focus on traits like plant architecture, branching geometry, root architecture, and stay-green traits to harvest the impact of elevated CO_2. Thus, to improve water-use efficiency (WUE) knowledge of genes should be utilized and a consolidated good implementing functional characterization of promising QTLs, high-throughput phenotyping, field validation of traits, improvements in photosynthetic efficiency and WUE by introducing C4-like characteristics in C3 cells, pyramiding and stacking of these traits into WUE coupled with modeling, providing important information for trait base selection-like root architecture model, water transport model and soil water model for improving crop water management under elevating atmospheric CO concentrations should be done.

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Soil Management for Better Crop Production and Sustainable Agriculture

4

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Abstract

Sustainable agriculture is of prime importance in the present conditions of rapidly increasing human population and decreasing cultivable land resources. Since soil is a natural medium for the growth of plants, a better soil health is considered as an important indicator to produce quality food. Soil quality is greatly affected by the presence of soluble salts, heavy metals and toxic compounds. In addition, soil loss by erosion, compaction, waterlogging, toxicity or deficiency of certain mineral elements and poor tillage practices lessens the area for crop production. Therefore, conservation and management of soil is crucial to augment crop production and ensure world's food requirement. Efforts have been done to summarize all the soil problems which degrade soil quality and thus

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suggesting control measures and modern approaches of soil management for sustainable agriculture.

Keywords
Soil health · Soil loss · Soil conservation · Sustainable agriculture

4.1 Introduction

Soil is defined as the unconsolidated upper part of the earth's crust that serves as natural medium for the growth of land plants. Soil provides mechanical support to the plants, space for root growth and development and an environment conducive for the respiration of living organisms in soil. It also serves as a reservoir of nutrients and water for plants growth. Soil resources are finite, fragile and susceptible to degradation owing to poor soil management and vulnerable to unforeseen climate changes (Kasel and Bennett 2007; Miao et al. 2011). According to an estimate 3500 M ha lands are prone to degradation processes (Fig. 4.1) which affect badly a large proportion of deprived people in these areas (Bai et al. 2008). Food production must be considerably increased to feed increasing population of 10 billion (Borlaug and Dowswell 2005). Therefore, productivity per unit area must be increased by adopting best management practices to bridge yield gap and avoid future land degradation (Lal et al. 2012). High yield gaps have been reported for various crops in different regions (Abeledo et al. 2008; Fischer et al. 2009; Mueller and Schindler

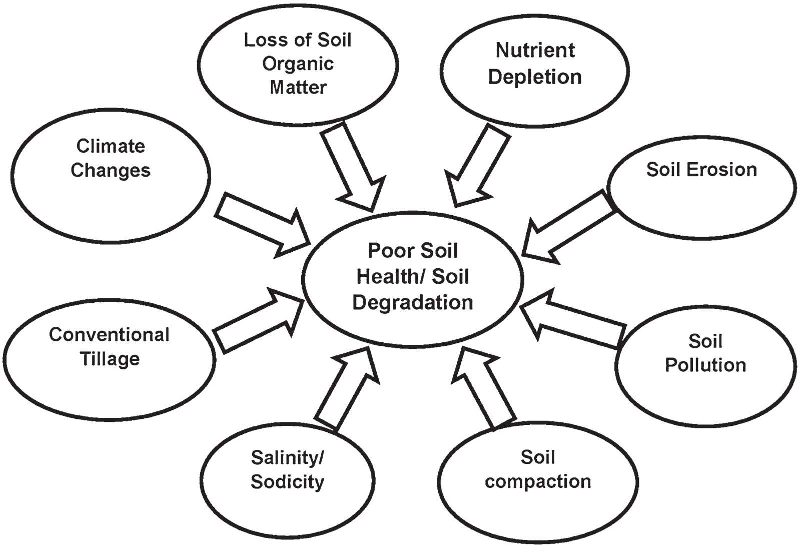


Fig. 4.1 Schematic diagram exhibiting soil loss or soil degradation

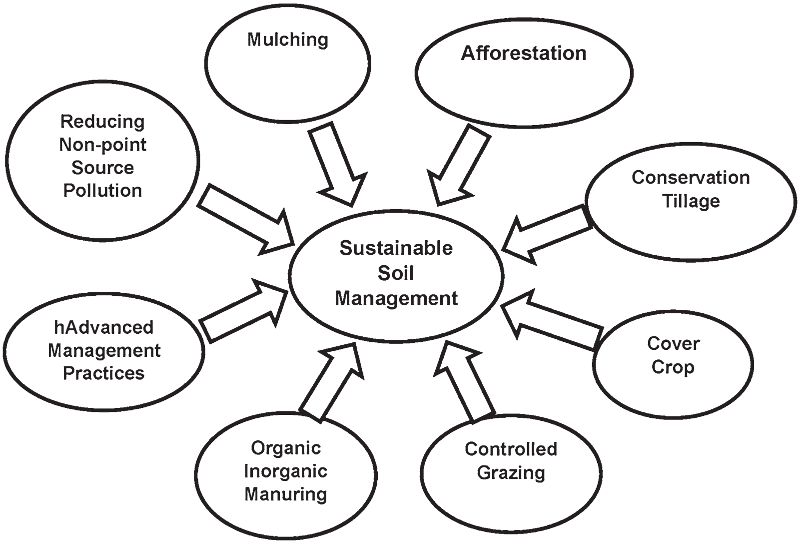


Fig. 4.2 Schematic diagram of control measures or soil management for sustainable agriculture

Mirschel 2010; Rockström and Falkenmark 2000), and soil degradation is a serious threat especially in underdeveloped countries where population pressure is increasing with every passing day (Bai et al. 2008). The basic causes for land degradation in different regions are numerous, interlinked and more or less the same in different agroecological zones such as development salinization, alkalization, compaction, erosion, loss of organic matter, depletion of soil fertility and loss of biodiversity (FAO 1999).

Therefore, concerted efforts are imperative to restore productivity of the degraded lands. Appropriate soil management and conservation technique must be adopted to restore the soil quality and productivity for sustainable agriculture to feed the current and coming generations. In this section, major soil problems are summarized, which degrade soil quality (Fig. 4.1) and sustainability. Furthermore, appropriate suggestions are made to control soil degradation and increase its productivity by adopting modern approaches (Fig. 4.2).

4.2 Soil Erosion

Soil erosion is the removal and translocation of upper layer of soil by the action of wind or water. It can also be categorized into geological or accelerated processes depending on the active force/agent/factor of the process. Normally, soil is eroded through regular geological processes involved in soil formation but at slow pace, whereas accelerated processes include human activities like stubble burning, deforestation, overgrazing, intensive cultivation and ploughing. It is well known that upper layer of the soil is often exposed to agricultural practices and contribute to crop production and food security. Hence, loss of upper layer(s) of soil results in nutrient losses by exposing the subsoil and pronouncing desertification. Since soil is a non-renewable resource (Lal 2001), it may take 3000–12,000 years to develop an agricultural productive land. Surprisingly, 5–7 M ha of world's arable lands are being converted into non-agricultural lands annually due to soil erosion that poses a huge threat to the food security. In Pakistan, approximately 11 M ha of land is affected by water erosion, whereas 3–5 M ha land is affected by wind erosion. There are two types of erosion, i.e. water and wind erosion, which are discussed below along with the erosion conservation practices.

4.2.1 Water Erosion

Detachment and movement of soil with water is called water erosion. Factors like rain water splashing, runoff, irrigation and melting of snow contribute to water erosion. Rainfall detaches soil particles due to splashing of high-speed raindrop on soil surface and disperses soil particles. Organic and inorganic particles of dispersed/detached soils are transported through water to lowland areas and are deposited as sediments in reservoirs, water channels and bare lands (Blanco and Lal 2008). Water erosion has several different types which are discussed below:

4.2.1.1 Types

4.2.1.1.1 Splash/Raindrop Erosion

Raindrops of different sizes and shapes when drop on soil surface after gaining acceleration due to force of gravity and produce soil splashing. A droplet of 5 mm size falls on the earth surface at the speed of 20 mph, whereas a drizzle drops (<0.5 mm) strikes the surface at 4.5 mph (Fig. 4.3). High-speed rain droplets hit the ground surface causing compaction and splashing of soil particles (Blanco and Lal 2008).

4.2.1.1.2 Inter-Rill/Sheet Erosion

After splashing of raindrops, detached soil particles move with water in a shallow flow forming small runoff rills. The movement of soil in rills continues till a thin sheet of whole field surface is removed. This process is called inter-rill/sheet erosion which is steady and not apparent or visible to detect with the naked eye.

4.2.1.1.3 Rill/Channel Erosion

Soil erosion in small channels/rills is called rill/channel erosion; however, it is due to rigorous operation as compared to shallow flow. The small channels are widened due to creeping soil particles and their flowing velocity (Fig. 4.4). The channels formed in this type of erosion are manageable though tillage operations.

4.2.1.1.4 Gully Erosion

In this type of erosion, channels of about 1 ft. depth and 1 ft. width are formed in V or U shape. These gullies cause concentrated runoff down the slope and remove

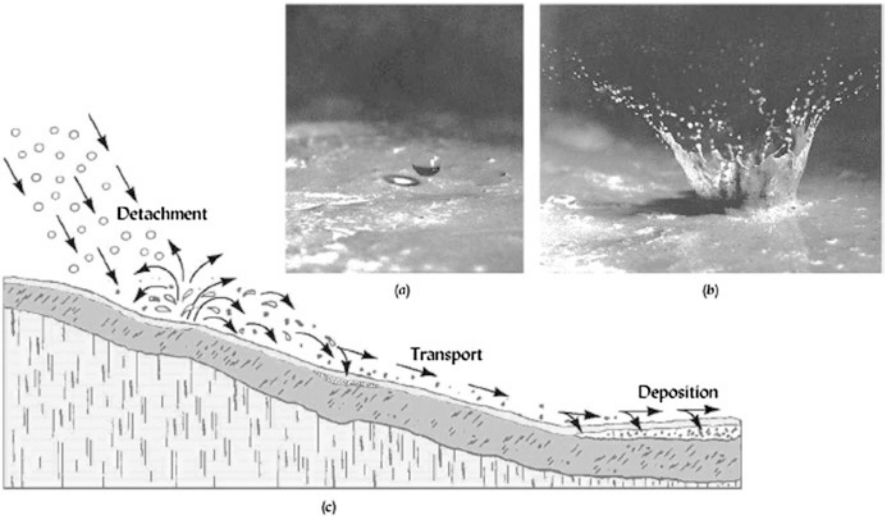


Fig. 4.3 Sketch explaining the water erosion; (**a**) raindrop falling on the surface, (**b**) splash impact of raindrop and (**c**) process of water erosion. (Adapted and modified from Stitcher 2010)

larger layers of soil profile. Usually occurs in uneven fields where increase in soil load for erosion increases the size of gullies. Some gullies are transient and some are permanent which can be managed by simple and intensive tillage practices, respectively.

4.2.1.1.5 Tunnel Erosion

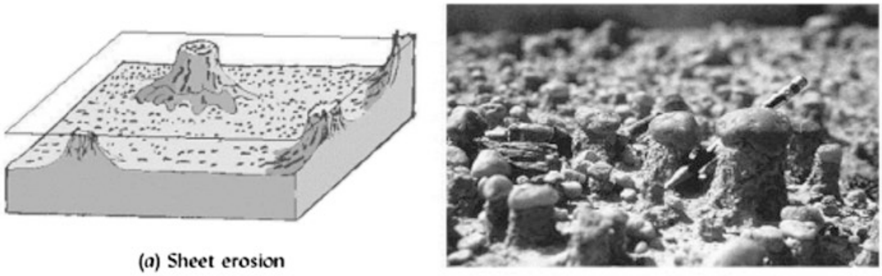
In arid to semiarid regions, tunnels of erosion are prominent due to highly degradable sodic B horizon and stable A horizon. Tunnels are usually formed due to the activities of burrowing animals in subsoil. The water moves in these tunnels moving the soil along. Tunnel erosion may affect the geomorphological and hydrological characteristics of the affected area. However, the impact of tunnel erosion can be reduced through deep slitting and repacking of soil, growing of deep-rooted trees/ grasses and diversion of drainage water to avoid pond's formation.

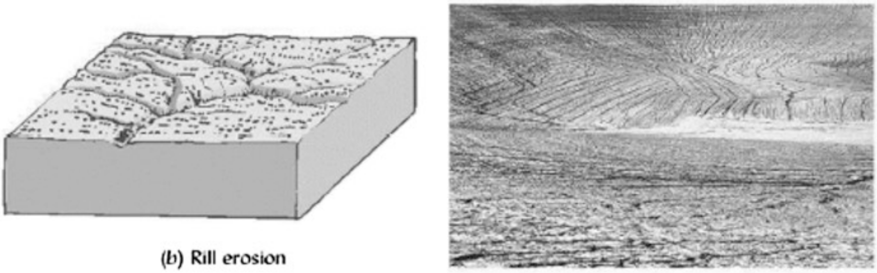
4.2.1.1.6 Stream Bank Erosion

Water erosion along the banks of rivers, streams, creeks and canals occurs due to the erosive power of water. Usually the soil erodes through vertical cracks in stream banks. However, stream bank erosion can be reduced through tree plantation, deep-rooted grasses, mulching stream borders and fencing (Blanco and Lal 2008).

4.2.2 Wind Erosion

Soils in the region of dry climate (very low rainfall) and high temperatures allow the carriage and transport of dispersed soil particles through wind to distant areas. This


(a) Sheet erosion


(b) Rill erosion

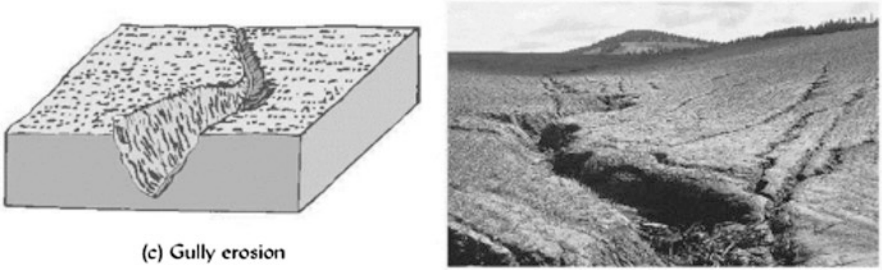

(c) Gully erosion

Fig. 4.4 Water erosion types: (**a**) sheet erosion, (**b**) rill erosion and (**c**) gully erosion. (Adapted and modified from Kilders 2015)

type of removal of soil layer by wind is called wind erosion. Soil particles floating with winds are probably of silt size, therefore, the deposits of wind eroded soil is called loess. Depth of loess deposits may range from 20 to 30 m.

Different factors might be responsible for aiding the problem of wind erosion such as trampling of soil surface by the hooves of grazing animals, fallowing of land, deforestation, excessive tillage practices and the wind speed. The rate of wind erosion varies in different climatic regions of the world which can be ordered as arid > semiarid > dry subhumid areas > humid areas, respectively. Wind, transport soil particles hence may contaminate more air and water as compared to water erosion (Blanco and Lal 2008). Wind erosion could be of different types according to the size and movement of the eroded soil particles.

4.2.2.1 Types of Wind Erosion

4.2.2.1.1 Suspension

Soil particles of size less than 0.1 mm are suspended and transported to very distant (>100 miles) regions. These soil particles settle on the ground if wind stops or obstacle or precipitation bring it down.

4.2.2.1.2 Saltation

While lodging the suspended soil particles of size 0.1–0.5 mm bounce on the ground surface till reach stationary state. Usually, 30 cm soil layer (top layer) is comprised of these particles.

4.2.2.1.3 Soil/Surface Creeping

Soil particles of the size 0.5–1 mm roll on the ground surface due to wind or move due to strike with saltating soil particles. It accounts about 5–25% erosion by wind.

4.2.3 Factors Affecting Soil Erosion

Different factors are involved in soil erosion which include:

(i) Slope: it is a foremost aspect controlling the rate of soil erosion process, steepness and length of slope determines the intensity of soil erosion.
(ii) Poor soil structure: aggregation of soil particles in a specified formation is disturbed by tillage and cultivation practices and causes soil compaction; soil structure determines the shape, size and distribution of pore spaces.
(iii) Low organic matter: OM serves as a binding agent of soil particles and make aggregates to stabilize against abrasive forces causing erosion.
(iv) Vegetation *cover*: it improves the standing of soil on its place, removal of vegetation soil cover through intensive cultivation or overgrazing cause soil erosion.
(v) Land use: type of activity performed on the land determines the fate of soil erosion; usually grasses and other crops reduce the soil erosion but mostly fallow lands experience intense erosion problem.

4.2.4 Soil Conservation Practices

Several conservation practices are adopted to take care of soil from wind and water erosion such as:

(i) Crop rotations: consecutive cultivation of different crops to avoid fallowing of soil.
(ii) Agroforestry: growing of new forests or orchids and trees for wood.

(iii) Soil synthetic conditioners: application of soil amendments or polymers to increase soil aggregation.
(iv) Reduced/zero tillage: least disturbance of soil for crop production.
(v) Riparian buffers: covering of stream banks with trees, shrubs and grasses to stabilize soil and to avoid soil erosion.
(vi) Cover crops: crops grown in fields to cover the soil and save it from erosion.
(vii) Vegetative filter strips: these are natural or established vegetative buffers besides a water body to filter the drainage water or increase water permeation in soil and filter the sediments and contribute in recharge of groundwater.
(viii) Crop residue: leaving crop residues intact in soil to hold the soil aggregates through root crown.
(ix) Canopy cover management: covering the soil through crown or canopy of trees which saves the soil from wind and splashing from raindrops.
(x) Contouring: growing of plants across the slope which could reduce about 50% erosion losses.
(xi) Mulching: covering top soil by application of surface litter or plastic to reduce water and CO_2 losses and thus enhancing soil carbon pools; if managed properly it can considerably improve soil productivity.

4.3 Soil Fertility

It refers to the ability of a soil to support plant growth, providing essential nutrients imperative to obtain high-quality and consistent yields (FAO 2016). Fertile soils have:

(i) Topsoil with ample soil organic matter.
(ii) Devoid of toxic substances that inhibit healthy plant growth.
(iii) Sufficient water retention.
(iv) Excellent internal drainage for optimal aeration and root growth.
(v) Supply adequate amounts and proportions of essential nutrients in plant available form.
(vi) Soil pH in the range 5.5 to 7.0 (suitable for most plants but some prefer or tolerate more acidic or alkaline conditions).
(vii) Presence of healthy plant growth-promoting microflora (FAO 2016).

However, intensive cultivation of crops has depleted the nutrients concentration in soils due to which crops are suffering from hidden hunger of macro and micronutrients (Sarma et al. 2015). A significant amount of agricultural crops yield is lost every year due to reduction in the optimal amount of nutrients to the plants. To solve the problem of low soil fertility, demand and application of inorganic fertilizers are continuously increasing (Hasina et al. 2011). In spite of this, chemical fertilizers are also costing a lot in terms of negative effects on soil and environment due to their enriched application in agricultural lands for crops production (Bockman et al.

1990). Due to overuse of nitrogen and phosphorus fertilizers, we have already lost our natural ecosystem (Vitousek et al. 2008).

It has been observed that out of total nitrogen fertilizer application, plants only consumed 50%, while remaining 2–20% is lost due to its volatile nature of NH_4, 15–25% chemically reacted with organic fractions and clay soil particle, and 2–10% become part of water (Sönmez et al. 2008).

Enrichment of lakes with phosphorus due to its high rate of application is also causing eutrophication (Bennett et al. 2001). It has been observed that the deficiency of Fe also resulted in the chlorosis especially in citrus, deciduous fruits and leguminous crops. Due to high pH, low organic matter and calcareous nature of parent material in Pakistan deficiency of boron also play an imperative role in deterioration of quality of food (Niaz et al. 2007; Moheyuddin et al. 2013). Micronutrient deficiencies are recognized as the most common reason for low-quality agricultural production (Donald and Prescott, 1975). For this selection of tolerant cultivars to Zn, Mn or Cu deficiency is a sustainable solution to enhancing productivity in areas deficient in micronutrients (Mortvedt et al. 1991).

4.3.1 Measures to Improve Soil Fertility

We can improve the fertility of soils by many ways such as introducing of cover and leguminous crops in conventional cropping systems, application of composts and manures (organic and inorganic), recycling of crop residues and adopting no till system of cultivation (Bronick and Lal 1995; Dinnes et al. 2002).

The efficiency of inorganic fertilizers can be enhanced by reducing their losses. Nitrogen losses through volatilization can be controlled to a large extent by not leaving the nitrogen fertilizers on the soil surface; by thoroughly incorporating them in the soils; for upland crops the basal does be drilled; broadcast of fertilizers be followed by hoeing and light irrigation; and practicing split application.

4.4 Soil Salinity/Sodicity

The problem of soil salinization and/or sodification is increasing in the world because of natural and anthropogenic causes such as high temperature, less annual precipitation, use of poor-quality water for irrigation, etc. (Ghafoor et al. 2004), overflowing by seawater (Rowell 1994) upsurge in brackish water table (Samdani 1995).

It has been estimate that more than 800 M ha soils of are salt-affected and about 77 M ha of irrigated land are degraded by anthropogenic activities (Oldeman et al. 1991). Salt accumulation in the root zone is one of the main reasons of the reduced crop production. Retarded growth and smaller plants having fewer and smaller leaves are general symptoms of salinity. Poor growth is the result of osmotic and specific ion effects. Salt–affected is a broader term and soils may be categorized into three categories the basis of ECe and ESP (US Salinity Laboratory Staff 1954).

4.4.1 Saline Soils

Worldwide nearly 40% salt-affected soils are saline in nature (Tanji 1990). Saline soils mainly contain neutral soluble salts comprising chlorides and sulphate of sodium, calcium and magnesium in excessive amount. These soils have electrical conductivity greater than 4 dS m^{-1}, exchangeable sodium percentage < 15 and pH <8.5. In general, saline soils have good physical conditions with satisfactory permeability (Soil Science Society of America 2006).

4.4.2 Sodic Soils

These soils have excess exchangeable Na and high pH to interfere with plant growth. Physical and chemical conditions of these soils are greatly impaired because of excess Na, which deflocculates and disperses soil colloids. Their EC is less than 4 dSm^{-1}, pH > 8.5 and ESP > 15. Subsurface sodic soils become dense and compact.

4.4.3 Saline-Sodic Soils

These soils contain excess salts as well as exchangeable Na. Electrical conductivity of such soils is more than 4 dSm^{-1} with exchangeable sodium percentage (ESP) greater than 15. Their pH is seldom greater than 8.5.

4.4.3.1 Reclamation of Salt-Affected Soils

The main objectives of reclamation of salt-affected soils are to reduce salinity and sodicity from the root zone to permissible levels to restore soil productivity, to increase water use efficiency and to improve farmers' living standard by increasing the productivity of a given area of land. For successful reclamation, good internal soil drainage, land levelling and deep groundwater (preferably below 3 m) are considered basics for reclamation (Muhammad 1996). Several methods are carried out to reclaim salt-affected soils. The suitability of each technique depends upon a number of factors such as internal soil drainage, basic soil characteristics, presence of hardpans in the subsoil, climatic conditions, concentration and type of salts present in the particular soil, quantity and quantity of water available for reclamation, depth of groundwater, gypsum requirement of the soil, availability and cost of the amendments, availability of the equipment for soil tillage, cropping pattern prevalent in the region and season (summer or winter) for reclamation (Zia-ur-Rehman et al. 2017). These approaches are discussed in following section.

4.4.3.2 Physical Approach

This includes subsoiling, deep ploughing, sanding, horizon mixing, profile inversion and trenching. These actions increase the permeability of soil. Deep ploughing is very beneficial where the subsoil contains gypsum or lime.

4.4.3.3 Biological Approach

In this approach, crops such as kallar grass (*Leptochloa fusca*) and dhaincha (*Sesbania aculeata*) are grown on the problem soils at the flowering stage. Large amounts of organic matter are added to the sodic soils during reclamation. Moreover, incorporation of straw and crop residues is also undertaken. Kallar grass has fibrous roots that grow about 1 m deep into the soil that enhances permeability, improves aeration and helps in leaching soluble Na salts. Kallar grass has a vigorous growth of its fibrous root system; a significant amount of organic matter is added into the soil which, besides improving physical conditions, results in the formation of organic acids. Hydrogen ions (H^+) produced on decomposition of organic matter replace Na from the soil exchange complex that is leached as sodium chloride or sulphate due to improved permeability. Other organic manures also improve soil's physical conditions and produce organic acids (humic and fluvic acid) which help to reclaim the soil.

4.4.3.4 Electro-Reclamation Approach

This approach can be used for the amelioration process of salt-affected soils using the principle electrodialysis technique. Several research studies reveal that use of electric current for the reclamation process speed up the reclamation mechanism manifolds. However, it is not the complete substitute for the conventional reclamation processes. This method enhances solubility of $CaCO_3$ to supply more Ca^{2+} to replace the exchangeable Na^+. Moreover, this method creates a setting, which is effective for leaching of soluble salts and exchangeable Na^+.

4.4.3.5 Chemical Approach

This involves the use of chemical amendments such as gypsum, sulphur and acids. Calcium cations in gypsum molecule replace excess Na from the clay particles and sodium sulphate is formed. Sodium sulphate is a soluble salt, therefore, is leached with excess irrigation water. Sulphur applied to the soil produces sulfuric acid that also helps in reclamation of sodic soil by replacing Na from the exchange complex. In calcareous soils, sulfuric acid produces calcium sulphate, which will reclaim the soil as gypsum does. The following steps help in rapid soil reclamation. Deep ploughing, chiselling and, if possible, application of sand in the field to improve permeability. Gypsum application at 50% of gypsum requirement (about 6 t/ha) and FYM at 10 t/ha and their incorporation in the soil. The field is irrigated for reactions to take place. After gypsum application, heavy irrigations are applied to leach the excess salts. For reclamation, fine gypsum powder (80–100 mesh) is better than coarse-sized gypsum (60 mesh). However, if good quality irrigation water is available, coarse-sized gypsum can also be used and vice versa.

4.4.3.6 Hydrological Approach

Leaching and drainage are basic requirements for successful reclamation of saline-sodic soils. When soils are permeable, artificial drainage is not required but such condition seldom occurs in saline-sodic soils. Various types of drainage systems used for soil reclamation such as vertical drainage by installing tube wells, horizontal drainage, tile drainage and surface drainage.

4.4.3.7 Synergistic Approach

In certain conditions, process of reclamation can be accelerated by combining the various reclamation approaches. In most of the cases, this approach is practised for the reclamation of salt-affected soils at farmers' level. Combined use of gypsum along with various organic amendments reduced the salinity/sodicity problems to a great extent. Combined application of gypsum with FYM; gypsum application with rice husk; and combination of gypsum with *Sesbania* green manure (Baig and Zia 2006) have revealed significant effects in reducing salinity/sodicity problem.

4.4.3.8 Saline Agriculture

Saline agriculture involves cultivation of salt-tolerant species of agricultural significance and adaptation of special agronomic practices to improve their productivity. In Pakistan, the generally recommended salt-tolerant species include 'Kallar' grass; *Atriplax* spp., *Acacia* sp. and *Eucalyptus* spp. In the world, there are more than 1500 salt-tolerant plants species; the major crops including rice, wheat, cotton and maize have different tolerance to salinity and associated problems. There is genetic difference among the genotypes of each crop. These other salt-tolerant plants which can be used in saline agriculture include sugar beet (*Beta vulgaris*), guar (*Cyamopsis tetragonoloba*), oats (*Avena sativa*), papaya (*Carica papaya*), rape (*Brassica napus*), sorghum (*Sorghum bicolar*), soybean (*Glycine max*), Rhodes grass (*Chloris gayana*) and khabbal grass (*Cynodon dactylon*). Salt-tolerant trees and grasses include date palm (*Phoenix dactylifera*), sugar beet (*Beta vulgaris*), wheat and semi-dwarf (*Triticum aestivum*), bermuda grass (*Cynodon dactylon*), kallar grass (*Diplachne fusca*), mesquite (*Prosopis juliflora*) and river salt bush (*Atriplex amnicola*).

4.4.3.8.1 Crop Selection

In salt-affected soils, the judicious and wise selection of crops that can provide suitable yields under saline conditions may be selected. Crop species and varieties differ in salt and sodium tolerance at various stages of growth, germination and seedling being generally more tolerant. This can be avoided by using higher seed rate. Good-quality water should be used at the earlier stages of growth. In salt-affected soils, earlier sowing should be preferred. Sodic soils must be tilled with great care because they are especially susceptible to puddling. Tillage when the soil is too moist will cause puddling, while if the soil is too dry, it will form clods.

4.4.3.8.2 Use of Manures and Fertilizers

Addition of organic manures to these soils should be routine practice. Green manuring should be carried out after every two or three crops. Chemical fertilizers like ammonium sulphate and 'single' super phosphate must be applied to overcome soil salinization. Nitrogen deficiency can be met by adopting the green manuring technique using sesbania species that also decrease the harms and hazards of salinity/sodicity. During the reclamation of the sodic soils, part of the N may also leach down along with the other soluble salts and Na^+. Some studies that we're conducting in Pakistan as well as in India reveal that application of higher dose of nitrogen than the requirement for the crops growing under saline/sodic conditions endow with more yield and production may be due to stimulation of dilution effect coupled with enhanced salt tolerance potential of plants. Yaduvanshi and Dey and Murtaza et al. recommended that rice and wheat crops grown in sodic soils should receive 25–30% N over and above the recommended rates for non-saline/sodic soils.

Sodic and saline-sodic soils usually have higher available phosphorus than the normal soils because higher concentrations of Na_2CO_3 results in the formation of soluble Na_3PO_4. On the basis of some studies, it has been proposed that the sodic soils after reclamation require less additional P fertilizer for some years. Similarly, it has been suggested that a 50% reduction in the recommended dose of P may be practised for a rice-wheat rotation grown up to 3 years during reclamation without yield loss. Increasing sodicity nearly always results in a deficiency of Ca^{2+} concentration in the soil. Fertilizers containing Ca^{2+} or ammonium sulphate and urea perform better than the equivalent rates of Ca-free or physiologically less acidic should be preferred over other nutrient sources.

Salt tolerance potential of various plants can be evaluated using the following criteria: a) the ability of the crop to survive on salt-affected soils; b) the acceptable yield of the crop on salt-affected soils, mostly 50% reduced yield; and c) the relative yield of the crop on a salt-affected soil as compared with its yield on a normal soil under the similar growing conditions.

4.5 Compaction

Globally, soil compaction is the worst type of land degradation, extensive reduction in agriculture productivity leading to soil desiccation displayed by poor crop production and detrimental environmental conditions. Soil compaction affects soil structure badly. It also decreases soil porosity, water infiltration and air exchange and makes root penetration problematic, and this leads to poor crop yield (Raghavan et al. 1992; Dexter 2004; Botta et al. 2007; Wolkowski and Lowery 2008). Soil texture, moisture content and plasticity, vehicle weight and its speed and ground contact pressure and number of passes cause soil susceptible to compaction (Smith et al. 1997; Wang et al. 2004; Materechera 2009). Soil compaction effects on soil properties in arid and humid regions vary due to different soil properties like soil moisture content. Moreover, in arid environments compaction because of tillage implements may cause soil-hard setting especially in dry days, making tillage difficult. In arid regions, high temperatures lead to high evaporation rates resulting in reduced moisture content displayed by formation of a hardpan and/or compaction (Lal 1995).

4.5.1 Control Measures

Organic matter in soil plays a key role in maintaining soil biological activities. High organic matter results in higher stability index and high soil quality and productivity, while lower organic matter contents in soil make soil more susceptible to soil compaction. Chisel or deep ploughing would be beneficial to reduce the soil compaction along with deep-rooted tree plantation.

4.6 Waterlogging

Excessive rainfall in tropical and subtropical regions is the major constraint for crop production. High levels of water in soil produce hypoxic conditions (decrease in the level of oxygen) within a short period of time. Consequently, plant roots undergo in anoxia condition, complete absence of oxygen (Gambrell and Patrick 1978). Generally, two types of flooding are present in the field: (1) waterlogging, in which root and some portion of the shoot goes underwater, and (2) complete submergence, where the whole plant goes underwater (Mohanty and Khush 1985).

4.6.1 Plants and Soil Under Waterlogged Conditions

Excess water in the root zone restricts root growth and therefore adversely affects plant growth. Due to excess water the problem of salinity also produced due to which plant growth adversely affect (Singh 2014). Excess water in soil is to replace air in the soil pores leading to oxygen deficient and reduced plant growth. In addition, low levels of O_2 may decrease hydraulic conductivity due to hampered root permeability (Else et al. 2001). After the disappearance of molecular oxygen, the concentration of CO_2 and toxic product of anaerobic microbial activity like methane and organic acids increase. In such condition, soil tends to accumulate nitrite as it tends to accumulate more reduced and phytotoxic forms.

4.6.2 Control Measures

Since the appearance of waterlogging in 1925, various control measures have been suggested by workers in Punjab, Indo-Pakistan. The important ones are discussed below.

4.6.2.1 Seepage Interceptor Drains

drains constructed to intercept seepage water from the source (canals) are called seepage interceptor drains. They are constructed parallel to the source of water. Their dimensions and lengths depend on the size and length of seepage source. Such drains are constructed along both sides of upper Chenab canal. They proved ineffective in controlling the groundwater.

4.6.2.2 Surface Drains

surface drains proved relatively effective in carrying away canal seepage water and rainfall runoff. Between 1933 and 1944 a large number of surface drains totalling about 5340 Km in length were constructed in the Punjab. Between 1967 and 1970 quit a few surface drains were also constructed in Sindh (Ahmad and Chaudery 1997).

4.6.2.3 Lining of Canals

in 1938–1939, lining in Haveli canal was established at the time of its construction. Later main Thal Canal, Balloki-Sulemanki Link and a portion of BRB Link were lined. The lining of canals reduced seepage by 75%.

4.6.2.4 Pumping of Groundwater

pumping out water has always been effective in lowering shallow round water tables. Pumping not only lowers the water tables but also provides additional water for irrigation where its quality is suitable. The construction of drains and pumping by tube wells proved to be quite effective against waterlogging.

After the success of these measures following Revelle's report, many salinity control and reclamation projects were established in Punjab, Sindh and NWFP. These projects were intended to lower the groundwater table and supply additional water for irrigation and reclamation of saline soils.

4.7 Role of Conservational Tillage and Cover Crops in Soil Management

Conservation tillage not only improves soil aggregation but also conserves soil structure and sustains soil fertility by increasing water retention and infiltration (Kumar et al. 2012c). Spargo et al. (2008) reported that minimum tillage caused lesser decomposition of residue and increased soil organic carbon (SOC). Soils physico-chemical properties and N transformations in soil, volatilization and denitrification in soil are also affected by soil tillage. It disrupts stable soil aggregates, whereas conservation tillage systems encourage the SOC contents of soil and reduce breakage of soil macro-aggregates and cause lesser exposures of micro-aggregate and free organic matter (OM) to microbial decomposition (Jacobs et al. 2009). Conservation tillage practices are one of several management practices that are useful in enhancing organic matter contents of prime cultivable agricultural lands (Kumar et al. 2012b).

4.8 Heavy Metals and Soil Quality

With presence of variety of chemical elements (e.g. metals; metalloids; inorganic ions; or salts), organic compounds or nanoparticles in concentrations above the permissible limit which can hamper the normal functioning of living organisms and disturb the ecosystem are called soil pollutants (Huang et al. 2009; Ahemad 2012;

Elbagermi et al. 2013). Entry of pollutants to soil may be natural (e.g. precipitation and wind) or due to human activities which adds up the contaminants to potential risk level. Proliferation of human population has significantly contributed through expansion of different industries to fulfil the human needs. Increased industrial production, inappropriate handling of waste materials and injudicious use of agrochemicals have caused a prolific release of pollutants in soil. Present literature review was conducted to summarize the causes of soil pollution by heavy metals and its effects on humans and ecosystem and evaluate suitability of two remedial technologies, namely, phytoremediation and bioremediation to decontaminate arsenic (As) and chromium (Cr) polluted soils (EPA 2007).

4.8.1 Sources

Weathering of minerals and anthropogenic activities like mining and electroplating and use of arsenic-based herbicides and chromated copper arsenate (CCA), a chemical preservative for wood, are some of the gateways of arsenic entry into environment which eventually contaminate soil. Chromium is used in electroplating, aircraft and electronic industries, manufacturing resistant alloy products, in tannery and paper industries (Nriagu et al. 2007; Abdelhafez et al. 2009; Wuana and Okieimen 2011; Ahemad 2015).

4.8.2 Remedial Technologies

Different in situ treatments like containment, solidification, soil incineration, chemical oxidation, flushing and use of permeable reactive barriers and ex situ treatments like excavation, pump and treat are employed to remediate the contaminated sites (Sheoran et al. 2010). Many of the technologies are not feasible economically (Hashim et al. 2011; Tangahu et al. 2011). Literature regarding phytoremediation and bioremediation is covered in this article

4.8.2.1 Phytoremediation and Phytoextraction

Phytoremediation has benefit over the others specifically removing the heavy metals from soil (Khan et al. 2010; Tangahu et al. 2011). It is the use of selected plants and associated soil microbes to reduce the concentration or toxic effects of contaminants in the environment. Plants with characteristic of hyper-accumulation of heavy metals are used to uptake the metals from contaminated sites. Phytoremediation is an autotrophic system to remove or immobilize heavy metals and biodegrade radionuclides and organic pollutants including aromatic hydrocarbons, polychlorinated biphenyls and pesticides. It is affordable, efficient and environment friendly technology (Sinha et al. 2007; Tangahu et al. 2011; Prabhavathi et al. 2014).

Phytoremediation is a broader terminology which covers phytoextraction, phytostabilization, phytovolatilization, rhizofiltration and phytodegradation, but the phytoextraction is most suitable and permanent remedy of heavy metals contamination.

Phytoextraction is the bioaccumulation of metals in the harvestable portion of plant, e.g. shoot. Fast-growing plants like willow, poplar and jatropha could be used as metal accumulator and finally as energy source. Overall efficiency of phytoextraction can be quantified by multiplying the tissue metal concentration with biomass produced (Macek et al. 2008; Vangronsveld et al. 2009; Abhilash et al. 2012).

4.8.2.2 Cultivar Selection

Plants grown on metal contaminated soils uptake metals which may impair physiological processes necessary for plant growth resultantly reducing crop production. Furthermore, higher concentrations of heavy metals in plants cause generation of reactive oxygen species (free radicals) which is highly toxic for plants. Other complications include ethylene stress and decline in iron sequestration. Selection of suitable plant species is a key factor for phytoremediation.

The potential of a plant to be used as hyperaccumulator is judged based on its bioconcentration and translocation capability. Bioconcentration factor describes the efficiency of a plant to accumulate the metal in its tissues, and translocation factor is the efficiency to translocate metal from its root to shoot (Padmavathiamma and Li 2007; Zhuang et al. 2007).

$$\text{Bio-concentration factor}\left(\text{BCF}\right) = \frac{\text{Metal concentration in harvested tissue}}{\text{Metal concentration in soil}}$$

$$\text{Translocation Factor}\left(\text{BCF}\right) = \frac{\text{Metal concentration in shoot}}{\text{Metal concentration in root}}$$

Hyperaccumulator plants should have shoot-to-root metal concentration ratio, greater than one, which is required to remove the contaminant by harvesting the plant shoot without disturbing the soil. Further process may be the burning of plant, gaining energy and recycling of metals from ash. (Erdei et al. 2005; Salido et al. 2003) Plant with higher metal accumulation and lower biomass production is preferable as it is easy to process or dispose low volume of metal-rich biomass than high volume of low-metal biomass (Chaney et al. 1997). Similarly, plants with multiple harvests in a single growth period have more potential for metal remediation. The brake fern (*Pteris vittata* L.) is tolerant to As and has the potential to hyperaccumulate As up to 22,630 mg/kg in 6 weeks when grown in soil containing 1500 mg/kg (Ma et al. 2001).

4.8.2.3 Transport Processes: Heavy Metals Mobilization

Metal availability in soil depends on many factors, e.g. soil pH, organic matter contents, calcareousness of soil and soil mineralogy. Mostly, available content of metals is fraction of total metal concentration in soil hence different chelating agents are used to increase metal's mobility in soil. Ethylene diamine tetra acetic acid (EDTA) increases uptake of metals from contaminated soils by making chelation complexes with metals and eventually enhances phytoremediation (Erdei et al. 2005; Salido et al. 2003). However, Bell et al. (2003) reported that EDTA-metal complex breaks near the root surface and only metal ion is transported to cell and EDTA is released to biosphere which is one of the reasons of its longevity in soil. However, high concentration of EDTA may cause a potential risk of groundwater contamination due to leaching of soluble EDTA-metal complexes (Wu et al. 2004). This risk can be minimized by using chemical additives instead of chelating agents.

Phosphate has synergistic effect on As availability in soil. Application of phosphorous either in the form of chemical fertilizers or organic amendments (compost) in soils, having significant amount of total As increases As availability (Hue 2013). Arsenate and phosphate both have the same uptake mechanism hence it may be difficult for plant to differentiate between the two thus the uptake by plants is competitive (Tu and Ma 2003). Thiosulphate ion has potential to mobilize the As and mercury (Hg). Hence thiosulphate is more suitable for phytoextraction in soils contaminated with multi-metals. Thiosulphate ion is converted to sulphate ion which competes with arsenate ion for exchange sites on soil and resultantly releases arsenic into soil solution. Fertilizers containing thiosulphate like ammonium thiosulphate, $(NH_4)_2S_2O_3$, can be used to speed up phytoremediation of arsenic.

4.8.2.4 Soil Mineralogy

Total concentration of metal in soil cannot be considered as available form for plant uptake. Metal availability depends upon its chemical form, chemical association of metal with different soil-solid phases and clay mineralogy. Andisol’s soil order possessing significant amount of Fe and Al oxides has more potential to sorb As than inceptisols and oxisols; hence bioaccumulation ratio would be higher in oxisols due to relatively higher available pool of As (Goh and Lim 2005; Hue 2013).

4.8.2.5 Bioremediation Complements Phytoremediation

Plant growth-promoting bacteria (PGPB) are also adversely affected by higher concentration of heavy metals; however, these bacteria facilitate plants in decreasing the level of ethylene stress. Metal-resistant, growth-promoting bacteria help metal accumulator plants to cope with metal toxicity, superoxide dismutase (SOD) stress and release of siderophores to enhance iron sequestration. Microorganism especially bacteria and mycorrhizal fungi increases bioavailability of heavy metals in soil (Sheoran et al. 2010).

Most of the metals are sorbed onto the exchange sites of soil particles and organic matter and desorption is the first step of phytoremediation. This desorption is enhanced by using surfactants otherwise it may take decades to convert these metals into available forms. Microorganisms naturally produce bio-surfactants which are more effective than synthetic surfactants.

4.9 Addition of Soil Organic Matter

Soil organic matter (SOM) is panaceas for sustainable agriculture. It is also known as an important indicator of soil productivity (Doran 2002; Wilhelm et al. 2004). It can be defined as the organic fraction of the soil exclusive of undecayed plant and animal residues (Soil Science Society of America 2006). It not only improves the soil's physical (soil texture, structure, porosity, bulk density, water holding capacity and soil colour etc.), chemical (pH, EC, cation exchange capacity, Al toxicity, allelopathy, availability of macro- and micronutrients) and biological properties (nitrifying and denitrifying bacteria, micorrhiza fungi and microbial biomass) and maintains sustainability of cropping systems but also reduces soil degradation (Stevenson 1991; Bauer and Black 1992; Mikha and Rice 2004; Fageria 2012). SOM enhances water holding and buffering capacities of soil and also makes soil aggregates stable and supplies plant nutrients upon mineralization (Carter and Stewart 1996). Climate, texture, hydrology, land use and vegetation are important factors which affect soil organic matter contents in soil. Organic matter decays more rapidly in arid and semiarid regions of the world due to higher temperatures and less precipitation as compared to temperate climate. More rapid decomposition in coarse textured soils because of better aeration than fine textured soils. Grassland contains more organic matter contents than forest soils and cropland. Arid and semiarid regions have lesser vegetation and less organic matter contents than temperate regions. Soils having meagre return of organic residues contain low organic matter contents particularly in arid and semiarid regions (Hussain 1996).

We can improve and/or stabilize SOM content of the soils by adopting appropriate soil and crop management practices such as adoption of conservation tillage (Lal 1997), crop rotation (Robson et al. 2002), use of adequate rate of fertilizers (Fageria et al. 2005), use of organic manures (Singh et al. 2004), cover crops/green manuring (Fageria 2007), addition of farmyard manures (Aoyama et al. 1999), composting of municipal waste (Brady and Weil 2002), recycling of crop residues (Cambardella and Elliott 1993), keeping land under pasture (Bronson et al. 2004) and liming acid soils (Fageria et al. 2005).

4.10 Impacts of Climate Change on Sustainable Soil Management

Natural and anthropogenic activities have changed the climate remarkably; however, natural changes are generally gradual and slow, and ecosystems adapt themselves. Whereas human changes are abrupt and rapid, ecosystems could not adjust themselves such as current land use and agricultural actions, and burning fossil fuels have aggravated the scenario. Deforestation, burning of biomass, conventional tillage practices, high cropping intensity, clean cultivation and burning of fossil fuels have considerably increased greenhouse gases, such as CO_2, CH_4 and N_2O in our environment (IPCC 2007). Climate change has increased global warming; arctic sea ice has started melting; hurricanes, floods and droughts are occurring frequently. Climate change has increased evapotranspiration. Increased soil temperature may enhance organic matter decomposition, soil structure deterioration, compaction and reduction in porosity, permeability and drainage (Lal 2004).

Soil management is function of soil water, air, and nutrient, soil organic matter and soil structure management, and management of soil microbial dynamics and nutrient cycling. Soil management should restore soil fertility and productivity, conserving soil and maximizing yield. The conventional soil and crop management practices such as tilling, harrowing, weeding, fertilizing, irrigation and drainage. These management practices have caused huge losses in soil organic carbon matter and greatly reduced diversity and abundance of microbes (algae, bacteria, fungi, nematodes and protozoa) in agroecosystem (Ingham 2006). Presently Soil management practices mitigating climate change impacts and adapting to climate change along with restoring soil health and sustaining sustainable yield.

4.11 Conclusions

It is the need of hour to develop new avenues of soil management which can cater the issues of climate change and help meet the food requirements of burgeoning population of the world. The old management practices such as intensive tillage, faulty nutrient management, imbalanced use of inorganic fertilizers have not only deteriorated the environmental quality but also badly affected soil quality and crop production. In the recent years, the use of conservation tillage, efficient use of cover crops proved beneficial in restoring soil health and improving physico-chemical properties of soil. The use of innovative and advanced management techniques is generally site-specific and according to the needs of every region and climate**.**

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Tillage Effects on Agronomic Crop Production

5

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Abstract

Tillage is the most important activity in agricultural operations that includes mechanical manipulation of soil, such as digging, stirring, and seedbed preparation. Agricultural mechanization is need of time for enhancing production to meet food requirement of burgeoning population. Tillage operations alters physico-chemical properties of soil and manipulate weeds and appropriate seedbed for crop plants, incorporate crop residues into the soil, make soil loose, enhance chemical reactions, and thereby improve physio-chemical condition of soil which results in better growth and yield. This chapter emphasized significance of tillage in loosening soil, reaping benefits of chemical reactions, enhancing moisture contents, and improving structure of soil and essential for successful cultivation of agronomic crops.

Keywords

Tillage · Tilth · Physical manipulation · Agronomic · Crops

5.1 Introduction

Tillage is the most important operation for crop production, which includes mechanical agitation of various types, such as digging, stirring, and overturning for preparation of seedbed. The system with the aid of forces are imparted and modifications in soil residences arise is called tillage that is comprised of some technical operations together with plowing and harrowing (Brady 1974). Farm mechanization is the need of the time to enhance our agricultural production to meet the food requirement of rapidly growing population. Most of our agriculture has already been fully or

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partially mechanized which includes tillage, seedbed preparation, sowing, planting, interculturing, harvesting, and threshing. But still there is a wide scope for further mechanization to boost the existing production. Tillage is a fundamental crop production practice to form a good seedbed for germination and subsequent plant growth. Tillage operation alters the soil bulk density and soil strength which improves soil aeration and provides ideal conditions for plant life. Tillage practices manipulate weeds and appropriate seedbed for crop plants, incorporate crop residues into the soil, make the soil loose, enhance the chemical reactions, and thereby improve the physiochemical condition of soil which in flip results in the growth and improvement of crop plants. Johnson (1978) emphasized the significance of tillage in loosening the soil, reaping benefits of chemical reactions, enhancing moisture contents, and improving the structure of soil. This condition is essential for any crop cultivation.

5.2 Tillage

The word tillage is derived from words "Tilian" and "Teolian" meaning "to plough and prepare soil for seed to sow, to cultivate and to raise crops." So tillage may be defined as "mechanical manipulation of soil with tools and implements for obtaining conditions ideal for seed germination, seedling establishment and growth of crops."

Tilth is the physical condition of soil obtained as a result of tillage. This physical condition determines the germination and growth of crop plants which may be of various types, e.g., coarse tilth, fine tilth, or moderate tilth.

5.2.1 Types of Tillage

Tillage has two major types:

A. On-season tillage
B. Off-season tillage

A. *On-Season Tillage*

"Tillage operations that are carried out for raising of crops and normally practiced at the onset of the crop season" are termed as on-season tillage. On-season tillage is further classified as (i) preparatory tillage and (ii) interculturing.

(i) *Preparatory Tillage*
(ii) *Interculturing is physical manipulation of soil with the help of tillage implements after sowing of a crop. It includes tillage, hoeing, earthing-up etc.*

This type of tillage refers to "tillage operations that are carried out to prepare the soil for crop sowing". It contains soil loosening at deeper depth to create favorable conditions for plant growth as well as incorporation or uprooting of weeds and crop stubble when the soil is in a workable condition.

5.2.1.1 Types of Preparatory Tillage

There are two main types of preparatory tillage:

(a) Primary tillage
(b) Secondary tillage

(a) *Primary Tillage*

The tillage operations that are done after the harvesting of crop to bring the land under cultivation are known as primary tillage. It is used for the opening of compacted soil with the help of different plows. Different primary tillage implements such as subsoiler, moldboard plow, chisel plow, tractor, and power tiller drawn implements are used for primary tillage.

(b) *Secondary Tillage*

The tillage operations that are practiced after primary tillage to prepare the good seedbed are known as secondary tillage. In other words, we can say that secondary tillage operations involve lighter or finer operations which are done to incorporate the manure and fertilizers, clean the soil, and break the clods. For this purpose, harrowing and planking are done. Planking is done to break the hard clods, to level the soil surface, and to compact the soil lightly. Different secondary tillage implements such as disk harrow, cultivator, and planker are used for preparation of final seedbed.

(i) *Intertillage/Interculture Practices*

"Tillage operations that are practiced in the standing crop after planting or sowing and prior to the harvesting of the crop plants." It includes harrowing, hoeing, weeding, earthing up, drilling or side dressing of fertilizers, etc. Different tools or implements such as spade, hoe, rotary weeder, bar harrow, etc. are used for intertillage.

B. *Off-Season Tillage*

"Tillage operations done for conditioning the soil suitably for the forthcoming main season crop or for conservation of rainfall water in the soil profile" are known as off-season tillage, e.g., postharvest tillage, summer tillage, winter tillage, and fallow tillage.

5.3 Special Purpose Tillage

Tillage operations practiced to serve special purposes are called special purpose tillage. Some of these are given as follows.

(a) *Subsoiling*

It is done to break the hard pan or plow pan below the plow layer occurring due to tilling soil at same depth or accumulation of salts. Similarly chiseling is performed to reduce soil compaction. Subsoiling/chiseling is essential once in 3–4 years where heavy machineries are used for field operations, seeding, harvesting, and transporting or in rice-wheat cropping system. However, subsoiling is done to obtain the following objectives:

- To obtain greater soil volume for cultivation of crops
- To percolate excess water
- To minimize surface runoff and soil erosion
- To penetrate roots of crop plants at deeper soil layer for the extraction of nutrient and moisture

(b) *Clean Tillage*

Cultivation of the whole field is such a way that all living plants are uprooted and destroyed. It is practiced to check weeds and control soil-borne disease and pests.

(c) *Blind Tillage/Hoeing*

Tillage practices are performed after crop either at the preemergence or in the early stages of growth so that crop plants do not get damaged, but weeds are uprooted, for example, hoeing in sugarcane or potato.

(d) *Dry Tillage*

Dry tillage is practiced for crops that are sown or planted in dryland condition having sufficient moisture for seed germination. This is suitable for crops like broadcasted rice, jute, wheat, oilseed crops, pulses, potato, and vegetable crops. Dry tillage is done in a soil having sufficient moisture (21–23%). The soil becomes more porous and soft due to dry tillage. Besides, the water holding capacity of the soil and aeration are increased. These conditions are more favorable for soil microorganisms.

(e) *Wet Tillage/Puddling*

The tillage practice that is done in a field in standing water is called wet tillage or puddling. It involved soil plowing repeatedly in standing water until the soil becomes soft and muddy. Puddling creates an impervious layer below subsoil to overcome water losses occurred through percolation and to provide soft seedbed for rice planting. Wet tillage destroys the soil structure and the soil particles that are separated during puddling. Planking after wet tillage makes the soil level and compact. Puddling hastens transplanting operation as well as establishment of seedlings. Wetland plows or worn-out dryland plows are normally used for wet tillage.

5.4 Modern Concepts in Tillage

Conventional tillage involves opening or loosening soil through primary tillage implements followed by secondary tillage to prepare seedbed for sowing or planting. With the use of weedicides in intensive farming systems, the concept of tillage has been changed. Continuous use of heavy plows create hard pan in the subsoil, which results in poor infiltration. It is more susceptible to runoff and erosion. It is capital intensive and increases soil degradation. To avoid these ill effects, modern concepts on tillage are in rule.

5.5 Minimum Tillage

It aims at disturbing the soil to a minimum level through reduced tillage operations necessary to ensure good seedbed. It has the following advantages:

- It saves time as well as cost by reducing tillage operations.
- Reduced soil compaction.
- Soil structure is not disturbed.
- Minimized soil erosion as well as water loss.
- Water storage is increased in the plow layer.

5.6 Zero Tillage (No Tillage)

In this, new crop is planted in the residues of the previous crop without any prior soil tillage or seedbed preparation, and it is possible when all the weeds are controlled by the use of herbicides. Zero tillage is applicable for soils having coarse texture surface, well drainage, and high biological activity with an adequate quantity of crop residue as mulch. These conditions are generally found in the humid and subhumid regions having Alfisols, Oxisols, and Ultisols soil type.

Advantages Soils become homogenous in structure due to higher number of earthworms.

- Less mineralization enhances organic matter content.
- Reduced surface runoff due to the presence of crop residues which act as mulch.

Disadvantages Higher amounts of nitrogen as well as herbicides are used for mineralization of organic matter and to control weeds, respectively, which enhances cost of production.

- Perennial weeds may be a problem.
- High number of volunteer plants and buildup of pests.

5.7 Conservation Tillage

The major objective is to conserve soil and soil moisture. In this tillage system, organic residues are not incorporated into the soil and retained on soil surface in such a way that they remain on surface as protective cover against erosion to check evaporation losses. The residues left on soil surface interfere with seedbed preparation and sowing operations.

Advantages Energy conservation through reduced tillage operations.

- Improve the soil physical properties.
- Reduce the water runoff from fields.

5.8 Effects of Tillage

Intensive cultivation of soil worldwide resulted in the agricultural soils' degradation, posing to reduce soil organic matter, negatively affecting soil functioning and causing a long-term threat to future crop yield (Pagliai et al. 2004; D'Haene et al. 2008a, b). It is obvious from many studies that shifting to conservation tillage alters both soil physical properties, such as bulk density, total porosity, infiltration rate and retention capacity of water, and pore connectivity, and chemical properties, such as organic matter content and nutrient status of soil (Cereti and Rossini 1995; Kribaa et al. 2001), and resultantly affects the crop yield.

5.8.1 Effect on Soil Properties

Tillage being a necessary farm practice had great impact on soil properties which in turn also affects the crop productivity. Soil type is an important tool used for deciding or choosing tillage system for that particular soil. Tillage systems greatly affect soil physical as well as soil properties which are discussed in detail in this chapter.

5.8.2 Effect of Tillage on Soil Physical Properties

Tillage is one of the most important management practices involving physical manipulation of soil for establishment that can change soil properties and create a complex soil ecosystem (Strudley et al. 2008; Jabro et al. 2015) and contribute up to 20% in crop production (Ahmad et al. 1996). Soil health is necessary for crop production that can be improved through optimization of tillage practices. Better quality and healthy soil favor crop yield under favorable as well as extreme climatic conditions (Congreves et al. 2015). Different soil physical properties such as structure, texture, geometry, soil aggregation porosity, hydraulic conductivity, infiltration rate, bulk density, and soil moisture content are affected by tillage practices and in turn affect crop yields (Slam and Weil 2000; Khurshid et al. 2006). It is observed that deep plowing with moldboard plow had adverse effect on soil health and quality parameters (Karlen et al. 2013). Conservation tillage practices such as minimum tillage have positive effects on soil health by improving soil organic matter, aggregating stability, and reducing oxidation of organic matter compared with conventional tillage (Beare et al. 1994; Halvorson et al. 2002). The use of heavy machinery may cause deterioration of soil structure due to soil compaction. Subsoil compaction may limit uptake and availability of soil, water, and plant nutrients, thereby limiting crop yields. Hence subsoil compaction may be pulverized through deep tillage and the selection of crop rotations with deep-rooted crops (Motavalli et al. 2003), as deep tillage removes hard soil layer, enhances root growth through exploring more soil volume, improves uptake of moisture and nutrients, and increases crop production potential (Bennie and Botha 1986).

5.8.3 Bulk Density (Mg/m^3)

Soil compaction is often a problem when heavy equipment is used for row crop production. How reduced tillage or no-till systems affect physical properties such as soil density is a concern to farmers and researchers. Soil bulk density and water infiltration rate vary with type, method, and depth of tillage (Hamza and Anderson 2005). Soil bulk density is decreased by increasing tillage depth. Tillage with deep tillage implements significantly lowers soil bulk compared with zero-tillage system (Gangwar et al. 2004). Increasing tillage intensity resulted in reduced soil bulk density. Conventional tillage practices adversely affect the soil bulk density and increase its value (1.65 g cm^{-3}) in the case of shallow tilled soil. Plowing the soil at deeper depth lowers soil bulk density (1.51 mg cm^{-3}) (Alamouti and Navabzadeh 2007).

5.8.4 Total Porosity

Total porosity is an important soil parameter which affects rate of water infiltration as well as root proliferation and affects crop yield. Tillage operations had significant effect on this important soil parameter. Various studies had elaborated the tillage effects on total porosity. Deep tillage improves the soil porosity, and higher total porosity (0.47 $m^3 m^{-3}$) was recorded in deep tillage where chisel plow was used followed, while the lower soil porosity was observed in the zero-tillage treatment (0.44 $m^3 m^{-3}$) due to more soil compacted and undisturbed soil. The higher value of total porosity in deep tillage treatment might be due to more porous soil as deep tillage disintegrates the soil particles completely and enhances soil pores.

5.8.5 Soil Moisture Contents

Soil moisture content is an important soil factor which has direct impact on crop growth and yield. Tillage systems greatly impact soil moisture, which are favored by deep tillage compared with no tillage especially under rainfed conditions as deep tillage opens and loosens the soil which improves infiltration of rainfall water and conserves more moisture. It is observed from a study that highest moisture contents were recorded from the conventionally tilled plots than no-tilled plots (Rashidi and Keshavarzpour 2007).

5.8.6 Water Infiltration Rate (mm/hr)

The tillage systems had significant effect on rate of water infiltration in soil. Conservation tillage practices such as minimum and zero-tillage reduce rate of water infiltration because of compacted soil surface and subsurface layer. While deep tillage enhances rate of water infiltration due to more soil porosity and less bulk density, it is observed that rate of water infiltration is improved under deep tillage compared with zero or minimum tillage.

5.8.7 Root Penetration Resistance (k pa)

Root penetration resistance is also an important soil parameter which affects root length, root length density, and crop yield as well as proliferation to extract water and nutrient and nutrient from soil profile. Generally, deep tilling or subsoiling has positive effects compared with heavy tillage as well as shallow tillage. Maximum root penetration (1729.6 kpa) was recorded in zero-tillage treatment followed by minimum (1675.5 kpa), conventional (1654.7 kpa), and deep (1631.8 kpa) tillage treatments. The order of root penetration is directly related with soil compaction. Soil compaction creates unfavorable conditions in subsoil which restrict root growth and crop yield (Hamza and Anderson 2005; Mosaddeghi et al. 2009). Tillage is one of the most effective agricultural operations that overcome or decrease soil compaction (Daniells 2012). Soil physical properties are affected by tillage systems which in turn had positive or negative effects on crop growth depending upon the depth of tillage (Mosaddeghi et al. 2009). It is observed that deep tilling the soil may reduce soil bulk density as well as improves soil porosity (Laddha and Totawat 1997) and water storage in the soil and increases root growth (Holloway and Dexter 1991), which leads to increased crop production (Ghosh et al. 2006).

5.9 Chemical Properties

5.9.1 Soil Organic Matter

It is a well-established fact that plowing and secondary tillage operations increase the rate of organic matter loss in a soil. Intensive tillage reduces organic matter content and causes physical degradation of soil. Therefore, it is no surprise that soils in no till for several years have higher organic matter content than those plowed. The major difference in soil organic matter when comparing the two tillage systems is distribution. No tillage enhances organic matter levels in surface soil layers (Crovetto 1996). Also, under NT management with crop residues over the soil, an increased activity of some enzymes has been found, mainly phosphor monoesterase, dehydrogenase, urease, and b-glucosidase. Soil management practices such as incorporation of crop residues may change the soil environment for organisms which participate in the decomposition of organic matter and nutrient cycling (Clapperton 1999). Numerous researchers have demonstrated that conservation tillage such as no tillage and minimum tillage is effective in improving soil properties and soil organic carbon (SOC) content (Peixoto et al. 2006; Thomas et al. 2007; Madejon et al. 2009). Concentrations of soil organic C was higher under zero tillage as compared with conventional tillage. This might be due to the reduced disturbance of the soil in this tillage system.

5.9.2 Biological Properties

Soil is the supporting habitat for diversity of microbes, which are necessary for the proper growth of plants. Decrease in soil tillage caused a recycling of biological properties. The soil biotic factors (i.e., soil enzymes, nitrogen, abundance of earthworms, soil respiration, and microbial communal metabolic profiles) are early and complex indicators of the effects of agricultural practices on soil parameters. Generally, organically fertilized and no-tillage plots led to highest values, while mineral fertilization and conventional tillage led to lower values of biological parameters. Effects of tillage practices on soil biota are prominent (Van Capelle et al. 2012) because of continuous and severe tillage of agricultural soil. This results in losses of soil organic carbon, physical properties, and soil fertility and soil biological activity (Moreno et al. 2010). Such type of effects of tillage and cropping systems affects the microbes, their diversity, and other processes like decomposition of organic matter and facilitation of plant nutrient accessibility (Dick 1983; Balota et al. 2004).

5.9.3 Enzyme Activities

Enzyme activities are very important biological factors for microbial diversity and control nutrient cycling in the soil. Generally, highest values were observed for no tillage and lowest values for conventional tillage. As no tillage conserves soil structure and animal slurry, in addition, it causes high soil organic matter contents. Particularly, soil habitat microbes, enzyme, and their activities had greater sensitivity to soil recycling due to heavy tillage practices as compared to total organic carbon (Madejón et al. 2007; Geisseler and Horwath 2009; Laudicina et al. 2011).

Nutrient cycling and organic matter decomposition occur by soil enzymes through catalytic reactions because enzymes play a vital role in environmental quality, energy transfer, and crop efficiency (Tabatabai 2004). Tillage, intercropping, or crop rotation and remains management may have various effects on different soil enzymes (Tabatabai 2004) and may cause difficulty in obtaining plant nutrients. Enzymatic performance generally becomes less with soil depth (Green et al. 2007).

5.9.4 Earthworms

Earthworms are contemporaneous in soil and affect soil parameters such as soil structure, nutrient availability, and organic matter (Edwards 2004). While soil parameters like organic matter, soil moisture, pH, texture, and soil management affect the earthworms (Curry 2004), earthworm resident's variation depends upon tillage intensity (Chan 2001; Curry 2004) and may be lower under cereal than root crops (Curry et al. 2002). Contradictory tillage sound effects on earthworms were displayed in literature (Chan 2001). On one hand, tillage severity can increase earthworm population and species variety (Capelle et al. 2012), while on the other hand, cultivating can really affect endogenic species by increasing organic matter accessibility to them (Eanst and Emmerling 2009). The intensity and depth of conventional tillage (i.e., moldboard plowing with disking) can lead to decreased earthworm abundance when compared with no-till or other conservation tillage systems (House and Parmelee 1985; Peigné et al. 2009). In addition, the number and frequency of the tillage processes are also known to impact on earthworm populations (Capowiez et al. 2012). Additionally, different reports show that diverse degrees of tolerance to soil tillage depend on ecological groupings, species, and maturity stages.

5.10 Wheat

Bread wheat (*Triticum aestivum* L.) is one of the most popular cereal crops as most of the people consider it as their staple food. In wheat, optimized tillage operations bring the soil in better health necessary for crop growth cycle. Improved yield up to 20% can be achieved by picking the best tillage implement and method (Ahmed and Morrall 1996).

In wheat, many types of conservation tillage practices have been used, which comprised of no tillage, reduced tillage, minimum tillage, and incomplete tillage. These types of tillage practices have been rejected by many scientists working in different regions on the world. In contrast, the conventional tillage which uses shallow to deep plowing tillage implements has been recommended in order to improve soil health and growth and yield of wheat crop (Putte et al. 2010). The conventional tillage has been found to be effective in enhancing the quantity of carbon in the soil which augments the activities of microorganisms in soil, and this ultimately reflects in better growth and yield of the crop (Babujia et al. 2010).

5.11 Rice

Tillage is very important for rice cultivation. In some countries, the wooden plow is still being used for land preparation (Satter et al. 1993), which requires more time for seedbed preparation (Kadir et al. 1999). In current years power tiller is used for land preparation. Deep tillage by power tiller decreases the bulk density and increases the soil porosity, infiltration rate, and hydraulic conductivity (Rahman and Mustafa 1989). The highest grain yield was founded with 15 cm depth with the aid of the use of power tiller and the lowest grain yield at 7.5 cm depth tillage through the usage of moldboard plow. So, power tillage gave greater yield than moldboard plow draft through animals (Rahman et al. 2004).

In compact soil, the processes like compaction of soil, improvement in rooting depth, control of weeds, depth of seeds, and harvesting sunlight can be improved by deep tilling using power tillers. In plowing, it is observed that the conservation of moisture was less in shallow tillage at the depth of 0–50 cm, while more moisture was conserved at deep tillage at the depth of 50–100 cm (Hong-ling et al. 2008). The use of deep tillage is beneficial in terms of improving soil physical and chemical properties; however it is not cost- and time effective.

5.12 Maize

Maize, after wheat and rice, is the third most important cereal crop. It plays a decisive part in the economy of agro-based countries. The maize seed consists of starch, protein, amino acids, fibers, glucose oil, and fatty acids.

Tillage, which is considered as one of the most beneficial operations in agricultural lands, is performed primarily in order to mingle up soil and organic and inorganic particles, to loosen up surface and subsurface soil, to eradicate weeds, and finally to establish a fine seedbed to facilitate seedling germination and plant growth. The effectiveness of physical and biological processes being governed in the soil is mainly due to the kind and intensity of tillage, which significantly influence the growth and yield of plant as well as the microclimate of the crop (Rashidi and Keshavarzpour 2007).

The conservation tillage lowers the temperature in the soil zones occupied by the seeds and results in slow emergence and germination when compared to conventional tillage. The conventional tillage was found to be effective to produce more leaf area index and growth rate of the crop as well as dry-matter production. Contrary results have also been reported where the higher values for crop growth parameters and yield were observed in no-till soils.

Soil manipulation is very important for better establishment and further growth of crop to receive higher yield. Tillage facilitates and increases the capacity of soil for aeration and provision of nitrogen to the plants through accelerating the process of mineralization (Dinnes et al. 2002). The compacted soil because of its low porosity and undue power restricts root growth only to the upper portion of soil, and roots fail to penetrate deep into soil for drawing moisture and nutrients (Lipiec et al. 2005). Soil compaction also hinders roots to contact with soil nitrogen. Nitrogen is essential for early plant growth, and in response the shoot growth and its quality become weakened.

Sandy loam soils also face the development of hard pans due to repetition of tillage operations at indistinguishable soil deepness. These problems can be overcome by using tillage performed at different ranges of soil depth. It is observed that the maize yield can be improved by tillage performed at 90 cm deep into the soil which loosens the soil and decreases root penetration. The use of chisel plow and moldboard plow, as compared to conservation tillage, improved soil bulk density and decreased soil hindrance to the roots in the soil for the uptake of nutrients and soil water and ultimately improved crop growth and yield by promoting number of grains per cob, 1000 grain weight and grain yield. In some studies the yield obtained under chisel plowing was similar to that of conventional tillage. Diazzorita et al. reported a gain in grain yield by 9% under deep tillage done by chisel or moldboard plow. The similar kinds of results were also obtained by Astier et al. by using chisel plow as compared with zero tillage. Marwat et al. and Rashidi and Keshavarzpour (2007) also recorded an increase in grain yield of maize in the case of conventional tillage rather than reduced tillage.

5.13 Tillage Effect on Yield of Oilseed Crops

5.13.1 Cotton

To control weeds plowing is considered the most operative technique. Brown et al. (1994) found that an increase of organic matter and a reduction of the soil pH after long-term use of no tillage cause adverse results at the upper layer of the soil due to the activity of some residual herbicides such as fluometron. To manage a comparable weed control to that of conventional, more herbicide applications are required (Brown et al. 1987). Postemergence application of directed foliar herbicides may also prove gainful (Brown and Whitwell 1985). With reasonable weed control, cotton growth and lint yield with conservation tillage in conventional crops are similar to the irrigated one (Denton and Tyler 1997). Yields may significantly increase in the dryland crops (Wiese et al. 1994) and periods with limited rainfalls (Vacek and Mutocha 1997). To reduce considerable production costs, conservation tillage provides an opportunity. Although herbicide costs are more with no tillage, long-term benefit increases over conventional tillage, because of increased yield and lower machinery depreciation costs (Harman et al. 1989). Crop residues on soil surface protect it from erosion (Yoo et al. 1988; Denton and Tyler 1997) while increase the organic matter at the upper layer of the soil. Increased organic matter improves soil structure and water holding capacity and prevents soil compaction (Helms et al. 1997; Harman et al. 1989). A crop production system that minimizes cultivation is a conservation tillage. Typically, maintaining 30% of a cover crop is considered the standard that describes conservation tillage. This system frequently utilizes cover crops such as barley, wheat, or rye, among others (Gajri et al. 2002), planted previously than the cotton to reduce soil erosion, conserve and trap rainfall within the field, and provide early season wind protection to the crop. Cottons with resistance to glyphosate allow the grower to control weeds using this herbicide, thereby decreasing the need to cultivate for weed control. Soil moisture loss is reduced due to less cultivation of the soil.

Use of reduced tillage systems has been expanding in the Texas Rolling Plains area due to lower production costs, with some advantages offered in reduced tillage over conventional tillage, and some researchers have found significant improvements with conservation tillage systems in cotton yield. This yield increase was attributed to improved soil moisture holding. Reduced evaporation from the soil is due to the use of heavy cover crop residue mulch in conservation tillage systems (Johnson et al. 2005; Lentz and Hanks 2005). In the tropics and subtropics, repeated intensive tillage on soils leads to soil loss, nutrient depletion, and oxidation of soil organic carbon and a decline in soil quality. Deterioration of soil structure decreases water infiltration and increases runoff losses and enhances the process of soil erosion. It also affects soil physical properties. However, conservation tillage has greater influences in reducing the erosion rates, and improvement in soil and water conservation results in higher yields of cotton crops from agricultural systems. However, Daniel (1999) reported that cotton yield and quality are not influenced by different types of tillage systems. Smith documented that subsoiling is more effective in improving cotton crop compared with tillage operation by disk harrow.

5.13.2 Canola

Early low-cost methods to reduce risk of yield loss such as crop rotation and tillage practices are of interest to farmers (Turkington et al. 2000). Tillage decreased pathogen survival by burying and cracking crop stubble and altering the soil environment where the pathogen is present (Kharbanda 1999). Based on amount of stubble retained on the soil surface, tillage systems can be grouped into three categories: conservation tillage, conventional tillage, and minimum tillage. Less than 15% stubble is retained on the soil surface after planting in conventional tillage systems. Reduced tillage systems or conservation tillage leaves 15 of 30% stubble on the soil surface, and practices that retain more than 30% stubble are considered to be minimum tillage systems, including mulch tillage, zero tillage, and ridge tillage (Workneh and Yang 2000). It is often hard to differentiate tillage systems between conventional and zero-tillage systems. Tillage reduces disease by burying, breaking up crop stubble, and changing the physical environment where the pathogen and decomposing microorganisms exist in the soil (Kharbanda 1999).

Tillage affects both grain yield and crop growth. Minimum tillage, with or without straw, improvement in moisture conservation in soil profile, and higher water availability during crop growth period increase the yield components, root mass, and seed yield in mustard (Asoodari et al. 2001). Gradual release of moisture regulates the soil temperature, and also the lower mechanical resistance leads to better growth of mustard (Rathore et al. 1999). Moreover, uniform distribution of crop residues in soil results in homogenous soil moisture regimes, thereby improving mustard yield. Deep tillage operations cause burial of nutrients due to deep inversion of soil, while uniform distribution of nutrient near soil surface and more nutrient availabilities in rhizosphere promote mustard growth in conservation tillage (Nagra et al. 1976). Moreover, more root densities of mustard crop in upper soil containing higher available nutrients improve fertilizer use efficiencies in zero-tillage system.

5.13.3 Sesame

In agriculture systems, use of new technologies with several other management practices is of great significance to reduce the production cost and increase the profitability of system. Hence, sustainable farming systems are more favorable due to less use of external inputs and minimum threats to the environment (Govaerts et al. 2005). Conservation tillage is proved to be more effecting than other alternative methods because of energy saving of 40% during seedbed preparation for sesame crop compared with other tillage methods (Canakci et al. 2005) and 30% lessening of tractor use for the post-wheat second crop of sesame (Özmerzi and Barut 1996). Improvement in sesame production using conventional tillage practices improves soil porosity and incorporation of residues (Dinnes et al. 2002). Increase in soil porosity under well-aerated conditions ensures oxygen availability for root respiration. Deep tillage improves root length and moisture availability compared with shallow tillage, thereby resulting in higher plant height and grain yield of sesame (Bahadar et al. 2007). Recently, reduced and no-till methods are becoming popular. Many researchers have reported during conventional tillage operations increase in soil disturbance and aeration enhances the organic matter decomposition and release of nutrients during mineralization (Dinnes et al. 2002), while in contrast, less disturbance of soil during zero tillage results in minimum exposure and decomposition of organic matter, thereby resulting in less susceptibility of nutrient losses by leaching and (Bahadar et al. 2007) tile drainage. Use of conventional tillage operations farming systems has been proved to increase plant growth by minimizing the hostile effects of high temperature due to rapid decrease in moisture contents and soil crusting (Bulent et al. 2012). Moreover, use of no till or reduced tillage improves soil aggregation, therefore decreasing hazards of soil losses during erosion process (Polat et al. 2006). Seed weight in sesame is not affected by drought stress; however, yields of auxiliary branches are more sensitive to water stress. Bulent et al. (2012) have reported that conservation tillage proved better in improving sesame plants.

5.13.4 Groundnut

To reduce weed competition (Buchanan and Hauser 1980; Shear 1968) and disease incidence (Boyle 1952, 1956) and to provide soil conditions favorable for root growth, many peanut (*Arachis hypogaea* L.) producers and researchers trust that tillage is necessary (Sturkie and Buchanan 1973). Usually, moldboard plowing has been done in early winter or late fall to insure the decomposition of present plant residues. Little data exists on optimal depth of soil preparation in peanut production, but most soils are plowed 15–20 cm deep to permit for weed seed and disease propagule burial. Conventionally prepared peanut seedbeds are normally disked quite a few weeks before planting to destroy weeds and level fields. A final disking just before planting is frequently used for incorporation of preplant herbicides. This method of land preparation has been called “deep turning, non-dirting” peanut culture by Boyle (1952, 1956). It has been used since the early 1950s by most US peanut producers because previous research (Garren 1959; Garren and Duke 1958; Mixon 1963) presented significant yield increases when this system was used compared to less-intensive tillage systems. For agronomic crops production, traffic, plow, or genetic hard pans in coastal plain soils have made in-row subsoiling, a popular tillage method for both conventional and minimum tillage (MT). However, in-row subsoiling and other forms of deep tillage rise fuel costs and may slow down planting operations (Elkins and Hendrick 1983). Use of a slit-plant system (Elkins et al. 1983) may reduce energy and draft necessities of subsurface tillage as much as 40% compared to old-style in-row subsoiling. Furthermore, numerous new production methods have been introduced since the original work, comparing gradations in tillage from disking to moldboard plowing for the production of peanuts, was conducted in the mid-1950s (Garren 1959; Garren and Duke 1958; Mixon 1963).

5.13.5 Soybean

Significant impact of tillage has been observed in soybean crop (Lueschen et al. 1991). However, some studies recorded better growth and yield of soybean under no tillage, and other experiments reported better crop growth and yield under conventional type of tillage operations (Philbrook et al. 1991). Study conducted resulted in that there may be a yield difference in different years, but both types of tillage systems, i.e., no tillage and conventional tillage, have not affected significantly on soybean yield.

In some studies it has been found that the soybean yield was improved when planted under different tillage systems as compared to no tillage (Vasilas et al. 1988; Guy and Oplinger 1989). These results were contrary to those of Pedersen and Lauer (2004) who observed enhanced biomass, plant height, and yield under no tillage as compared to conventional tillage. However, Yusuf et al. (1999) found little increase in biomass accumulation of crop under no-tillage production system, while he obtained no yield differences under both types of systems. This ambiguity in the results might be due to the environmental factors. Meese et al. (1991) recorded that the reduction in growth and yield parameters might be subjected to premature vegetative growth in cooler soil temperatures and better soil deposit cover under no tillage. To attain sustainable agriculture system, minimum tillage (MT) and other elements, such as diversity of cultivated species, crop rotation, use of legumes in crop rotation, and use of organic matter, are planned components of the system. All the physical, chemical, and biological soil properties are affected by minimum tillage (MT). Minimum tillage (MT) enriches soil organic carbon content when applied for long term; it influences the stability of structural aggregates; and helps conserving the soil humidity. The conventional systems contribute significantly to the degradation and depletion of the natural resources leading in the end to higher costs (CS) but at the same time achieves increased grain yields.

5.13.6 Sunflower

In sunflower crop, different types of tillage systems affect seed yield, oil content, and protein contents as well as growth parameters of the crop. Yalcin and Cakir (2006) received higher seed yield under conventional tillage system while lower seed yield under no tillage. It was observed that sunflower yield was improved in silt-loam soils when sown under ridge tillage, and the same kind of results was also observed by Yalcin and Cakir (2006). De la Vega and Hall (2002) declared nonsignificant effect of tillage systems on seed yield, oil content, and protein content of the seed. In contrast, Lopez et al. (2003) found higher grain protein content under no tillage than under conventional tillage.

5.14 Tillage Effects on Yield of Pulses

Mungbean yields obtained with zero tillage were higher and acceptable vegetative straw on the soil surface as compared to conventional tillage. Chassot et al. found that the surface of soil in no tillage is usually colder and wetter and bulk densities higher than conventional tillage. This has had an effect on the growth of chickpea root and the absorption of nutrients. Amini and Movahedi Naeini concluded that reducing the yield of products in no-tillage system is directly affected by more mechanical soil resistance or lack of moisture and access to nutrients. The conservation tillage practices, developed mainly for large-scale mechanized agriculture, need to be adopted for rainfed pulses in India. Giorgio and Fornaro results showed that environmental and production cost can be decreased with minimum tillage application to broad bean crops cultivated. Hugii and Kalaghatagi studied that among two tillage practices, higher growth parameters like plant height, number of leaves, leaf area index, dry-matter accumulation in leaves (g), dry-matter accumulation in stem (g), total dry-matter accumulation in plant (g), and test weight (g) (average of seven crops 87.31, 26.60, 1.11, 6.81, 15.54, 22.30, and 9.21, respectively) were recorded under zero tillage due to more moisture retention in soil as a result of lesser losses through evaporation and higher microbial activity as compared to minimum tillage. Among interactions, significantly higher grain yield was recorded by maize crop grown under zero tillage (3350 kg ha^{-1}). Net returns were higher in black gram crop grown under zero tillage (Rs. 91,530 ha^{-1}), and significantly higher benefit cost ratio was recorded under black gram crop grown under minimum tillage. Salehi et al. found that in the first year, the results of analysis of variance showed that the effect of tillage was significant only on grain yield at 5% level. However, the effect of tillage on moisture content was not significant in the studied properties. In the second year of experiment, the tillage factor also had a significant effect on grain yield, biological yield, and moisture content at the depth of 0–20 cm at 5% level, and it was significant on moisture content at the depth of 20–40 cm at second phase at 1% level. Since the yield of the crop was lower in no tillage than in other cases, the use of no tillage has caused that there is no place for agricultural equipment and machinery in the farm which caused density in soil. It should be noted that these machines and equipment are so expensive; this issue is very important in economic terms; therefore, the use of no-tillage system is proposed. Mahata et al. explained that early stages of growth and dry season cultivation improved the shoot and root gain per plant, number of secondary roots/plant, rooting deepness, and number of nodule per plant for both crops black gram and cowpea. Plowed soil gave faster growth and higher grain yield of black gram (21% and 40% in two seasons of study).

5.15 Tillage Effects on Yield of Fodder Crops

Fodder crops have greater importance from farming point of view as dairy sector has greater impact on Pakistan’s economy and an important part of agriculture GDP. Growing fodder crops helps the farmers to rear more animal. So agriculture practices including tillage systems play a significant role in improving fodder yield as well as quality. Conservation tillage has become an integral component of sustainable farming by decreasing production costs and soil loss, conserving energy, reducing soil erosion and labor costs, and eliminating extensive land preparation prior to planting. Reduced tillage produced taller plants (211 cm), more leaves per plant (9.3), and higher fresh and dry fodder yield of maize. Conservation tillage improves maize fodder yield of corn by conserving soil moisture and reducing its temperature. Soil physical properties such as soil bulk density and soil porosity are greatly influenced by tillage operations and have greater impact on fodder yield. The yield levels of cereals, e.g., oat, barley, and wheat, increase 2–8% with decreasing tillage intensity, whereas yields of fodder beet (*Beta vulgaris* L.) were increased under plow tillage. Yields of *Brassica* crops were greatly affected by tillage intensity. Average yields for *Brassica* fodder were 23%, 52%, and 59% higher with deep-tine cultivation, shallow-tine cultivation, and minimum tillage, respectively, than with plow tillage. Positive residual effects of reduced tillage systems were found on the yields of both Brassicaceae and Gramineae crops. Reduced tillage intensity may thus be recommended for all crops studied, with the exception of fodder beet, on morainic loam soils.

5.16 Sugar and Fiber Crops

5.16.1 Root Growth

The profundity of the sugarcane root framework decides the volume of soil accessible for water and mineral take-up. Evans found that underlying foundations of old sugarcane assortments could develop to a profundity of 6 m under extremely good conditions. The root framework profundity in live sugarcane plants is especially difficult to survey. Over the top utilization of overwhelming hardware and executes cause the dirt compaction resultantly mass thickness may impact the transmission of water and air through the dirt, difference in warm limit diminish the measure of supplements mineralized from the dirt, which comes about the lessening in edit yield. Compaction advances hard container beneath the dirt surface. This hard dish limits the root entrance, and over the top water system may not deplete downward which causes impediment of plant development. So removing this hard subsoil layer through deep tillage may enhance root growth which improves water and nutrient uptake and enhances crop growth and yield.

5.16.2 Yield and Quality

Sugarcane is planted on wide range of soil types throughout the world. Contrasting and the other sugarcane delivering nations, Pakistan positions fifth, in real estate, and eighteenth, in yield per unit territory. Sugarcane contributes around 64.6% of the aggregate world sugar production. One of the vital reasons for its better yield is the technologically developed strategy of planting sugarcane. The traditional cultivator is regularly used with tractor as essential and auxiliary tilling implement, ordinarily works up to a depth of 8–10 cm, and had negative impact on sugarcane yield, whereas in sugar beet, shallow tillage practices also deteriorate its yield and quality because it is a tuber crop and porous soil is essential for its root growth. A typical and clear explanation behind the sugar beet yield is shallow tillage. However, decreasing tillage depth to 12–18 cm decreases sugar beet yield up to 9%. Soil mass thickness, penetration resistance (PR), and water infiltration strongly depend on tillage depth. In this manner, surveying the impact of tillage systems and technique on these physical properties may have greater impact on yield of sugar crops. In different research investigations, water invasion was more notably found in disturbed soil compared to no-till soil.

5.17 Effect of Tillage on Fiber Crops

5.17.1 Root Growth

Cotton is an important fiber crop, and there are numerous reasons with respect to why tillage is used in cotton production as cotton seedlings are influenced by soil conditions. Yield incremented development depends mainly on root firmness in the subsoil layer. Development of strong and vigorous root system is critical to take into account for the extraction of water and nutrients. Hindrance in root development at flowering in cotton crop affects its yield and productivity which is greatly affected by tillage operations. Soil compaction may likewise happen because of using heavy machinery or same tillage implement which restricts root growth. Precisely recognizing and finding areas of subsoil compaction by profundity is imperative and gives a superior comprehension of how culturing can be utilized to remove compaction and take into consideration ideal root growth (Raper et al. 2000).

5.17.2 Fiber Crop Yield and Quality

Decision of tillage technique relies upon area of crop cultivation and soil type. A few expenses related with tillage include fuel and time. Soil plowing is not generally important for cotton cultivation but also important for other crops. A long-term tillage involves the improvement in soil's physical and chemical properties and corrects the subsoil compaction which improves root proliferation and crop yield. Soil compaction can be caused and impacted by numerous variables and largely affects plant development and yield. Reduced cotton under subsoiling was observed compared with no tillage (Touchton et al. 1986).

5.18 Insect, Pest, and Diseases

Soil tillage is one of the major and essential farming practices used for growing crops. It can be a helpful tool for managing harmful pest and diseases. Though tillage is mainly associated with weed management, different tillage systems are also helpful for managing or controlling plant fungal pathogens and insect pests. The impact of tillage on the incidence of fungal pathogens (*Mycosphaerella graminicola* on winter wheat and *Pyrenophora teres* on spring barley) was significant only in interaction with soil tillage and straw management. Higher attack of some pests, e.g., *Dasineura brassicae*, larvae of family Elateridae, and *Ostrinia nubilalis*, has been observed under minimum soil tillage. Reduced tillage creates conditions that are suitable for lower number of weed species; therefore the diversity of species is decreasing. Differences in seed burial depth can also have important implications for relative time of weed emergence, survival of weed seeds, and distribution of weed species. Minimum tillage retains crop residues on the soil surface which act as a shelter for causal organism for diseases. An increase in leaf diseases was reported in wheat in minimum tillage systems compared to conventional tillage (Brandt and Zentner 1995; Krupinsky and Tanaka 2001). But contrary to this, more disease development was observed in moldboard-plowed plots compared with no tillage (Abrahamsen and Weiseth 1999).

5.19 Greenhouse Gases Emission

The agricultural practices are an important source of greenhouse gases (GHG), with carbon dioxide (CO_2) as major gas and contributes about 81%, followed by methane (CH_4) (11%) and nitrous oxide (N_2O) (6%) (EPA 2016). However, the global warming potential of CH_4 and N_2O is 25 and 298 times greater than that of CO_2, respectively. Agricultural practices such as different tillage practices, crop rotation, and use of fertilizers account for 80% of the total N_2O emissions in the USA annually (EPA 2016; Venterea et al. 2011). Tillage had great impact on CH_4 and N_2O emission through altering the soil properties (Al-Kaisi and Yin 2005; Yao et al. 2009). Adapting conventional tillage (CT) to no tillage (NT) can significantly reduce CH_4 and N_2O emission (Matthias et al. 1980; Estavillo et al. 2002).

5.20 Effect of Tillage on CO_2 Emission

The CO_2 outflow from soil to the air is an essential component of C misfortune from soils, which is ascribed to the digestion of plant roots and widely varied small-scale vegetation. Rates of soil breath are controlled by a few variables including soil temperature, amount and nature of soil organic matter (SOM), soil dampness, and the CO_2 focus slope between the dirt and the environment. CO_2 discharges in the environment are impacted by agricultural practices, for example, culturing as well as residue burning. Different tillage systems such as conventional tillage, reduced tillage, and no tillage were compared for more than 10 years in two Brazilian Oxisols. It was noted that carbon stocks in no tillage were 0.35 Mg ha^{-1} year^{-1} which was higher than the other tillage systems in tropical soils (Bayer et al. 2006).

The transitions of CO_2 between the air and the dirt are a vital connection in the C cycle, and the procedures that intercede these motions influence the environmental convergence of CO_2. Conservation tillage is one of the management practices for expanding soil organic carbon (SOC) pool in biological soil systems. It is observed from study that no till (NT) resulted in a normal soil C increment compared with conventional tillage practices. It is a fact that intensive tillage may enhance decomposition of soil organic matter due to more soil loosening and hence lead to more emission of CO_2 compared with conservation tillage practices like no tillage or minimum tillage.

5.21 Effect of Tillage on Nitrous Oxide Gas Emission

Nitrous oxide (N_2O) gas emission is directly affected by farming practices such as N application rate and source, tillage, and crop type (FAO 2000). Similarly, fertilizer application timing, method and use of other chemicals, irrigation, and residual N and C from previous crops and fertilizer all affect N_2O emissions. Nitrogen application promotes N_2O production through nitrification and denitrification.

In addition to this, tillage practices greatly affect the emission of N_2O. In recent years, use of no tillage has been proposed as effective ways to enhance crop yield and reduce N_2O emission (Sainju et al. 2014). Conventional tillage practices significantly increased N_2O emission up to 35% compared to the no-tillage practices, and this increased N_2O emission under conventional tillage was mainly because of lesser crop N demand and higher soil water loss (Deng et al. 2016). N_2O emission depends upon the tillage systems as well as soil type. Long-term tillage studies were performed to compare no-till and tilled soils, and it was observed that no tillage generally increased N_2O emissions in poorly aerated soils with a humid climate but was neutral in soils with good and medium aeration (Rochette 2008). Different studies showed different results for no-tillage effect on N_2O emission; some showed increased, while other showed decreased N_2O emission. Intensive tillage practices massively impact soil properties, which may impact the degree of N_2O outflows. Use of heavy tillage practices brings about loss of soil organic matter (SOM) and weakens soil structure. Receiving lessened or no tillage (NT) may influence N_2O outflow yet the net impact is conflicting and not very much evaluated universally (Smith and Conen 2004). The impact of lessened tillage on N_2O discharges may rely upon soil and climatic conditions. In a few zones, less tillage promotes N_2O discharge, while somewhere else it might lessen outflows or have no quantifiable impact.

5.22 Effect of Tillage on Methane Gas Emission

Methane (CH_4) is an imperative ozone harming gas. As indicated by the Greenhouse Gas Bulletin of World Meteorological Organization, the centralizations of air CH_4 and N_2O achieved 1833 and 327 ppb in 2014, individually, while consolidation of rice buildups by tillage diminished N_2O outflows because of N immobilization. Normally, undisturbed soils go about as a net CH_4 sink; however a sensational decline on the CH_4 oxidation rates is experienced when soils are changed over to agribusiness, whose impact has been chiefly identified with the ammonium-based N preparation. Usage of protection culturing frameworks has been recommended as a key system to diminish CH_4 outflows to climate by reestablishing CH_4 sink quality in agriculture soils. In any case, most investigations have confirmed a little impact of soil administration on soil CH_4 production in soils, and quite a few years might be required for giving a critical impact of the conservation tillage frameworks on soil CH_4 sink quality. Decades might be required for giving a critical impact of the conservation tillage frameworks on soil CH_4 sink quality.

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6

Alternate Wetting and Drying System for Water Management in Rice

Khuram Mubeen and Khawar Jabran

Abstract

Alternate wetting and drying (AWD) is aimed at saving water and maintaining comparable grain yields in the rice farming. It is a system of water management which involves the drying and rewatering of rice fields periodically. Rewatering is done to about 5 cm depth after the water level has fallen to 15 cm soil depth. This practice is repeated during the whole crop growing period except the flowering stage where the water level is maintained at up to 5 cm water depth. In order to get the best out of the AWD, it is important to select the right soil type, maintain the optimum plant population, apply nitrogen timely, and maintain the correct duration of wetting and drying. Fields under AWD may be ponded with water for 2–3 weeks for the cultural control of weeds. A good coordination among stakeholders may assist in attaining the maximum benefits from AWD. AWD also reduces arsenic in the rice grains and methane emission from the rice fields. It improves growth of root and canopy structure. Correct implementation of AWD can impart intended outputs on sustainable basis to tackle water scarce condition without losing rice productivity.

Keywords

Rice · Water scarcity · Irrigation · Alternate wetting and drying · Weeds

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6.1 Introduction

In the recent past, water scarcity situation has worsened rapidly, while development of water resources is very limited. Importance of water for crop production is well established and prioritized in crop production system (Aranda et al. 2012).

Rice (*Oryza sativa* L.) plays an instrumental part to ensure world food security (Chauhan et al. 2017). Rice covers 30% of irrigated cropland globally (Lampayan et al. 2015). Worldwide around 80% of rice harvested area and 92% of rice production are under irrigated and rainfed lowland rice systems (Dobermann and Fairhurst 2000; Chauhan et al. 2017). About three-fourth of the world's rice is cultivated under flooded conditions (Chauhan et al. 2017). Growing of rice by the conventional flooded method needs more water, time, energy, and labor than the non-flooded rice cultivation or the cultivation of other field crops (Ehsanullah et al. 2007; Farooq et al. 2011; Jabran et al. 2015a, b, c). Failure in getting an optimum plant population is an important cause for low rice yields in developing countries like Pakistan (Ehsanullah et al. 2007). Growing rice using less water offers promising alternative to conventional rice production under water scarce conditions (Calzadilla et al. 2011; Kumar and Ladha 2011; Liu et al. 2015).

After a significant decrease in the water availability, researchers in many of the rice-growing areas have been working to develop water-saving rice production methods (Farooq et al. 2011; Jabran et al. 2012; Nie et al. 2012). Hence to improve water use efficiency by growing rice with less water, technologies must be worked out. Alternate wetting and drying (AWD) is one such water-saving rice cultivation technique being developed in rice-growing areas around the globe (Nie et al. 2012; Ye et al. 2013; Jabran et al. 2015a, b, c, 2016, 2017a, b). Such system does not involve a standing layer of water as is the case with the flooded one (Nie et al. 2012).

Rice grain yield under AWD system is very much variable as some studies reported reduction (Linquist et al. 2015; Xu et al. 2015; Jabran et al. 2015a, b), and many other studies documented no variation in yield (Belder et al. 2004; Dong et al. 2012; Yao et al. 2012), while some reported even increased yield with AWD (Liu et al. 2013). Jabran et al. (2015a) reported that sowing of fine rice varieties under AWD could significantly decrease the water input for rice production, but this was accompanied with a decrease in yield. Water-saving systems including AWD could reduce the water input by 18–27% and resulted in higher water productivity, but there was also a yield decrease of 22–37% (Jabran et al. 2015b). This differential yield response or yield losses in many instances are a hurdle in adoption of AWD though this variation is due to highly variable techniques adopted for water management under varying soil types in different environments. Yield difference or losses could be overcome by using techniques such as soil mulching that not only helps in increasing the water retention in the soil but also helps in improving the rice grain quality (Jabran et al. 2015b, c).

AWD may influence grain yield by changing nitrogen cycling in rice production systems (Dong et al. 2012). Wetting and drying cycles cause denitrification-nitrification in soil layers with minimal nitrogen loss (Buresh et al. 2008). However the duration for which wetting and drying is done is very crucial. For example, if drying cycle is prolonged, nitrogen loss (including N_2O) may increase through nitrification while may denitrify upon re-flooding (Cai et al. 1997; Hussain et al. 2015). Hence water management and time of N application should be kept in mind to avoid high N_2O emissions. Sarwar et al. (2013) concluded that intermittent flooding and drying condition with combined micronutrients application (boron and zinc) can be a good and economical option for water-saving rice cultivation.

Arsenic (As) accumulation in rice grains has been a concern especially among communities with high rice consumption (Gilbert-Diamond et al. 2011; Williams et al. 2007; Zhu et al. 2008). Under the flooded rice cultivation conditions, As (III) form (more mobile) predominates over the As (V) form (strongly adsorbed), bringing more As in soil solution and increased entry into rice plants (Zhao et al. 2010). AWD reveals reduced grain As accumulation (Linquist et al. 2015), due to change in soil redox potential due to drying events causing reduction in mobility and uptake of As.

Furthermore the drying event will improve not only root growth in rhizosphere but will also facilitate water transport to rice plants even under water deficit conditions. Irrigation water saving will not only provide a relief to farmers but will also have a positive effect on environment due to reduced fuel cost for pumping additional water and reduced ground water withdrawal. Globally, more than 50 kg of rice is used per person per year (FAOSTAT 2016). Major areas of rice use and production are extended in west from Pakistan to east in Japan. Higher rice production in irrigated rice production system resulted in water shortage.

6.2 Global Warming Potential

Reduction in CH_4 emission by AWD has been reported to be 48–93% (Linquist et al. 2015; Qin et al. 2010; Xu et al. 2015). There is no overall reduction in global warming potential through AWD in general though (Linquist et al. 2015; Xu et al. 2015). Hence the reduction in amount of CH_4 emitted during the growing season following the first drying event is negligible with pronounced reduction in CH_4 in spikes. On the other hand, N_2O is increased negating the reduction in GWP brought about by reduction in CH_4 emission (Akiyama et al. 2005; Lagomarsino et al. 2016). More than half of the man-induced non-CO_2 greenhouse gas emission particularly nitrous oxide (N_2O) comes from nitrogen addition in soil and emission of CH_4 from livestock and cultivation of rice (Smith et al. 2014).

6.3 Water Management in Rice

Currently about four billion world population is under the threat of water shortage (Mekonnen and Hoekstra 2016). This situation demands minimizing water use and increasing productivity for growing population. Limited water supply is among the most important rice production constraints (Yeston et al. 2006). Water scarcity in most of the rice-producing countries has become more acute than past, demanding higher water use for efficient rice production in future. About 80% of fresh water resources for irrigation is used for rice production in Asia (Bouman and Tuong 2001). In water scarce area, some people are in favor of avoiding growing of high-water requirement crops like rice, but it is well-regulated agricultural industry in countries like Australia and Taiwan. Irrigation water quantity and quality are affected by world population growth, climate change trends, and economic development. Sustainable development of rice production systems depends on better understanding of factors which affects water resources management for efficient water use.

6.4 Alternate Wetting and Drying System of Irrigation

Irrigated rice fields are traditionally flooded starting from transplanting (or sowing) and ending at completion of grain formation or physiological maturity (Jabran et al. 2015a, b, c, 2017a, b; Takayoshi et al. 2016). Flooding results in water losses through percolation, seepage, and evapotranspiration. The International Rice Research Institute (IRRI), Philippines, has found that flooding is needed only at rooting and flowering stages in paddy fields (Van der Hoek et al. 2000). Consequently, the AWD technology was developed. Intermittent irrigation involving periodic drying and re-flooding in paddy fields except the rooting and flowering stages (field is kept continuously flooded at these two growth stages) is called AWD. The field is allowed to dry till level of water drops to 15 cm under soil after 2 weeks of transplanting. Rewatering is done to pool water in the field at 3–5 cm depth of water. This is exercised periodically other than at flowering where water maintained at 3–5 cm depth of water. If field is heavily infested with weeds, AWD should be delayed for 2–3 weeks to suppress weeds by the ponded water and improve the herbicide efficacy (Anonymous 2018). Nitrogen can preferably be applied on the dry soil just before irrigation.

Plastic pipe 30 cm long can be used as field water tube, or bamboo can be used to make field water tube having diameter of 10–15 cm. Such water tube will make visible the water table inside soil and may be removed easily if required. The tube should be perforated on all sides with many holes for free water flow. Insert the tube into the soil in a way that 15 cm remains above the soil surface. Water tube does not penetrate through the plough layer, and hence care is needed during installation. Tube bottom should be kept visible by removing the soil present within the tube. After flooding, the field water level inside and outside of tube should be same. If it does not happen, the compacted soil may have blocked the pores thus requiring reinstallation of the tube. The water level raised inside the tube represents depth of water table. Good access to the tube is helpful for effective monitoring of water level inside the tube (Michael and Samuel 2017) (Table 6.1).

The soil drying can be controlled by different means like monitoring non-flooding days, fixing soil water and leaf water potential, recording the soil moisture content, looking the plant leaves and soil visually, etc. (Jabran et al. 2015a, b; Ye et al. 2013; Yao et al. 2012; Zhang et al. 2009, 2008, 2010, 2012. Liu et al. 2013, Belder et al. 2004). AWD reduces water use by 30% and also maintains yields that

Table 6.1 A summary of the benefits obtained by following alternate wetting and drying method of rice cultivation

Benefits of AWD	References
Eliminates water losses in the form of seepage and deep percolation and saves water up to 44%	Lampayan et al. (2015) and Rejesus et al. (2011)
Increase in water productivity compared to the conventional rice production method	Jabran et al. (2015a, b)
Decrease in production cost compared to the conventional rice production method	Jabran et al. (2016)
Reduces arsenic accumulation in rice grain	Linquist et al. (2015)
Abscisic acid levels in plants increases with moderate AWD during soil drying event	Yang et al. (2001, 2002, 2004), Yang and Zhang (2006) and Chen et al. (2016)
Can reduce greenhouse gas emissions, especially methane	Wassmann et al. (2010) and Li et al. (2006)
Global warming potential reduction (GWP – CH_4^+ N_2O) is 45–90% compared to continuously flooded systems	Linquist et al. (2014)
Reduction of methyl mercury concentration in the soil	Rothenberg et al. (2016)
Drying of rice fields was effective in controlling the rice water weevil, the most economically important insect pest of rice in the U.S.	Quisenberry et al. (1992)
Fertilizer losses with percolation and seepage water are reduced	Mao (1996)

are comparable to flooded rice (Bouman et al. 2007). Rewatering is done after the tube water lowers to 15–20 cm below the soil surface. Watering will saturate the soil to about 2–5 cm in comparison with conventional irrigation that saturates the soil up to 5–10 cm. To avoid sterile spikelets, field is flooded at flowering. The soil which drains at 5 days interval is generally considered fit for AWD. Rainfed areas are not suitable for AWD because of uncertainty of water availability when needed for field wetting (Richards and Sander 2014).

Other than these factors, grain yield may be affected in AWD by changing cycling of N in rice production system (Dong et al. 2012). Planned use of AWD did not reduce productivity but could even increase yields through effective tillering and better growth of roots (Richards and Sander 2014). If, before flooding the field, relatively higher nitrate is present, denitrification losses are likely to occur at rapid pace (Buresh et al. 2008). So, to avoid such losses, low soil inorganic N levels must be ensured before applying water through AWD.

For harvesting maximum advantages from AWD, irrigation design and coordination among farming community and related governmental authorities is a prerequisite. Incentivizing farmers for adoption of AWD may vary with farmers and irrigation design being used by them. In areas where farmers pay water rates for canal irrigation based on area and season, incentivizing AWD for adoption will pay little. In areas where rice is grown on tail end of the irrigation canal or where irrigation water cannot reach due to different reasons, farmers use pumps. Farmers have to buy fuel to operate pump which increases fuel cost of rice production. However adoption of AWD by farmers will reduce fuel expenses and increase farmers' income.

6.5 Potential Problems with Alternate Wetting and Drying

AWD also carry some challenges which need to be resolved for its successful adoption. Weeds are important pests of rice (Kraehmer et al. 2016), and a higher of their intensity is expected in AWD than the flooded rice (Jabran et al. 2015a). Flooded rice has a standing water layer that suppresses weeds, but AWD does not possess such layer of water (Jabran and Chauhan 2015). Therefore more labor and herbicides will be needed to keep weeds population below economic threshold level. Tabbal et al. (1992) reported that in case of high weed infestation, keeping fields flooded till panicle initiation followed by continuous saturation saves 35% of water than continuous flooding. It reflected no reduction in yield or no increase in weeds population. Furthermore, if weeds are in abundance, the field may be flooded for weed suppression or to improve the herbicide efficiency by delaying AWD for 2–3 weeks.

Availability of nutrients like phosphorus is reduced under dry soil conditions (Dobermann and Fairhurst 2000; Kirk 2004). Availability of some micronutrients like zinc reduces in flooded soils, though more available in aerated soil conditions with improved uptake in grains (Wissuwa et al. 2008). Availability of water at critical stages and quick soil drying could be problematic. However it could be dealt by using mulches (we got good results in our experiments) (Jabran et al. 2015b, c, 2016). Other challenges may include loss of predators, a complex system of water management, etc.

6.6 Conclusion

AWD for irrigated rice saves water, reduces greenhouse gases emissions, and decreases rice grain arsenic in specific regions and under the right conditions. Effective implementation of AWD results in efficient water use with improved rice grain yield. More research on AWD is though needed to investigate the water conservation and improved crop yields in an integrated way under water scarce conditions especially under changing climate scenario.

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7

Tools and Techniques for Nitrogen Management in Cereals

Ahmad Naeem Shahzad and Shakeel Ahmad

Abstract

Nitrogen is indispensable for highly productive agriculture. A number of sources supply nitrogen to growing crops. These sources include synthetic fertilizers, atmospheric deposition and fixation by soil microorganisms, and manures. It is estimated that about half of the total nitrogen fertilizers are applied to three cereals, namely, wheat, rice, and maize. However, only 33% of the total nitrogen applied could be converted to harvestable yields. Most of the nitrogen applied is lost to the environment, which contributes to the emission of greenhouse gases. The nitrogen losses have huge impact on environmental pollution and farm economics. Despite grave concerns, the increase in nitrogen use would probably continue to meet the food demands of the growing population. We have analyzed different approaches used to study the global trends for nitrogen use and nitrogen productivities for three major cereals, i.e., wheat, rice, and maize. These approaches include total N input, use of fertilizer N, N use efficiencies and agronomic efficiency for N, apparent N recovery, N surplus, and partial factor productivity for N. Additionally, we have also discussed the importance of development of nitrogen dilution curves for cereals under different environmental conditions and at regional and global scales. Use of these N performance indicators could help in improving the N productivities in cereals at regional, national, and global levels. We have explored the possible routes of N loss and modern agronomic techniques to improve nitrogen use efficiencies in cereal production systems.

Keywords

Nutrient · Cereal · Growth · Yield · Nitrogen

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7.1 Introduction

Intensive cultivation of crops has major impact on natural resources, and it is becoming a global apprehension. Due to exponential growth of human population, the demand of food, fiber, and other agricultural products is imposing a continuous pressure on water and land resources (Ahmad et al. 2009, 2013, 2018). In intensively managed agricultural systems, low input use efficiency due to use of high input resources is becoming a major concern (Ahmad and Hasanuzzaman 2012; Ahmad et al. 2012a, b). Consumption of high inputs in combination with low utilization efficiency causes many environmental (emission of greenhouse gases, acid rain), soil (soil degradation), and water (groundwater pollution and eutrophication) problems (Fig. 7.1). There is need of time to adapt a sustainable agricultural system that is efficient, profitable, and environmentally safe (Spiertz 2009; Fatima et al. 2018; Hussain et al. 2018). Nitrogen (N) is an essential macronutrient for plants because it constitutes a major portion of proteins and nucleotides. To produce dry biomass of 1 kg, almost 20–50 g N is taken up by roots of non-legumes plants. Natural supply of N is not sufficient to meet the needs of cropping systems to give optimum yield (Robertson and Vitousek 2009; Ahmad et al. 2015; Sultana et al. 2014) which requires application of synthetic fertilizers. Three cereal crops (wheat, maize, and rice) consume 50% of the synthetic nitrogen fertilizers produced globally (Galloway et al. 2004; Fowler et al. 2013). To feed the growing population,

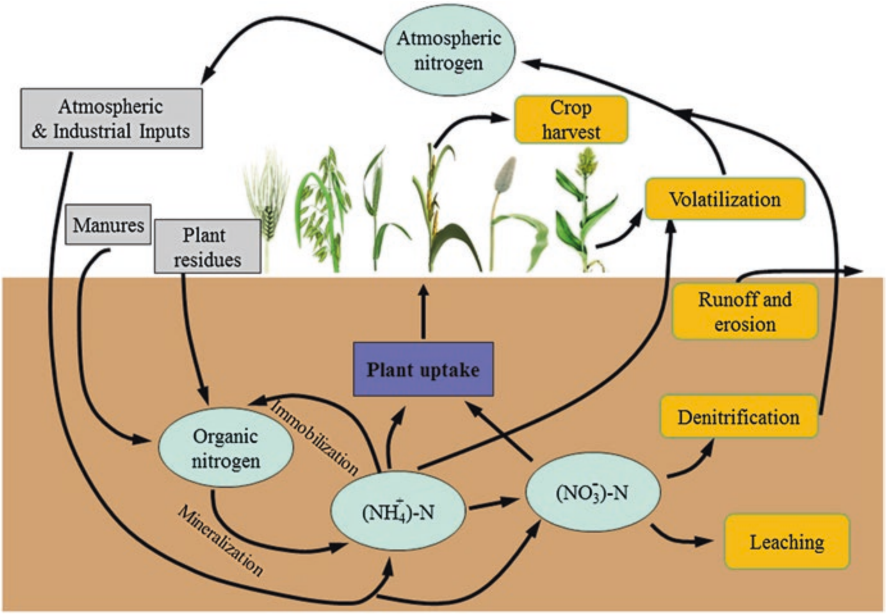

Fig. 7.1 Comprehensive N cycle signifying various inputs, losses, and plant uptakes for C_3 and C_4 cereals. (Source: Fatima et al. 2018)

cereal production must be increased that requires additional application of N fertilizers (Ahmad et al. 2016a, b). Of the total fertilizer N used, 33% is converted to reactive forms (Nr) (nitrate, ammonia, and nitrous oxide) and lost to the ecosystem (Vitousek et al. 1997). Deposition of Nr from agricultural activities is inducing threat to global biodiversity (Payne et al. 2017). Reduction in N pollution can provide potential assistance to sustainability of biodiversity (Jones et al. 2018).

The use of N has increased at a very exponential and imbalanced rate during the last five decades (Lu and Tian 2017). Major portion of global production of urea is utilized in developing countries with estimated NUE of 20–35% only. The excess N that is leached in the soil and volatilized in atmosphere not only lessens NUE but is also detrimental to environment (Naz and Sulaiman 2016). During a 50-year (1961–2010) analysis, Ladha et al. (2016) estimated that fertilizer N contributed 48% N to the total N harvested by three cereal crops. They further revealed the importance of N contribution from other non-fertilizer sources such as nonsymbiotic N fixation, manure N, and atmospheric N deposition. Among these non-fertilizer sources, nonsymbiotic N fixation is far more important than generally realized as it contributes 24% N to the N harvested by cereals (Ladha et al. 2016). To address global food security concerns, future cereal production has to still rely on an increase in fertilizer N inputs. However, opportunities to increase nonsymbiotic N fixation in cereal fields should be explored. Roper and Gupta (2016) have explored various approaches including agronomic management practices and molecular techniques to increase nonsymbiotic N fixation.

7.2 Pathways of Nitrogen Losses from Cereal Cropping Systems

Nitrogen that is lost from the soil system not only takes part in reduction of soil fertility but also leads to low input use efficiency. The loss of N in environment drives disturbance in terrestrial and aquatic ecosystems (Sutton et al. 2011). Leaching is loss of water-soluble nutrients beyond root zone of plants. It is a phenomenon in which downward movement of water causes washing of dissolved nutrients. Major form of N that can be leached down easily is NO_3^-. Moisture availability in soil has great influence on N loss through leaching (Fang et al. 2006). Soil properties like soil texture and soil structure also play a role in nitrogen dynamics. In sandy and loam soil, there is more tendency of N loss through leaching. Heavy irrigation or high rainfall has synergetic effects that aid in N loss.

Among cereals, nitrate leaching is more pronounced in puddled rice which can be reduced by introduction of maize in paddy-rice cropping systems (He et al. 2017). In puddled rice, the tendency of N leaching is independent of fertilizer application rate, while in wheat, N leaching mostly depends on the amount of N fertilizer applied (Yu-Hua et al. 2007). The N loss through leaching in maize is higher than wheat because in summer due to high rainfall, excessive availability of soil moisture provides assistance to N leaching (He et al. 2017). Avoiding over irrigation, prevention of water leakage from field, improving retention capacity of soil, and judicious dose of nitrogen and N application according to demand of crop could help in reduction of N leaching and maintain cereal yield (Fang et al. 2006). Tillage practices not only have effects on various soil properties and root penetration but also greatly influence the translocation and accumulation of nitrogen.

Runoff is a phenomenon that involves the movement of surface water due to elevation difference (high to low elevation) or due to flow of water. Water movement from one place to another causes loss of nutrients accumulated on the soil surface. Runoff includes the water that is neither penetrated in soil to meet groundwater table nor evaporates. Heavy irrigation and high precipitation are the chief stimulants of runoff including others like overdose of N fertilizers and accelerated nitrification process. The major form of N that is lost through runoff process is NO_3 (Yang and Toor 2016). Application of N fertilizer is correlated with NO_3 amount present in runoff water (Woodley et al. 2018). In rice-wheat rotation system, N runoff losses occur more in rice season than wheat. Nitrogen accumulated in wheat season accelerates the N loss form rice field (Cao et al. 2017a, b). N runoff losses mostly occur in puddled rice because of pounding water, but some studies have also reported that in direct seeded rice, there is more tendency of nitrogen loss than seedling transplantation methods of rice cultivation (Zhang et al. 2018). Total N runoff increased significantly in dry direct seeded rice up to 76% (Zhang et al. 2018). Integrated nitrogen management, application of chemical fertilizers along with significant proportion of organic-N, can reduce N loss through runoff (Cao et al. 2017a, b).

Volatilization is a phenomenon in which volatile compounds (in the form of gases) are lost to atmosphere. Major forms of nitrogen that are lost through volatilization process are NH_3, N_2O, and NO_2. Depending upon soil and environmental conditions, ammonia (NH_3) volatilization can occur up to 65% of applied nitrogen (Cameron et al. 2013). Several factors affecting N-volatilization from soil are rate of N application, time of fertilizer application, days after fertilization, pH of water and soil, NH_4^+ amount in fertilizer, and environmental variations such as rainfall, wind velocity, temperature, and humidity (Cameron et al. 2013). Many cultural practices can take part efficiently to reduce N loss in the form of ammonia vitalization such as use of slow-releasing fertilizers, biochar amendments, and floating duckweed (Sun et al. 2016). Fertilizer application methods also affect the N loss. Deep placement of N fertilizers not only improves NUE but also reduces N loss through NH_3-volatilization in non-tilled rice field (Liu et al. 2015). Use of urease inhibitors such as NBPT (N-(n-butyl)thiophosphoric triamide) also reduces NH_{3-}volatilization in puddled rice (Dempsey et al. 2017; He et al. 2018). N loss in the forms of NH_3-volatilization is also reported from direct seeded rice fields (Liao et al. 2015). NH_3-volatilization is also affected by water and fertilizer management in direct seeded rice fields (Liao et al. 2015) and puddled rice (Xu et al. 2012) as well. Use of nitrification inhibitors in puddled rice field reduces N loss from volatilization process (Sun et al. 2015). Fertilizer application rate, type of fertilizer, and soil type also affect NH_3-volatilization (Li et al. 2017). Application of controlled released urea (CRU) in combination with non-flooded control irrigation has high potential in reducing volatilization losses (Xu et al. 2012).

7.3 Use of Nitrogen Performance Indicators as a Tool to Assess Nitrogen Productivities

During the past 50 years, a linear increase in grain yields along with increase in nitrogen application rates has been recorded for many countries. However nitrogen use efficiencies in many countries have gradually declined or stabilized. The three cereal crops maize, wheat, and rice consume half of the global nitrogen fertilizer; therefore, an overview of the N performance of these crops will help in understanding the overall performance of N in global agriculture systems. We have compared the N productivities for maize, wheat, and rice among the top producer countries (these countries produce more than 85% of the global production) using different performance indicators. Data was collected for the year 2015 from multiple sources (FAOSTAT 2018; Heffer et al. 2017; Ladha et al. 2016). Mean grain yield was calculated by dividing annual production with area under cultivation for each crop and each country. Mean N fertilizer application rate was by dividing annual N consumption with cultivated area for 2015. Partial factor productivity for nitrogen (PFP N) was calculated as the ratio of mean grain yield and mean N fertilizer rate. Partial nutrient balance for N (PNB N) was commuted as the ratio of kg N harvested per ha and mean N application rate. Nitrogen use efficiency was calculated from N removed in grains (kg/ha) and total N inputs (kg/ha). Total N inputs include the N contribution from synthetic fertilizer, manure, crop residue, biological fixation, and atmospheric deposition. Nitrogen surplus was calculated as the difference of total N removed by crop (straw N + grain N) and total N inputs.

Global estimates can provide an overview of N performance at crop level and at national and regional level. Based on global estimates of different N performance indicators, we have classified nations in four groups (Tables 7.1, 7.2, and 7.3). Although grouping slightly varied for different cereal crops, it still provides useful information on N performance at country level. High nitrogen productivities were observed for group I nations like Argentina, Russia, Brazil, Ukraine, the European Union, and Canada. High N productivities in countries of group I were associated with low fertilizer N inputs and average mean yields indicating mining of soil mineral resources. Historical analysis on N utilization showed that several rich countries of Europe (OECD) experienced an increase in NUE from 1970 to 1980 onward by producing more grain yields from lesser N inputs (Conant et al. 2013). While in some countries like Russia, high NUE due to decreased N input indicates mining of soil N resources (Conant et al. 2013). High N outputs in terms of grain N and crop residue N in Western Europe, New Zealand, Argentina, Brazil, some parts of China, and Southeast Asia are mainly because of high crop yields per unit area (Liu et al. 2010).

Group II includes a mix of countries for different cereals. Group II nations exhibited average N productivities along with low mean yields and average N fertilizer inputs. In group II nations, nitrogen use efficiencies are generally average, but N surplus is also low. Group III includes those nations which have high yield and high N fertilizer input farming systems. In group III countries, the USA, China, Egypt, and Turkey, average N productivity in cereals is accompanied with high N surplus.

Table 7.1 Nitrogen performance indicators of top producer countries for maize crop

		Area	Production	Mean grain yield	Mean N fertilizer	PFP N	NUE	PNB N	N surplus
			(million ton)	(ton /ha)	(kg/ha)	(kg yield/kg fertilizer N)	(%)	(kg N removed/ kg fertilizer N)	(kg/ha)
	High N productivity	Argentina	34	7.31	46	160	100	2.14	−60
	Average mean yield	Russia	13	4.93	61	81	63	1.08	−2
	Low fertilizer N input	Brazil	85	5.54	69	80	62	1.08	0
I		Ukraine	23	5.71	81	71	60	0.95	5
		EU-28	104	5.83	84	69	59	0.92	8
		Canada	14	10.34	153	68	65	0.90	−10
	Average N productivity	Philippines	8	2.93	52	56	47	0.75	20
II	Low mean yield	South Africa	10	3.75	101	37	36	0.50	59
	Average fertilizer N input	Indonesia	20	5.18	118	44	45	0.59	43
	Average N productivity	China	225	5.89	122	48	44	0.65	52
III	High mean yield	Turkey	6	9.33	174	54	54	0.72	30
	High fertilizer N input	USA	345	10.57	218	49	50	0.65	58
		Egypt	8	7.35	251	29	33	0.39	142
IV	Low N productivity	India	23	2.60	96	27	26	0.36	80
	Low mean yield	Pakistan	5	4.42	125	35	34	0.47	77
	High fertilizer N input	Mexico	25	3.48	125	28	25	0.37	109
		Viet Nam	5	4.54	139	33	33	0.44	86
		World	952	6.54	127	51	–	0.95	–

PFP N Partial factor productivity for nitrogen; *PNB N* Partial nutrient balance for nitrogen

Table 7.2 Nitrogen performance indicators of top producer countries for wheat crop

		Area	Production	Grain yield	N fertilizer	PFP N	NUE	PNB N	N surplus
			(million ton)	(ton /ha)	(kg/ha)	(kg yield/kg fertilizer N)	(%)	(kg N removed/ kg fertilizer N)	(kg/ha)
	High N productivity	Russia	62	2.39	24	101	56	1.87	16
	Average mean yield	Morocco	8	2.47	27	92	73	1.69	−2
I	Low fertilizer N input	Ukraine	27	3.88	47	83	68	1.53	4
		EU-28	258	4.19	53	79	58	1.44	24
		Argentina	12	2.87	55	53	46	0.97	41
	Average N productivity	Australia	24	1.92	45	43	45	0.79	29
	Low mean yield	Iran	12	2.02	54	37	35	0.69	55
II	Average fertilizer N input	Brazil	6	2.23	73	31	30	0.56	78
		Canada	28	2.88	81	36	42	0.66	51
		Turkey	23	2.88	80	36	41	0.66	53
	Average N productivity	USA	56	2.93	93	31	38	0.58	67
III	High mean yield	Uzbekistan	7	4.82	130	37	38	0.68	107
	High fertilizer N input	China	130	5.39	141	38	43	0.71	90
		Egypt	10	6.59	163	40	54	0.74	55
	Low N productivity	India	87	2.75	125	22	27	0.40	119
IV	Low mean yield	Pakistan	25	2.73	148	18	22	0.34	154
	High fertilizer N input								
		World	771	3.41	79	43	–	0.79	–

PFP N Partial factor productivity for nitrogen; *PNB N* Partial nutrient balance for nitrogen

Table 7.3 Nitrogen performance indicators of top producer countries for rice crop

		Area	Production (million ton)	Grain yield (ton/ha)	N fertilizer (kg/ha)	PFP N (kg yield/kg fertilizer N)	NUE (%)	PNB N (kg N removed/kg fertilizer N)	N surplus (kg/ha)
I	High N productivity	EU-28	4	6.41	69	93	40	1.05	60
	Average mean yield	Japan	10	6.63	76	87	37	0.98	76
	Low fertilizer N input	Indonesia	75	5.34	84	63	38	0.71	59
		Brazil	12	5.75	85	68	35	0.76	81
	Average N productivity	Philippines	18	3.90	72	54	31	0.61	69
II	Low mean yield	Bangladesh	51	4.51	90	50	28	0.57	96
	Average fertilizer N input	Viet Nam	45	5.76	104	56	33	0.63	89
		Iran	2	4.43	109	41	23	0.46	138
	Average N productivity	China	210	6.89	128	54	33	0.61	108
III	High mean yield	USA	9	8.37	250	33	27	0.38	198
	High fertilizer N input	Egypt	5	9.43	299	32	27	0.36	213
	Low N productivity	Thailand	28	2.85	101	28	20	0.32	110
IV	Low mean yield	India	157	3.61	114	32	21	0.36	130
	High fertilizer N input	Pakistan	10	3.72	182	21	15	0.23	217
		World	637	4.87	111	44	–	0.81	–

PFP N Partial factor productivity for nitrogen; *PNB N* Partial nutrient balance for nitrogen

Extremely low N productivities were observed for group IV countries such as India and Pakistan, Mexico, and Thailand. Low N use efficiencies in these nations are caused by very low mean yields and high N fertilizer inputs, eventually resulting in a high N surplus. Global pattern of N productivity in cereals seems to be country-specific but not crop-specific. Across all nations, rice has the lowest nitrogen use efficiencies and a very high N surplus. Overdose of nitrogen is associated with many environmental problems. Reducing the dose of N fertilizer can be one of the solutions as mitigation strategy for climate change (Stuart et al. 2014). High application rate of N in maize and wheat does not have any significant effect on yield increment of both cereals (Fang et al. 2006).

7.4 Nitrogen Best Management Practices

The primary aim of nitrogen management in agricultural ecosystem is the provision of nitrogen that is enough for crops to perform at their maximum potential and provide significant yield. At the same time, it is necessary to prevent translocation of nitrogen to other ecosystems and water bodies where it can cause disturbance and potential damage. The source of nitrogen received by other ecosystems is inconsequential, because they retort in similar way, either it is from industrial or from biological fixation (Robertson and Vitousek 2009). Nitrogen is mobile nutrient and it is difficult to retain. The forms of N that are present in agricultural ecosystems are reactive and, when these are transported in other ecosystems, cause considerable disturbance.

Efficient N management within fields is a complex mechanism as it relies on a number of environmental and management factors. Hatfield and Prueger (2004) have analyzed several studies on maize yield response to varying N application rates and found that variations in maize yield responses are more often temporal than spatial. Agronomic management of nitrogen is a key factor for variance in N performance in the farming systems (Oenema and Pietrzak 2002), and it can account up to 50% of the variations in N performance in crop fields. Combining different approaches instead of a single one can be helpful in sustainable production of agricultural crops without environmental risks (Nath et al. 2017). Integration of nitrogen application rates with nitrogen application methods, soil organic matter, soil moisture status, and crop type will increase nitrogen use efficiency (Hatfield and Prueger 2004).

The following strategies reviewed in several studies can be adopted to improve N use efficiency: (1) adjustment of crop rotations, (2) avoiding overuse of N fertilizers, (3) equipping farmers with decision support systems, (4) better decision-making for irrigation to prevent leaching losses, and (5) application management of fertilizers such as timing, placement, and chemical composition of N fertilizers (Cherry et al. 2008; Robertson and Vitousek 2009). Depending on the environmental conditions, fertilizer type, and soil properties, the proportion of N loss from mineral N fertilizer volatilization in the form of ammonia (NH_3) may vary from 0 to 50% (Sommer et al. 2004). Fertilizer application methods also affect the N loss. Deep placement of N fertilizers improves NUE and decreases N loss through ammonia volatilization in non-tilled and irrigated rice field (Liu et al. 2015; Bandaogo et al. 2018). Deep placement of fertilizer can improve rice NUE and yield both in continuous standing water and alternate wetting and drying irrigation regimes by 13–20% and 21–26%, respectively (Islam et al. 2018).

Excessive and non-judicious use of elemental nitrogen is becoming common practice in cropping systems of rice-wheat rotation. Disproportionate addition of mineral nitrogen results in low N use efficiencies and N losses to environment and water bodies. In rice-wheat (summer-winter) rotation, there is possibility of reduction in N fertilizer application without substantial reduction in grain yield of both crops, and fertilizer cost can be reduced up to 20% of rice and 50% of wheat (Hofmeier et al. 2015). The reduction in N fertilizer rate is possible by 15–25% for rice and 20–25% for wheat without significant decrease in grain yield (Hofmeier et al. 2015). In cereals having small biomass, reducing the N fertilizer rate will not only prevent N loss, but it could also lessen the N pollution in water bodies (Yu-Hua et al. 2007).

The NUE can be enhanced by utilization of slow-releasing encapsulated fertilizers (Naz and Sulaiman 2016). Use of nitrification inhibitors in puddled rice field reduces N loss from volatilization process (Sun et al. 2015). A significant reduction in N-volatilization (23–62%) and N runoff (8–58%) was observed by use of polyurethane-coated urea and degradable polymer-coated urea (Li et al. 2018). Improved NUE and rice yield were observed with organic-N combined with inorganic application of slow-releasing fertilizers (Li et al. 2018).

Zero tillage and residues retention in wheat can help to improve soil organic matter and minimize greenhouse gas emissions (Nath et al. 2017). No tillage in rice can be a sustainable approach for mitigation of NH_3 emission and improved NUE (Liu et al. 2015). Avoiding over irrigation and prevention of water leakage from field can help in the reduction of N leaching (Fang et al. 2006). Site-specific management of nitrogen in direct seeded dry rice by chlorophyll meter and leaf color chart (Kaur and Ram 2017) is good technique to enhance NUE. Modern technologies like optical sensors can be utilized in their best ways for site-specific management of flooded rice and winter wheat that not only reduce N losses but also improve NUE (Purba et al. 2015; Thind et al. 2017). Remote sensing can be one of the possible options for site-specific management of N fertilizer in rice (Tripathi et al. 2017; Kaur and Ram 2017). Site-specific nitrogen management can enhance NUE and WUE of maize (del Pilar Muschietti-Piana et al. 2018). Precision nitrogen management (PNM) by using active canopy sensors (ACS) like Green Seeker (GS) and Crop Circle (CC) is also gaining popularity (Cao et al. 2017a, b; Zhou et al. 2017; Colaço and Bramley 2018). Cropping system that includes legumes in rotations would also decrease the need for N fertilizer inputs (Cai et al. 2018).

7.5 Soil Amendments to Improve NUE

Soil amendments have also shown promising results in decreasing N losses. To reduce the N loss from agricultural ecosystem without compromising yield of crop, better crop production strategies should be adopted. Incorporation of rice straw biochar has potential to improve productivity of puddled rice through soil retention of nitrogen (Dong et al. 2015). Use of urease inhibitors such as NBPT (N-(n-butylthiophosphorictriamide) reduces the NH_3-volatilization in puddled rice (Dempsey et al. 2017). Organic amendments along with reduced dose of inorganic-N could be the one of possible solutions in rice-wheat rotations (Xue et al. 2014). Use of high dose of N results in high rate of N leaching, while addition of compost can reduce N leaching process (Plošek et al. 2017).

Use of biofertilizers can be another strategy for efficient nitrogen use in crop production. To achieve improved NUE in paddled rice, *Azolla* biofertilizer can be utilized for their biological nitrogen fixation properties (Yao et al. 2018a). *Azolla* application combined with reduced dose of N improved rice yield up to 8% while increased recovery efficiency of fertilizers by 69% and NUE up to 52% (Yao et al. 2018a). Combining deep placement of urea along with *Azolla* biofertilizer application is a potential approach for reduction of N loss through volatilization and improvement of N recovery (Yao et al. 2018b). DPU + *Azolla* decreased N loss by 47% and increased N recovery by 58% in rice (Yao et al. 2018b).

7.6 Development and Use of Nitrogen Dilution Curves to Improve Nitrogen Efficiencies at Farm and Regional Level

Overuse of N fertilizers in many regions is mainly intended to increase farm yields and farm income without considering the other yield-limiting factors like soil moisture, soil fertility, yield potential of cultivar, etc. that might be getting altered. In many countries like India and Pakistan, farmers lack awareness regarding the importance of soil and plant N status while estimating the N requirement of a crop at field level. Another issue is that N application rates are not often linked with the overall soil yield potential. There is a tendency to use high N application rates in soils that are marginal and have low intrinsic yield potentials that result in a further decrease in yields and NUE. The decision of N fertilization rates should be integrated with soil fertility status, local climatic conditions, crop and cultivar type, and yield potential of the soil.

Different analytical techniques such as chlorophyll readings (Piekkielek and Fox 1992) and remote sensing (Hansen and Schjoerring 2003) are used to estimate crop nitrogen status in order to optimize N application rates. However, these techniques may overestimate or underestimate the actual N requirements (Dwyer et al. 1995). The development of nitrogen nutrition indexes (NNI) for different crops under different environmental conditions can be used for in-season estimation of crop nitrogen requirements (Neuhaus et al. 2017). The NNI links crop N status with maximum vegetative growth ensuring maximum grain yield and is calculated as the ratio of actual nitrogen concentrations to the critical nitrogen concentrations (Neuhaus et al. 2017). These nitrogen indexes to achieve maximum yield potential could be developed for different varieties, soil types, management practices, and climatic conditions and then integrated to avoid overuse of N fertilizers. Recently, this approach was implied for precision nitrogen management and achieved maximum yield potential for rice cultivation in China (Ata-Ul-Karim et al. 2017).

7.7 Conclusions and Future Perspectives

A constant pressure of ever-growing global population has forced crop systems into a high input intensive agriculture that is threatening the ecosystems and sustainability of agriculture. Nitrogen is one of the major inputs, overuse of which has been a major concern during the past few decades. Top cereal-growing countries have however responded differently to nitrogen management. Less nitrogen application rates in some countries have substantially improved nitrogen use efficiencies on one side; soil mining for N has made the cereal production unsustainable over the longer run. Countries of the Western Europe have however achieved improved NUEs with little or no increase in N application rates. Owing to advances in breeding and management practices, few countries like China, the USA, and Egypt have evolved into high input–high yield production systems with slight improvements in NUE but high N losses. A major concern is the countries (India, Pakistan, Thailand, and Mexico) where overuse of fertilizer N and very low mean cereal yields have resulted in very low nitrogen productivities. Low N productivity in these countries is not only damaging the environment but is also jeopardizing food security and farm economics. A plausible understanding of the various N indices (Tables 7.1, 7.2, and 7.3) can be helpful in resolving the issues of N management at national and regional level. However at the farm and crop level, a substantial improvement in agronomic N management is essential. At farm level, in-season assessment of crop N requirement using N dilution curves can be useful. For precise N management, future studies should focus on the development and integration of N dilution curves using different cultivars, soil moisture regimes, management practices and at different growth stages. Policies need to be developed at regional, national, and farm level in order to improve N productivities of cereals while considering environmental pollution, food security, and farm economics at the same time. This would require a resilient approach integrating agronomic management practices with variability in weather and soil conditions.

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Biological Nitrogen Fixation in Nutrient Management

8

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Abstract

The use of costly chemical nitrogen fertilizers for increased food production is a global concern due to their economic and environmental effects. It is the dire need of the day to find out some alternative to the nitrogen fertilizers which is economical and environmentally safe. Biological fixation of atmospheric diatomic nitrogen into a form useable by the plant is a possible alternative to the chemical nitrogen fertilizer which is economically viable, ecologically desirable, and environmentally safe with reduced external inputs. In most of the symbiotic systems, *Rhizobium*-legume association contributes its major part in providing the N to most of the cropping system, whereas *Anabaena* and *Azolla* can be important in reduced conditions such as flooded rice. Despite the importance of nitrogen fixation, there are a number of sociocultural and scientific constraints that limit the adoption of BNF system in agriculture. The major limitation is the hindrance in the management of nutrients in the soil using the BNF as sustainable system. However, if these limitations are handled carefully on scientific basis, then BFN can be a potential source for the management of soil nutrients. Crop residues from nodulated crops also provide nutrients especially nitrogen to the subsequent crops. By adopting the BFN as cropping system, it can cut the heavy use of nitrogen fertilizer which is not only costly but also polluting the environment especially the groundwater. However, optimization of nitrogen fixation can balance the use of fertilizer and thus can help to manage the nutrients for the crops in a sustainable manner. In the present chapter, it is discussed how BNF can be crucial in managing the nutrients.

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Biological nitrogen fixation · Nutrient management · Inoculation · Nitrogen · Root nodules · Sustainable agriculture

8.1 Introduction

Over the last century, the world population has multiplied many times. In 1915, the world population was 1.8 billion which is estimated to be 7.3 billion in the first two decades of the twenty-first century (Melorose et al. 2015). This rising population demands increased food production worldwide. To fulfill this increased demand, farmers are trying to increase crop production, either by increasing the cultivated land to grow crops by using less fertilized uncultivated lands or by enhancing the crop production on already cultivated land through artificial fertilization techniques. Over cropping and extensive use of chemicals for crop fertilization and protection not only increase the input cost but also decrease the soil fertility by depleting the soil nutrients. However, in the recent past, chemical fertilizers play a key role in increasing the global food production and became the indispensable portion of the agricultural systems. The green revolution was also brought about using the practices heavily dependent upon chemical fertilizers. It is also a fact that most of the areas of the developing nations are deprived from the availability of synthetic fertilizers or they are too costly to be used by poor farmers. Even in developed countries, many social, economic, and environmental constraints compel the scientists to find out the biological or organic alternatives to chemical fertilizers especially to N fertilizer. One option is to use natural biological nitrogen fixation (BNF) systems, an alternative to nitrogen fertilizers. Under BNF phenomenon, atmospheric N is fixed to ammonia and other organic compounds that could be uptaken by the plants. It is estimated that globally 346 thousand tons of N is fixed each year through the process of BNF (Table 8.1).

Adoption of cropping system with biological nitrogen fixation not only can help to manage the soil N but will enhance the productivity, eliminate the risk of nitrate contamination of groundwater, and enhance the quality of dietary food. This chapter

Table 8.1 Estimated global N fixation by different biological and non-biological processes

Source	Amount of N fixation (000 tons)
Legume	39
Non-legume	10
Land	153
Sea	40
Others	104
Total biological	346

Source: Brady and Weil (2002)

focuses on the role of biological nitrogen fixation in crop productivity and nutrient management of soils. After introduction, the process of biological nitrogen fixation is described briefly (Sect. 8.2), while in Sect. 8.3, the role of BNF in nutrient management through BNF is elaborated. Section 8.4 discusses the different constraints in the adoption of BNF, and the last section explains the different strategies that can be used to promote BNF as a nutrient-providing system.

8.2 Biological Nitrogen Fixation

Nitrogen is one of the essential nutrients for plant growth. Chlorophyll pigment which is responsible for photosynthesis is largely composed of N. It is also a component of many other essential biomolecules such amino acids which are building blocks of proteins and also found in the synthesis of ATP and nucleic acids. It is predominately found in gaseous form (N_2) in the Earth's atmosphere. However, this form is not directly available to plant, and it must be transformed to nitrate and ammonium forms before plants use it. Thus, these forms of nitrogen are available to plant by the following ways: (1) addition of ammonia- and/or nitrate-containing fertilizers (from the Haber-Bosch process), (2) the release of inorganic form of N ($NH_4^+$and NO_3^-) during decomposition of soil organic matter, (3) fixation of atmospheric nitrogen into plant available form by natural processes like lightning, and (4) BNF (Vance 2001).

Nitrogenase is an enzyme that mediates BNF process that involves the fixation of atmospheric nitrogen (N_2) to ammonia (NH_3) (Beijerinck 1901). The prokaryotic organisms include in BNF are (a) aquatic prokaryotes such as cyanobacteria; (b) bacteria freely living in soil, such as *Azotobacter*; (c) associative bacteria such as Azospirillum; and (d) most importantly bacteria, those developing symbiotic relationship with legumes or other crops such as *Rhizobium* and *Bradyrhizobium*. These organisms are presented in Fig. 8.1.

8.2.1 Nitrogen Fixation Process

Nitrogen in gaseous form composed of two N atoms which are strongly attached to each other with a triple covalent bond. Thus, conversion of this form of nitrogen into plant available form is a complex process, and large amount of energy is required to carry out this reaction. Therefore, nitrogen fixing microorganisms utilize 16 moles of ATP to convert one mole of gaseous nitrogen in plant available form. The energy used in this process comes from the microbial oxidation of organic molecules present in soil. Free-living non-photosynthetic nitrogen fixer take these molecules released from other organisms, while associative microbes and symbiotic microorganism obtain these organic substances from the rhizosphere of host plants.

For industrial production of nitrogenous fertilizer, Haber-Bosch process is followed to reduce nitrogen which results in many consequences, including use of fossil fuels to produce energy and emission of CO_2 leading to pollution and global warming (Erisman et al. 2008).

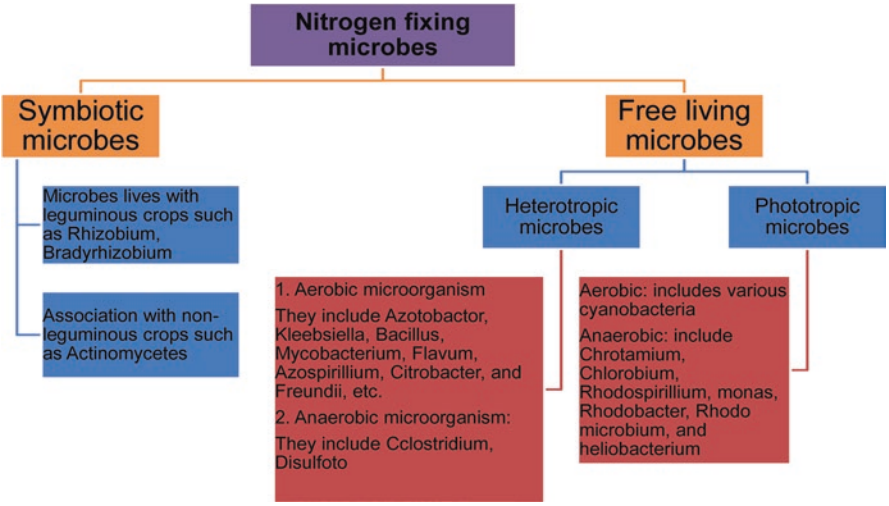

Fig. 8.1 Nitrogen fixing process of microbes in the soil

Overuse of synthetic fertilizers has some environmental constraints and upsets N cycle that resulted in surface and groundwater pollution. Excessive uses of N fertilizers cause nitrate leaching and contamination of groundwater. Surface runoff losses cause accumulations of nutrient into rivers and lack and initiate the process of eutrophication. That causes the proliferation of green algae, and when they die, microbes use water oxygen during the process of decomposition which results in depletion of O_2, thereby causing the death of aquatic animals and further aggravating the problem of water pollution.

8.2.2 Biological Nitrogen Fixation by Free-Living Microorganisms

Some species of heterotrophic bacteria such as *Azotobacter*, *Bacillus*, *Clostridium*, and *Klebsiella* freely live in the soil and fix a significant amount of nitrogen without any symbiotic or direct relationship with other organisms. As previously noted, these organisms obtain their energy from the oxidation of organic matter in soil; however, there are certain species which have chemo-lithotrophic capabilities and use inorganic compounds for energy production (Reed et al. 2011).

Because oxygen inhibits the activity of nitrogenase enzyme, therefore, these free-living nitrogen fixing organisms behave as anaerobes or microaerophiles during nitrogen fixation. Due to less availability of organic carbon for oxidation, the role of these microbes is supposed to be very minor in contributing BNF on global scale. However, proper maintaining of crop residues which serve as carbon source for these microbes and low available N in soil would facilitate the activity of free-living microbes. It has been documented that proper management in wheat rotation farming system free-living microbes has fixed up to 20 kg per hectare each year to fulfill the long-term N needs of the cropping system in Australia (30–50% of the total needs) (Vadakattu and Paterson 2006).

8.2.3 Associative Nitrogen Fixation

Different species of *Azospirillum* have the ability to thrive in the rhizosphere of the various members of *Poaceae* family and fix appreciable amount of atmospheric nitrogen into plant available N. Important agronomical crops which are found in close association with these bacteria include wheat, corn, oats, and barley. In associative relationship, the ability of *Azospirillum* to fix N depends upon the temperature of rhizosphere which is important for the optimum growth of these microbes, availability of suitable amount of carbon source and low atmospheric oxygen pressure in rhizosphere, the competitiveness of the bacteria, and the efficiency of nitrogenase (Van Dommelen and Vanderleyden 2007).

8.2.4 Symbiotic Nitrogen Fixation

Symbiotic relationship is common in different species of plants and microorganism. These plants provide photosynthates that are utilized by these microorganisms as source of carbon and energy. In return nitrogen fixed by these microbes is used by plants for their growth. For example, a cyanobacterium *Anabaena azollae* colonizes in the cavities formed at the base of *Azolla* fronds and forms a symbiotic relationship which results in a significant amount of nitrogen fixation in specialized cells called heterocysts (Adams 2000; Rai et al. 2000).

In South Asia, rice paddies are usually covered with *Azolla* “blooms” for the purpose of N fixation, and it results in fixation of up to 600 kg N ha^{-1} per growing season (El-Refai et al. 2005), and this association is being used for at least a thousand years as a biofertilizer for rice growth. Similarly, certain microbes develop symbiosis with trees and shrubs, for example, actinomycete *Frankia* live in association with alder (*Alnus* sp.) and helps. Though these aforementioned interactions between microbes and plants play an important role in fixing atmospheric N, however, among all of them, the most important symbiosis relationship is established between *Rhizobium* and *Bradyrhizobium* bacteria and legumes plants, and they contribute more in BNF compared with other associations. Some *Rhizobium* species living in association with legumes are shown in Table 8.2. Alfalfa, clover, beans, lupines, cowpeas, soybean, peanut, and vetches are the important legumes, and these are grown throughout the world of agriculture. Among these soybean contributes to 68% of the total legumes produced in the world, and 50% of the total cropping area of the word is devoted to the legume production (Vance 2001).

Table 8.2 Specific rhizobia species live in association with legumes

Crop	*Rhizobium* species	References
Alfalfa	*Rhizobium meliloti*	Wall and Favelukes (1991)
Chickpea (*Cicer arietinum* L)	*Mesorhizobium ciceri*	Martínez-Abarca et al. (2013)
Lentil (*Lens culinaris* M)	*Leguminosarum* biovar *viciae*	Rashid et al. (2012)
Soybean (*Glycine max* L.)	*Bradyrhizobium elkanii*	
	Bradyrhizobium japonicum	Mishra et al. (2009)
	Sinorhizobium fredii	Krishnan (2002)
Drybean (*Phaseolus vulgaris* L.)	*Rhizobium etli*	Martínez-Romero et al. (1998)
	Rhizobium leguminosarum	Broughton et al. (2003)
	Rhizobium tropici	Karaca and Uyanöz (2012)
Pea (*Pisum sativum* L.)	*Leguminosarum* biovar *viciae*	Novak et al. (2002)
Mung bean (*Vigna radiata* L.)	*Rhizobium leguminosarum*	Chudasama and Mahatma (2016)
Cowpea (*Vigna unguiculata* L.)	*Bradyrhizobium japonicum*	Nyoki and Ndakidemi (2013)

8.2.5 Nodulation in Legumes

Rhizobium colonization in the root system of host plants causes the development of nodules which provide habitat for these bacteria where they start to fix atmospheric nitrogen. During nodule formation, uptake of this nitrogen by plants increases the photosynthetic activity of plant that results in nitrogen-rich seeds. On the other hand, if leguminous plants failed to develop nodulations, they suffered from N deficiency and resulted in stunted growth and low seed production.

In legumes like alfalfa, clover, and soybeans, when the process of nodulation begins, flavonoids are released from the host plants that attract the *Rhizobium* toward those plants, and these microbes attached with the epidermal cell of root hairs. In the first step, bacteria attach to root hair using Ca^{2+} binding protein called rhicadhesin. Second, strong association occurs due to cellulose fibrils and/or lectins and fimbriae produced by the bacteria and host plant, respectively.

Rhizobium releases a certain type of chemicals, called NOD factors that stimulate the plant to produce curl root hair called as shepherd's crook. Afterward, penetration of *Rhizobium* into root hairs forms a tubular structure which is called an infection thread. Rhizobia stimulate the cortical cell divisions that cause nodule formation, and as it happens, plant-derived membrane surrounds the *Rhizobium* and bacteria are released inside plant cells forming the nodule. These bacteria inside the nodules loss their cell wall and exist in large masses with irregular-shaped branching cells called bacteroids. After it, establishment of relationship entirely depends on the host plant for food and energy, and in return these bacteroids fix atmospheric nitrogen for the host plant.

This association is entirely host specific, and a particular species of *Rhizobium* develops interaction with specific plant genera. For example, *Rhizobium meliloti* and *Rhizobium leguminosarum* biovar *trifolii* will only develop nodulation in alfalfa clover (*Trifolium*).

The abovementioned NOD factors are basically lipochitin oligosaccharides, and variations in their structures are responsible for the host specificity. Besides these lipochitin oligosaccharide structures, production of leghemoglobin also plays an important role for this relationship between the rhizobia and the host legume (Appleby 1984). It is produced in fully functioning nodules and has similar function just like the hemoglobin. This heme protein is formed by combination of apoprotein and heme (porphyrin ring bound to an iron atom) produced by the legume and bacterium, respectively. It transports the oxygen to the *Rhizobium* in the nodules. As it has been discussed that nitrogenous enzyme activity is sensitive to oxygen and is restricted in excess of oxygen, thus, leghemoglobin carries oxygen to *Rhizobium* for cellular respiration but is regulated to avoid the inactivation of nitrogenase.

8.3 The Role of N2-Fixing Symbiotic Association in Agricultural Nutrient Management

Role of BNF in contributing N in terrestrial ecosystem has been estimated to range from 139 to 170 × 10^6 tons of nitrogen per year. However, this amount of N fixed by BNF is very small compared with total N reserves, (105,000 × 10^6tons N), while this amount is still greater than the N added by the synthetic fertilizer, i.e., 65 × 10^6 tons of nitrogen per year (Paul 1988). Considerable amount of this fixed N comes from various symbiotic associations such as legumes/*Rhizobium* spp., actinorhizal associations of plants, and microorganisms. However, free-living fixers (diazotrophs) contribute little to the aforementioned amount of fixed N into ecosystem. BNF associations in different cropping systems are presented in Fig. 8.2.

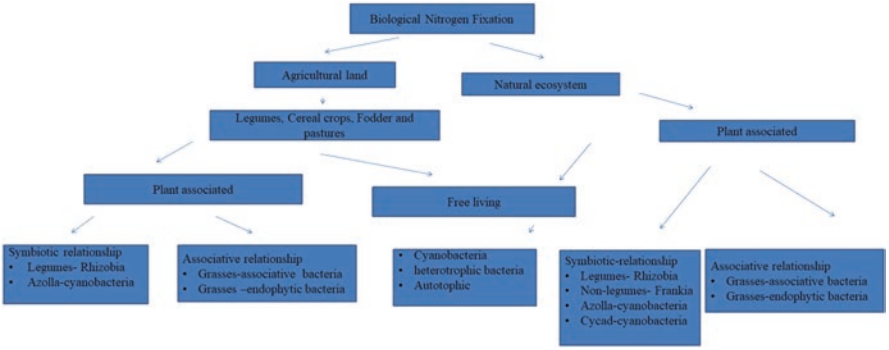

Fig. 8.2 Biological nitrogen fixation under different systems

The relative contribution of N fixation by symbiotic relationships and free-living organism contributes to 70% of the global N fixation (Paul 1988). However, in cropping system the share of symbiotic nitrogen fixation has been considered not less than 80% of the global fixed nitrogen (Burns and Hardy 1975; Lobell et al. 2009). In ancient time legumes and their subsequent incorporation in soil had played an important role in traditional farming systems. However, introduction of synthetic fertilizers led to the widescale abdication of legume pasture mostly used for green manuring in Europe and North America. Similarly, recently in China and Japan, use of milk vetch (*Astragalus sinicus*) and *Azolla* as fertilizers has declined because of high labor charges and easy availability of synthetic fertilizers.

In developed countries, adaptations of organic farming and reduction in excessive use of nitrogenous fertilizers have resulted in the increased use of BNF systems. In humid and subhumid upland soil due to higher rainfalls, excessive leaching causes the depletion of both total and plant available nitrogen. Moreover, due to improper land management, deforestation and over grazing may result in rapid losses of nitrogen. This trend is widespread due to intensive cultivation for increasing crop production to feed the increasing human beings. Yield of major crops is often limited by N supply, and considering the economic value due to higher prices, N fertilizer is being used in limited extent (Myers and Wood 1987). However, introduction of BNF system into farming systems assures that it will fulfill all or at least its own requirements of N, and additionally improvement in rhizosphere will facilitate the growth of companion crops and also on subsequent crops. However, capacity of BNF system for nitrogen fixation depends upon environmental, nutritional, and biological factors and disturbances in any of these factors limit nitrogen fixation, and it cannot be assumed that BNF contribute largely in global N cycle (Chalk 1991).

8.3.1 Role of Legumes

Legumes are important source of vegetable protein and are widely used for food, shade, fodder, timber, fuel, and green manuring. They are grown in rotations with other crops and are incorporated into soil as green manure to improve various physiochemical properties of soil. These are grown as cover crops and intercrops in tree crops such as coffee, cocoa, rubber, tea, and oil palm. Various tree legumes are grown in agroforestry systems and used for grazing purpose to increase the sustainability and productivity of farming systems.

8.3.1.1 Food Legumes

About 90% of human dietary protein comes from plants, while 17–34% of protein is contributed by legume seeds. The distribution of crop legumes is generally determined by their adaptation to particular climates and environments (Ludwig and Asseng 2006; Hatfield et al. 2011). The variations in consuming legumes as source of food depend upon the introduction of legumes into cropping systems and also their uses as fodder crops (Byth et al. 1986). Different legume species are widely grown in lowland and upland cropping systems. Some of them are grown for oil seed purpose such as groundnut and soybean, while some are important pulses such as chickpea, cowpea, gram, and bean.

The amounts of N fixation by legumes depend upon various factors like microbial inoculation, water supply, fertilizer application, crop rotation, and soil fertility. In a situation where legumes have access to adequate amount of N in soil, it would result in low level of N fixation. It is evident from previous reported studies the proportion of nitrogen fixation is reduced with increasing level of soil available N, and this is the most important factor in reducing the nitrogen fixation by microbes.

Legume crops are not only growing as single crop, but in many parts of the world, they are grown in intercropping systems with other crops, and this results in intensification of crops because it more effectively exploits the environment. The selections of crops for intercropping depend on the length of season, but generally crops with early and late maturity are selected in order to better utilize resources in mixed cropping pattern (Ofori and Stern 1987). The amount of N fixation in legume systems depends upon the morphology of legumes, number of legume plants and management practices, and the competition of component crops in intercropping. Generally, legumes with indeterminate growth and climbing habit have the most successful N fixation.

8.3.1.2 Green Manures

Leguminous tree and shrubs are widely used to reclaim problematic lands, as mulching material slowing down the process of soil erosion, as source of fuel wood, and as green manure. The potential for the integrated use of these species is well illustrated in alley-farming systems. This cropping system involves the growing of agricultural crops in rows between these leguminous trees and shrubs which are maintained as hedge rows and the leaves and twigs of these plants which are incorporated into soil as green manure. In the humid regions, these hedge rows are established along the contours on slope lands to reduce water erosion, and these hedgerows serve as natural terraces (Mutegi et al. 2008). In many countries of tropics, rubber and oil palm are widely cultivated, and during the initial period of the year, the row spaces between these tree species which represent 70–80% of the land are widely occupied by weeds which cause diseases and pests attack. In order to control this situation, perennial leguminous cover crops are grown which protect from weed infestations and soil erosion, and incorporation of these cover crops increases fertility and quality of soil. The use of legumes as cover crop is not only restricted with the long-term alley system, they are widely grown in rotation with short-term agronomic crops such as rice. For this purpose both food and perennial legume species are grown. Species of *Aeschynomene* and *Neptunia* and *Sesbania rostrata* could be successfully grown in rice system because they can grow well and produced nodules in flooding situation. Organic matter inputs into the soil are of great importance in terms of increasing soil fertility and retaining nutrient and moisture, thereby increasing crop productivity in degraded soils (Tschakert et al. 2004). Incorporation of leguminous crops into soil increases the organic matter of soil and improves the supply of nitrogen on decompositions of the organic residues. Integration of legumes in cropping system has the potential to improve the growth and yield of crops. Advantage of legumes over grown non-leguminous crop is that they show exceptional ability to uptake and utilize inaccessible soil phosphorus and potassium, thus maximizing the availability of these nutrients for subsequent crops. Use of legumes as green manure has great advantage when the time of decomposition of incorporated residues matches the nutrient requirement of subsequent crop, thereby increasing the supply of essential nutrients for crop growth.

8.3.1.3 Contribution of Legume Residues

The amount of nitrogen utilized by the legume crop (Nl) emanates either from the N_2 fixation (Nf) or is uptaken from the soil solution. The total amount of nitrogen in food legumes is divided into two parts, i.e., seed nitrogen (Nls) and vegetative nitrogen. The vegetative portion includes stems, leaves, and nodulated roots. All these are generally rendered as crop residues.

The net nitrogen fixation that is contributed to N balance of a soil subsequent to legume crop can be calculated as:

$$\text{Net nitrogen balance} = \text{Nf} - \text{NIs}$$

During the growth and development of legume crop, leaf fall and roots each can contain up to 40 kg of nitrogen per hectare. The food crops usually require more nitrogen than the N fixed by the *Rhizobium*. In many cases, the level of fixed nitrogen in the field might be too high, but these levels are always lower than the nitrogen removed with the harvested seed. Obviously, if the food legumes contribute substantial amount of N to the soil, then net nitrogen balance must be high after harvesting. The crops with high seed production need high amount of nitrogen and thus cause net loss to soil nitrogen, and this loss would be high if the crop residues are removed and used as animal fodder. However, the persistent use of legume crops increases the fertility of the soil and thus improves the nutrient status of the soil. If the cereal crops were grown after monocropping legume system, then increase in yield is about 30–35% when compared to cereal-cereal cropping system. When addition of nitrogen from the legume is measured as nitrogen fertilizer, then as much as 70 kg N per hectare was needed in cereal-cereal cropping system to gain the similar yield increase. Different factors can affect the increase in yield that might be cropping system, season of the crop, and soil type used for the cropping.

The surplus yield might result because of:

1. Legumes break the insect cycle that is detrimental in yield reduction. Further, many crops and their residues also have allelopathic effects.
2. Growing of legumes improves the soil structure, thus improving the nutrient availability due to the incorporation of residues.
3. Crop residues enhance the organic matter that ultimately increases the water holding capacity and buffering capacity of the soil.
4. Soil microbial activity enhanced many times when nitrogen-rich residues are incorporated in the soil following the legume crop.

5. When compared with the non-legume crops, legume crop leaves more nitrates in the soil after harvesting.

The net high nitrate level following legume crop might be due to the lower uptake by the legume crop or enhanced mineralization rate under a legume crop. When in the case of legume much of the N is removed with harvested seed and no or very little net N is gained by the soil, then how much the loss might be expected from the non-legume crop when seeds are also harvested.

However, to measure the equivalence of fixed N to N fertilizer, much care is required because fertilizer use efficiencies can vary, and amount of added N can be volatized. This might show the over efficiency of legume over N fertilizers. When crop is harvested and seed is removed, then ratio of nitrogen in different organs of plants varies. These organs also vary in their potential to release the N to the soil, and this would affect the yield of subsequent crop. This release of nitrogen from legume residues or its transformation to plant usable form is affected by physical and chemical properties of the soil, temperature of the area, and method of crop residue management, and in the case of rice crop, flooded condition may also be important in N transformation. Many other factors have direct influence in N release including the lignin and polyphenol content. However, the major factors are the water status of soil, C/N ratio of legume residues and its nitrogen concentration that determine the rate of mineralization, and thus availability of released nitrogen to following crop. Leaves of most legume crops contain high C/N ratio that enhances the mineralization process and so increases the availability of N to subsequent crop.

To enhance the nitrogen fixation at its maximum that will give the maximum yield of nitrogen, the legume crop must be grown in a favorable growing season. It may be wet season with enough irrigation water. However, in Pakistan, the winter wet season or area under irrigation is mostly reserved for cereal crops, and legume crops were grown in dry areas with no irrigation that leads to lower legume yield. Other factor of legume low yield is the application of lower rates of fertilizers by the farmers to the legume field (Craswell et al. 1987). As a result, yield of legume crop is critically low due to nutrient deficiencies.

When a green legume is grown and entire crop is incorporated to the soil, then the amount of nitrogen incorporated and concentration of nitrogen in the legume are higher than the crop where seed is harvested from the legume crop. In this scenario the rate of decomposition might also be high due to lower C/N ratio. Experiments on decomposition of residues from the alley crop reveal that half of the N from incorporated legume is released to the soil within 1–9 weeks. This release of nitrogen is affected by the environmental condition and amount of nitrogen already present in the soil. It is obvious that incorporation of green legumes can provide enough amount of nitrogen to the soil that significantly increases the yield of following crops.

Soil nutrient of flood areas during the transition period from dry to wet season can be managed by the flood-tolerant species of green manure legumes where they tolerate the short-term waterlogging. Due to the reluctance of farmers in the use of inorganic fertilizer because of uncertainty of the climatic conditions, alternative crops cannot be grown.

Legume crops are also grown as a source of green manure in conditions other than exhaustive agriculture. Local legume species are cropped to improve the fertility of soil in shifting cultivation system. Legume tree can also be used to restore eroded or degraded land. It is recorded that litter and leaf fall from the *Leucaena* in the dry tropics can increase more than ten tons of organic matter to the soil per hectare annually. This organic matter contributes up to 250 kg of N to the soil (Sandhu et al. 1990). However, decomposition of this organic matter under hard dry condition is tough and slower than the continuous agriculture system, and rates of nitrogen release depend upon the C/N ratio of organic matter from leaf and litter. Therefore, it can be predicted that out rate for N release for fruit leaf and litter with lower C/N ratio (17–18) would be higher for woody parts and twigs with higher C/N ratio (>33). Even so, it is expected that up to 80% of the N in the leaf and litters is released to the soil annually that shows a major portion to the N cycling in infertile, eroded, and degraded soil (Sandhu et al. 1990).

8.3.2 Nutrient Management and Non-legumes

8.3.2.1 Actinorhizal N Fixation

Other than nitrogen fixing legumes and those species that form nodules by *Rhizobium* sp., approximately more than 200 plant species comprising of 8 families and nearly 17 genera in arid and semiarid areas fix atmospheric nitrogen by forming nodules by actinomycetes. The actinorhizal plants are much fewer than N_2-fixing legume plants. However, they have potential to regenerate the poor soils and preserve the land surfaces from erosion. Among these, Casuarinas have too much potential for agriculture. However, very scanty information is available regarding *Frankia* inoculation.

8.3.2.2 Azolla

Azolla is an aquatic fern which is found everywhere in the world and has N_2-fixing heterocyst cell. *Azolla* can grow in N limiting conditions where other water plants cannot grow due to their N_2-fixing ability. In tropic zones, it forms dense layers on the surfaces of drainages, ditches, marshes, ponds, and rice paddies. *Azolla* is also being used to suppress weeds and as green manure in paddy fields. It is also being used as feed for dairy animals and cattle, fish, or farm ducks. Under favorable conditions, it can regrow with the same mass in 2–3 days. Its dry matter content comprises of 4–6% of nitrogen, and its one reap can uptake 30–100 kg of N per hectare. Therefore, it can contribute annually 450–840 kg N per hectare under optimum conditions. This too much nitrogen percentage shows a high increase in N of rice-based agricultural soils. Many factors can affect the potential on *Azolla* that include very high or very low temperature, high light intensity, and deficiency of essential nutrients especially phosphorus. Rate of decomposition of *Azolla* depends upon the method and time of addition and its quantity incorporated. However, under ideal conditions, its decomposition rate is rapid. Its incorporation and release of nitrogen is nearly equal to inorganic fertilizer efficiencies especially in flooded paddy field.

8.3.2.3 Nutrient Management Through Nitrogen Fixing Grasses and Cereals

There are many genera of associated nitrogen fixers (diazotrophs) that are found in the roots of many cereals and grasses. Acetylene-reduction assay has been used to demonstrate the N_2 fixation in cereals such as sorghum and maize. Now it has been confirmed from N15 techniques that many plants from the grass family such as wetland rice, sugarcane, and grasses under some conditions get nitrogen from associated N_2-fixing bacteria. Inoculation of these bacteria can help to manage nitrogen deficiency in the soil.

8.3.2.4 Nutrient Management Through Nitrogen Fixing Forage Grasses

Many studies provide the data regarding the N fixation in C_4 forage grasses especially Kallar grass. Kallar grass is widely distributed in Pakistan. It is observed that N_2 fixation from these grasses can contribute up to 40 Kg of N per hectare per annum in the production of pasture (Chalk 1991).

8.3.2.4.1 Sugarcane

Many experiments have shown associative nitrogen fixation with sugarcane crop. As sugarcane crop is a most exhaustive crop, therefore associative N_2 fixation can play a key role in managing the nutrient needs of the crop. Each crop harvest of sugarcane can remove up to 200 kg of nitrogen per hectare. With this so much N removal if compensated from associative nitrogen fixation, then a good yield can be obtained even in continuous cropping (Thompson 2004). Further, the potential of sugarcane for associative N_2 fixation can be improved through breeding techniques.

8.3.2.4.2 Rice

Acetylene-reduction assays on different field experiments have confirmed measurable quantities of associative N_2 fixation in rice plants. But extensive importance of associative nitrogen fixation with paddy crop is tough to measure because many of the investigations did not confirm the N_2 fixation activity. However, some experiments show varietal differences in the potential of rice to establish potential associations regarding N_2 fixation. In tropical and subtropical agriculture, it is tough to evaluate accurately the role of N_2-fixing non-legumes because very few studies are conducted to measure the ability of N_2 fixation using reliable methodology. However, it can be concluded that the potential of non-symbiotic plants for biological nitrogen fixation is too low as compared to symbiotic actinorhizal plants and *Azolla*.

8.4 Constraints Associated with Utilization of BNF

Although much work has been done on N_2 fixation, still there are many unknowns in the subject which should be explored for improving fixation mechanism in the future, and some of these unknowns are restricting the application of N-fixation technologies. Much of the explored work is still not being practiced particularly in developing countries. Implementation of BNF technologies in field crops is difficult due to practical, socioeconomic, and human-resource barriers. These complexes can be resolved through scientific research, education and awareness, training, and growth of private enterprise. To attain full benefit of BNF system, constraints should be properly addressed and resolved so that farmers can easily adopt the technology. These constraints can be named as biological, environmental, methodological, and sociocultural constraints.

8.4.1 Environmental Constraints

The modern biotechnology improves the life of humans by introducing genetic engineering techniques, i.e., one can change and modify the genetic composition of organisms. Techniques are available, but due to lack of knowledge how to match the genetic buildup of the living systems to the environment. For instance, how N-fixing organisms will respond in different soil environment. For successful implementation of N-fixation techniques at farming levels, complete understanding of N-fixing systems is prerequisite. Numerous environmental factors affecting the activity of legume-rhizobia symbiosis (Provorov and Tikhonovich 2003) and actinorhizal (*Frankia*) symbiosis (Torrey 1978) have been reported. Soil constraints to symbiotic performance have been reported by a number of researchers. The host-microbe symbiotic interaction is mainly affected by soil pH, aluminum and manganese toxicity at low soil pH (Panhwar et al. 2015) and calcium deficiency, phosphorus (Kabir et al. 2013), salinity (Soussi et al. 1998), and flooding (Choudhury and Kennedy 2004). Nitrogen release from organic sources is also a limiting factor for symbiotic interaction within a plant community. Competition between native microbes and N-fixing microbe is one of the major barriers to successful implementation and efficiency of N_2-fixing systems especially for legume inoculants. Soil temperature or P and K enrichment is among such environmental factors which can influence the competition patterns. Moreover, population size of indigenous rhizobia and crop response to applied rhizobia affect the establishment and activity of applied inoculants. For example, in tropical environment, inoculation-induced increase in yield and nodulation of cowpea is dependent on population and competitive nature of native *Bradyrhizobium* sp. (Danso and Owiredu 1988). However, very less information is available to support the misconception-based idea that leguminous crops grown in tropical regions do not respond to rhizobial inoculation. Whereas response of soybean to *Bradyrhizobium* rhizobia inoculation was significant, when applied rhizobia become naturalized, no response was observed in the following crops in rotation (Salvagiotti et al. 2008). For this purpose, ecological models have been proposed based on population size of indigenous rhizobia and soil nitrogen status to predict the likelihood and response of legume crops to applied inoculants of rhizobia.

8.4.2 Biological Constraints

The major biological constraints to BNF practices' implementation include microbial genetic potential and their interaction with environmental factors. In symbiotic interactions, biological constraints affect the association of both partners, e.g., quantity of fixed N is directly or indirectly affected by disease and predation, and consequently amount of N becomes available to other parts of the cropping system. Quantity of fixed N and host plant growth potential are directly related to each other especially in leguminous crops. For example, when crop growth is restricted by disease or by other constraints, N fixation will be reduced accordingly.

8.4.3 Methodological Constraints

Difficulty in identification of a specific nitrogen fixing bacteria for different BNF systems to make this strategy successful is one of the main constraints for failure of this technology. However, due to development of serological methods, it is relatively easier to identify and monitor the specific rhizobia for different legumes which involve symbiosis. With the genetic analysis with DNA probe (Holben et al. 1988), this system will be simplified in the near future. Inoculation technology is fully developed for legume inoculant, but for the inoculants of actinorhizal and other BNF systems, there are still many issues. Nevertheless, *Frankia* can be grown successfully in pure culture, but large-scale production is always a problem. Even for legume, large-scale production of inocula still has many issues such as selection and availability of appropriate carrier material, shelf life of packed materials, and preservation of microbial germplasm in developing countries due to load-shedding problems. Another important methodological constraint is the accurate measurement of BNF due to the lack of reliable techniques under field conditions.

8.4.4 Production-Level Constraints

There are various field level production constraints related to the introduction of BNF systems into the farming system; thus there is no guarantee that development of BNF system will successfully prevail in a system. Cereals are dominantly grown in cropping system all over the world, and introduction of legumes into this system is a task of challenging complexity regardless of the nitrogen fixing abilities of legumes. In humid tropic regions, higher precipitation and humidity in rainy season and uncontrollable proliferation of insects, pest, and diseases are the major factors that constrained the production of leguminous crops at large scale (Ratnadass et al.

2012). Similarly due to hydrophilic characteristic of grain legumes, seed quality deteriorates very rapidly in such conditions (Shanmugasundaram 1989). Therefore, precautionary measures are needed for grain legumes compared to the cereal crops. Besides leguminous plants are indeterminate types, and they have low grain to plant biomass ratio in wet season, thus resulting in low seed yield in humid climate. Therefore, in order to get good yield they must be grown in the in humid uplands of all tropical continents severe acidity and P in ultisols and oxisols soils results in lower production of legumes unless nutrients are added and soil reclamation strategies are adopted (Sanchez and Uehara 1980). Moreover, low BNF in these soils is due to excessive available N. In humid tropics leguminous green manures have played a critical important role in nitrogen fixation in rice production system, but the contribution of legumes in BNF declined with the introduction of synthetic fertilizer in cropping systems. Although *Azolla* is one of the potential candidates responsible for BNF in rice production system, however, due to many farm-level constraints, such difficulty in maintaining availability of inocula of *Azolla* throughout the year and its susceptibility to insects and diseases limit the adaptation of this technology by farmers. Legume crops flourish well and play an important role in BNF in the semiarid tropics compared to the humid tropics, and they are mostly grown with cereals. For example, in India, pigeon peas are intercropped with sorghum, while in West Africa cowpeas are grown commonly with sorghum or maize.

8.4.5 Sociocultural Constraints

It is important to note that BNF technologies not only have scientific constraints but are also influenced by cultural, educational, economic, and political values. Therefore, efforts should be made for training, education, and technical assistance in order to make BNF system successful. Socioeconomical restrictions should be evaluated and provide information publicly to remove or reduce these constraints. Many farmers in developing countries have no knowledge about the nodulations in legumes and their potential benefits in nutrient managements and soil fertility. Farmers have been growing leguminous crops since ancient time just considering them as valuable component of cropping system rather than their nodule characteristics and importance in BNF. Normal extension mechanisms are unable to transfer difficult BNF technology effectively at the farm level because of insufficient illustrative and explanatory materials and other aids. Furthermore, in developing countries, only few of the senior decision-makers who are responsible for determining the agricultural policies have knowledge of opportunities for legume-based BNF technology in the agriculture sector of their countries. Among those only a smaller number of peoples recognize that adaptation of such technology will be beneficial for their prevailing farming systems. Hence, special educational material should be developed for such group of peoples to bring their attentions to adapt this technology. The lack of technical persons who can disseminate and transfer BNF technology to farmers at field level is also a big constraint. A subsidy on nitrogenous fertilizers is also a factor for avoidance of BNF by farmers. Similarly, most of the subsidy programs for crop productions are limited to cereal crop productions around the world which create a wide gap of interests for legume productions. For example, in America most of the farming systems are cereal based. However, in some parts of the world like in Australia, there is no discrimination for subsidies among crops exploitation of cereal-legume systems is a dominant feature of agriculture.

8.5 Strategies to Enhance N_2 Fixation

The increment in quantity of N_2 fixation should be achieved by:

(a) Improving leguminous crop yield as affected by cultural, fertility, supervisory, and environmental obstacles.
(b) Minimizing quantity of nitrate in rhizosphere through tillage management, time of sowing, and grazing management.
(c) Selection and inoculation of rhizobial strains to attain optimum population and breeding approach for selective nodulation.
(d) Breeding techniques to minimize the inhibitory effects of nitrate on nodule formation or by improving nodulation through introduction of required inoculants in rhizosphere and properly manage the soil under different environments, two important practices of which are discussed below.

8.5.1 Tillage

Land cultivation enhances the decomposition of soil organic matter and commonly increases nitrate N in the soil profile and minimizes the process of denitrification, immobilization, and nitrate leaching. Under no till, cereal crops need additional N to overcome deficiency of soil nitrate N, whereas N_2 fixation by legume crops enhanced at lower nitrate in soil. Additionally, soil structure is also improved under no till system favoring soil moisture and temperature for plant growth. Soybean grown in subtropical environment showed higher nodule formation and N fixation under no till as compared to disturbed soil. Although N balance is found positive for both no till and tillage systems, but sudden increase is noted under no till systems.

8.5.2 Removal of Plant or Animal Products

Grazing management and cropping pattern influence the availability of nitrate N to legumes. Growing leguminous crops in rotation to cereal crop can fix higher amounts of N as compared to fallow land cultivation (Van Kessel and Hartley 2000). For example, the N harvested by soybean seeds was significantly enhanced from -44 kg N ha^{-1} after fallow to $+39$ kg N ha^{-1} in previously cropped land (Bergersen et al. 1985). Thus along with other factors, crop rotation is also important for N_2 fixation. On the other hand, intercropping maize and rice bean has resulted in obtaining higher P levels as attained during single cropping. This is due to competition between legume and maize crop for indigenous soil N. The intercropping resulted in higher total N harvested by intercropping with legumes as compared to combined weighted N yield of single crops of maize and rice (Chu et al. 2004; Yilmaz et al. 2008). Similar strategies might be followed for forage systems. To maintain lower levels of soil nitrate N and to improve N_2 fixation, legume crops can be introduced in competition with vigorous grasses or through grazing to remove leguminous N or sequential cut and carry practices. On the basis of compatibility to rhizobial strains, there are three main groups of legumes (Peoples et al. 1989). First group includes leguminous crops which can perform effective symbiosis with variety of strains. These species are enriched in tropical soils, and members of this group are nodulated by cowpea-like rhizobial. Some host-strain association specificity in this group is also observed. Second group members can nodulate with several rhizobial species, but some strains result in effective N_2 fixation. Third group legumes are highly specific to strains especially when grown to new areas, and their association is usually successful. Factors/reasons restricting effective host-strain association include (1) lack of similar legume crop in previous cropping pattern, (2) same crop in rotation resulting in poor nodulation, (3) legume-non-legume rotation, (4) during land amelioration, and (5) unsuitable environment for *Rhizobium* survival (e.g., variation in soil pH, long-term flooding, and drying before planting). The effective and successful host-strain association in field is dependent on procedure followed, technicality of operator and presence of toxic agrochemicals, and variation by soil factors (Brockwell et al. 1988). These strains are practically used in Australia and the USA. They establish legume-based pasture and cropping systems. Two countries in Latin America use inoculants to any extent; in Brazil, the main producer of seed legumes, common beans, did not use inoculants but rather use N fertilizer (Freire 1982).

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Use of Biofertilizers for Sustainable Crop Production

9

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Abstract

Sustainable crop production is the need of hour, and for optimum plant growth and development and higher productivity, availability of nutrients should be balanced and sufficient. In developing countries, among resource-poor farmers, soil infertility is the most important constraint for higher crop yield. In order to maintain soil fertility and higher crop production, use of synthetic fertilizers has been used widely. However, incessant use of fertilizers causes decline of soil quality as well as productivity. Continuous use of nitrogen and phosphorus fertilizers leads to soil acidity and enrichment of P in vegetable production. Improvement in soil fertility could be restored efficiently through adaption of integrated soil fertility management like biological nitrogen fixation (BNF) for increasing efficiency of inputs and higher productivity of crops.

Keywords

Biofertilizer · Crop productivity · Soil fertility · Soil productivity

9.1 Introduction

Sustainable crop production is proving as one of the toughest job nowadays. In crop production there is no uniformity in agricultural practices throughout the world, but one thing is common more or less which is use of fertilizers. For optimum plant

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growth and development, availability of nutrients should be balance and sufficient (Chen 2006). Among the resource-poor farmers in developing countries, soil infertility is the most important constraint for limited crop yield (Mohammadi and Sohrabi 2012). To maintain the soil fertility and crop production, use of synthetic fertilizers has been accepted widely. But the incessant use of these fertilizers causes the decline of soil quality as well as productivity (Yang 2006). Continuous use of nitrogen and phosphorus fertilizers leads to soil acidity and enrichment of P in vegetable production (Liang et al. 2013). To restore the fertility in these regions, farmers have to get improved varieties and productive cultural practices. The improvement in soil fertility could be restored efficiently through adaption of integrated soil fertility management including an approach for nutrients management based on natural resource preservation by biological nitrogen fixation (BNF) though increasing the efficiency of inputs (Vlek and Vielhauer 1994).

9.2 What Are Biofertilizers?

Biofertilizers play an important role through improving the nutrient supplies and their crop availability in the years to come. These are non-bulky, environment-friendly and low-cost inputs in agriculture. A biofertilizer is an organically produced product with specific type of microorganism either obtained from plant roots or from the soil in the plant root zone (Swathi 2010). Biofertilizers are also called microbial inoculants and can be generally described as containing living microorganism of efficient strain for nitrogen fixing, solubilization and mobilization of P and K, increasing organic carbon, balanced carbon/nitrogen contents, promotion of plant growth through enhancing absorption of nutrients, antagonistic activity against plant pathogens and plant hormones production useful for agriculture (Borkar 2015).

9.3 Why Biofertilizers?

Farmers haphazardly use different chemical fertilizers for enhancing growth and productivity of different crops to meet the emerging demand of food supply. These actions have led to toxifying and highly damaging the soil health, microbial activity and friendly insects. However, excess use of chemical fertilizers as a result made the crops more susceptible to diseases and fertility of soil (Mahanty et al. 2017; Aktar et al. 2009). In the year of 2020, the world population will be 8 billion. To feed this population, a target of 32.1 million tons of grain food will be required, and the nutrient requirement will be 28.8 million tons. Therefore, the availability of nutrients will be 21.6 million tons hence creating a deficit of about 7.2 million tons from the required nutrients (Arun 2007). Generally, among the applied chemical fertilizers, only 10–40% is taken up by the plants and the remaining applied fertilizer lost.

So, to overcome the deficit amount of nutrients, the production of agriculture needs to improve, and that should be sustainable and environment-friendly. Therefore, it is compulsorily required to reconsider most of the existing agricultural practices which include fertilizers, fungicides, insecticides, herbicides and pesticides (Pretty and Bharucha 2015). In view of these harmful effects of chemical fertilizers, the safe alternative of chemical inputs is biofertilizers which are thought to do minimum ecological disruption to a great level. Biofertilizers are cheap and ecofriendly in nature, and their long-term use improved soil fertility considerably (Mehdi et al. 2010). Biofertilizers can enhance the crop yield about 10–40% by increasing protein contents, vitamins, essential amino acids and nitrogen contents (Bhardwaj et al. 2014). With the application of biofertilizers as a seed or soil inoculant, they increase and contribute in cycling of nutrients and benefit the crop yield (Singh et al. 2011). The biofertilizers are excellent source of organic matter and economical source of nutrients and also help in secretion of growth hormones and stabilize the adverse effects of chemical fertilizers (Gaur 2010). Many types of microbes are present in the soil and play a crucial role in different biotic activities within the soil profile which helps in making the soil more dynamic for nutrient mobility and sustainable crop production (Ahemad and Kibret 2014).

9.4 Different Types of Biofertilizers

The classification of biofertilizers depends on the type and group of microorganisms they comprise. Different types of microorganisms used in different biofertilizers are shown in Table 9.1**.** These include:

9.4.1 Nitrogenous Biofertilizers

These biofertilizers contain *Azospirillum*, blue-green algae and *Rhizobium* spp. They can fix atmospheric nitrogen and convert it into organic form within the soil and nodules of roots in leguminous crops, thus making them available to the plants. These N fixing biofertilizers are crop specific (Choudhury and Kennedy 2004). Nitrogen biofertilizers help to accurate the nitrogen deficiency within the soil. Nitrogen is a controlling element for vegetative growth of plant because plants need a certain quantity of nitrogen in the soil to flourish. Most of the biofertilizers have a satisfactory effect in different soils, so the choice of nitrogen biofertilizer to be used depends on the cultivated crop.

9.4.2 Phosphorus Biofertilizers

Phosphorus is also a most important nutrient required for plant growth as nitrogen. Phosphate biofertilizers are of two types as solubilizer and mobilizers. Phosphate solubilizing microorganisms include *Bacillus* spp., *Aspergillus* spp. and *Pseudomonas* spp. Phosphorus is present in the soil in the form of insoluble phosphate which cannot be absorbed by the plant roots. These microorganisms solubilize the insoluble form of phosphate within the soil which can be available to plants

Table 9.1 Biofertilizers used for crop production

Groups	Type of biofertilizer	Role in plant growth	Target crops	References
Free living	*Azotobacter*, *Beijerinckia*, *Clostridium*, *Klebsiella*, *Anabaena*	Nitrogen fixation	Non-leguminous crops having high organic matter like mustard, sesame	Dhanasekar and Dhandapani (2012)
Symbiotic	*Rhizobium*, *Frankia*, *Anabaena*, *Azolla*		Leguminous crops like groundnut, gram, soybean, etc.	Rittika and Uptal (2014), Kumar (2018) and Sabry et al. (1997)
Associative symbiotic	*Azospirillum*		Barley, maize, oat, sugarcane	Trabelsi and Mhamdi (2013), Khan et al. (2009) and Vessey (2003)
Bacteria	*Bacillus* spp.	Phosphate solubilization	Soil application for all crops	Kumar (2018), Ju et al. (2018) and Khan et al. (2009)
Fungi	*Penecillium* spp., *Aspergillus awamori*		All crops	Banerjee et al. (2010)
Arbuscular mycorrhiza	*Acaulospora* spp., *Glomus* spp., *Gigaspora* spp.	Phosphate mobilization	Wheat, sorghum	Whitman (2009) and Mehrvarz et al. (2008)
Bacteria	*Bacillus* spp.	Zinc and silicate solubilized by production of organic acids and growth promotion (auxin)	Cereals	Jetiyanon and Pliabanchang (2011)
Bacteria	*Bacillus* spp. and *Pseudomonas* spp.	Potash mobilizers	Sorghum, cowpea,	Bhattacharjee and Dey (2014)

easily, though a number of soil fungi and bacteria have the capacity to convert the insoluble phosphate in soluble form by releasing organic acids through lowering the pH of the soil and break the bonds of phosphate which make them available to plants (Gupta 2004). Phosphorus mobilizing microorganisms include *Mycorrhiza* spp. which can scavenge the phosphate within the soil and mobilize them from insoluble to soluble form in which soil they are applied (Chang and Yang 2009). Phosphorus biofertilizers help the soil to reach its ideal level of phosphorus in the soil. Unalike nitrogen biofertilizers, the usage of phosphorus biofertilizers is not reliant on the crops cultivated on the soil (Ju et al. 2018).

9.4.3 Potash Biofertilizers

These biofertilizers are broad-spectrum in nature. These include *Bacillus mucilaginous* and *Aspergillus niger* bacteria. Potassium mostly presents in the silicate minerals which cannot be taken up by plant roots. So, to release this potassium mineral, process of weathering and solubilization should occur. These microorganisms released organic acids which solubilize the silicate mineral and help the potassium minerals to make them available for the plants.

9.4.4 Sulphur Biofertilizers

Sulphur biofertilizer contains *Thiobacillus* spp. microorganism which oxidized the sulphur into sulphate form and making them available to the plants.

9.4.5 Silicates Solubilizing Biofertilizers

These biofertilizers contain *Bacillus* spp. which are capable of degrading the silicates and aluminium silicates. These microorganisms secrete organic acids like citric acid, hydroxyl carbolic acid, oxalic acid and keto acid which promote the hydrolysis.

9.4.6 Microphos Biofertilizers

They are proclamation phosphate from preordained and intricate states, e.g. *Bacillus polymyxa*, *Pseudomonas striata*, and *Aspergillus* species.

9.4.7 Liquid Biofertilizers

At present, biofertilizers are abounding to the farmers as carrier-based inoculants. As an alternative, liquid formulation technology has been developed which has more rewards than the carrier inoculants.

9.5 Major Role of Biofertilizers

In many developing countries, agriculture contributes a main share on national and export earnings, through ensuring income and food security and providing employment to an enormous percentage of population. Decline in soil fertility is the major complaint from the farmer's point of view. As a consequence, to improve soil fertility and control soil erosion are the most important issues on the policy development agenda nowadays. Fertilizers containing microorganism contribute widely essential services for sustainable crop production and ecosystem. Through primary agent for nutrient cycling, regulating dynamics of soil organic matter, greenhouse gas emission, amending physical properties of soil structure, soil carbon sequestration and improving the proficiency of nutrient procurement by the vegetation and improving plant health. These services are very essential for the functioning of natural ecosystem but also establish a significant means for sustainable crop production and environmental ecosystem (Singh et al. 2011). The major roles of the biofertilizers are as follows:

- Biofertilizers act as a supplement to the chemical fertilizers in meeting the nutrient requirement of the crops.
- Biofertilizers application results in the increased uptake of water, development of roots, vegetative growth, increased minerals and increased fixation of nitrogen.
- Biofertilizers play a role as antagonists and stop the occurrence of soil-borne plant pathogens, thereby promoting the biocontrol of diseases.
- They tend to enhance the fertility of soil and the soil productivity.
- They release some substances which are growth promoting and vitamins which aid in the maintenance of soil fertility.
- Biofertilizers act as a recycling agent of plant nutrients.
- Biofertilizers tend to increase the rate of decomposition in compost pit.
- Biofertilizers are cheaper than the chemical fertilizers and act as a saving agent in place of chemicals.
- Biofertilizers solubilize the insoluble forms of phosphate like tricalcium, iron and aluminium phosphate into available forms, hence increasing the soil fertility.
- They edify the plant growth without detrimental side-effects (Fig. 9.1).

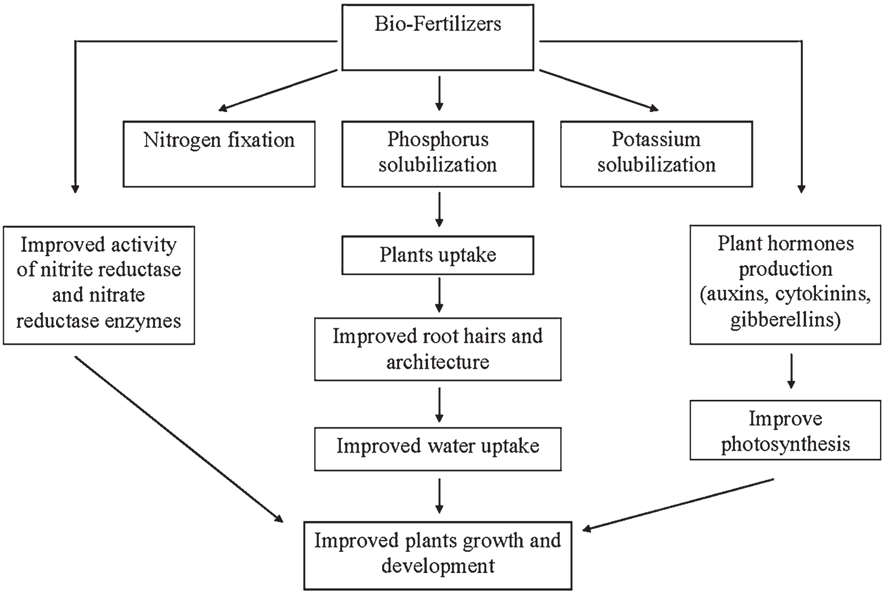

Fig. 9.1 Role of biofertilizers in crop production

9.6 Biofertilizer Production

There are numerous things that must be considered in biofertilizer production like the type of microorganism, their growth profile, optimal conditions for organisms and preparation of inoculum. However, formulation of inoculum, application method and storage of the ready product are also critical for the stability of product in the market. Generally, there are six major steps for the biofertilizer production: first, choice of active microorganism; second, isolation and selection of target organism; third, suitable method and carrier material; fourth, best propagation method; fifth, trial basis testing on small scale; and sixth, testing on large scale. So, first select all active microorganisms. For example, decide whether to use P or K solubilizer, N fixer or combination of two or more microorganisms. Next, isolate the target organism from their inhabitation. Generally, isolation is done from plant roots by persuading it using decoy such as placing cool rice underground. Then, from the isolated microorganism, selection of the best contestant will be made on the basis of their trials in petri plates, shake flask and glasshouse. The basic aim of selection of propagation method is to find out the most favourable condition for the organism. This could be attained by obtaining growth profile at different stages and conditions. Later, prototype test is usually performed at different farms. Finally testing of final product on a large area at different surroundings will be done to explore its effectiveness and flaws.

For the transportation of product, right choice of carrier material is the most important step. For example, if biofertilizer is produced in powdered form, then peat or flour of tapioca is the right choice for carrying the product. Generally, the production of biofertilizers depends upon inoculants having effective microorganisms. To keep high number of inoculant bacteria and long duration storage, sterilization of carrier material is necessary. For sterilization autoclave or gamma radiation method can be used. Different kinds of materials could be used as carrier for soil and seed inoculation. The carrier must be good, cheap and available in sufficient quantity. It should be non-toxic to plant as well as to inoculant bacteria and has good moisture absorption and good adhesion to seeds. Most importantly the carrier must have good buffering capacity and be easily processed (Mohammadi and Sohrabi 2012).

9.7 Working of Biofertilizers

The association of fungi with roots of higher plants is called mycorrhiza. While it remains a problem to know the exact mechanism of stimulation of growth within the root cells due to fungus colonization. During symbiosis, up-regulation of transporter genes indicates the transportation of useful compounds like oligopeptides, polyamines and amino acids from one organism to another. The nitrate and ammonium can be taken from the soil by free-living mycelium and then reach at the mantle (a dense hyphal sheath) and heritage net (interface between fungal hyphae and plant root cells) and ultimately transferred to plants. For the formation of symbiotic interface, between fungus and plant cysteine-rich proteins (MISSP7) act as effectors and facilitators. Genes related to synthesis of auxin and root morphogenesis showed up-regulation during fungal inhabitation (Plett et al. 2011; Splivallo et al. 2009; Abdel-Raouf et al. 2012; Ansari et al. 2013).

The inorganic P transporters and glutamine synthase gene present on fungal hyphae help in the absorption of P within the soil. However, glutamine synthase genes help in N metabolism on mycorrhizal hyphae and later on transported to plants (Salvioli et al. 2012). Biologically active compounds released by mycorrhiza and rhizobium are perceived to the host plant roots for the activation of signal transduction pathway which prepares the plant for symbiotic relationship (Kosuta 2003; Roberts et al. 2013). This relationship brings some molecular anatomical changes with first contact. In this process calcium serves as a secondary messenger in the region of root hairs (Sieberer et al. 2009; Ramachandran et al. 2011). Rhizobium secretes indole acetic acid (IAA) which induces the production of nitric oxide acting as secondary messenger to trigger the complex signalling network leading to efficient root growth and development (Molina-Favero et al. 2007).

Root remodelling and many defense-related genes up-regulated during the entry. Consequently, permits the foundation of pre-penetration apparatus (Bucher et al. 2009). A number of genes like subtilisin protease 65, phosphate transporter 66 and two ABC transporters 67 are identified to be involved in AMF formation (Zhang et al. 2010; Tromas et al. 2012).

Therefore, nitrogen fixing genes are used to fix N to create engineered plant under low concentration of N and oxygen (Santos et al. 2012). Remarkably, sugarcane sprouts, inoculated with a wild strain of *G. diazotrophicus*, have established fixation of radioactive N_2 when compared with the *G. diazotrophicus* mutant that has mutant nif D gene which verified the importance of nif genes. Competency of N_2 fixation is reliant on the consumption of carbon (Sevilla et al. 2001; Bertalan et al. 2009).

9.8 Biofertilizers and Crop Production

The major contribution of rhizobium and mycorrhizal fungus is to assimilate the nutrients for their own need as well as available in sufficient quantity in soluble form within the soil profile. A number of microorganisms like *Pseudomonas*, *Bacillus*, *Micrococcus*, *Flavobacterium*, *Azospirillum*, *Fusarium*, *Enterobacter*, *Sclerotium*, *Burkholderia*, *Aspergillus*, *Penicillium*, *Pantoea*, *Azotobacter*, *Erwinia* and *Serratia* have been used in active solubilization (Pindi and Satyanarayana 2012; Kravchenko et al. 2004). Nitrogen is an essential element in the growth and development of crop production as it is part of ATP, RNA, DNA, chlorophyll and protein (Kumar 2018). The wheat plants inoculated with *Azospirillum* had improved the growth, mineral and chlorophyll contents (Meena et al. 2016). The seed priming of *Azospirillum brasilense* in maize has increased the 1000-grain weight, grain yield, chlorophyll contents and root/shoot dry biomass (Costa et al. 2015; Singh et al. 2015). Application of *Azolla* as biofertilizer helps in decomposition of soil which efficiently releases its nitrogen to the plants (Al Abboud et al. 2013). Inoculation of rhizobia has increased the surface area of leaves in rice plants as well as improved the stomatal conductance, net photosynthetic rate and water-use efficiency (Mia and Shamsuddin 2010).

A bacterial strain NII-0909 derived from *Micrococcus* sp. was found to induce phosphate solubilization, production of auxin, ammonia as a nitrogen source and siderophore production (Dastager et al. 2010; Ahmad et al. 2008). Likewise, a mycorrhiza which isolated from decomposed cassava alters the cassava waste through semi-solid fermentation technique to phosphorus biofertilizers (Ogbo 2010). Another bacteria *Burkholderia vietnamiensis* which are stress tolerant secrete gluconic and 2-ketogluconic acid, involved in phosphate solubilization (Park et al. 2010). *Enterobacter*, isolated from sunflower rhizosphere, is involved in the production of siderophores and indolic compounds. These compounds are helpful in the solubilization of phosphate (Ambrosini et al. 2012).

The *Aspergillus*, *Bacillus* and *Clostridium* seem to be efficient in solubilization of potash within the soil and its mobilization in different crops (Mohammadi and Sohrabi 2012). Mutual symbiosis of fungi with the plant roots fulfils plant nutrient demand which leads to improved plant growth and development and keeps the plant safe from environmental stresses and pathogen attack (Kogel et al. 2006; Lamabam et al. 2011) contents in cotton. Biopriming of potassium-solubilizing bacteria (*Bacillus edaphicus*) increased the potassium contents up to 30% and 26% in rape. The N, P and K uptake and root and shoot growth were also improved in both crops (Sheng 2005). KSB-1 and KSB-7 inoculation increased the plant growth and K uptake (Prajapathi 2016). Inoculation of potassium solubilization bacteria in tea increased the chlorophyll contents, carotenoids, quality parameters and nitrogen, phosphorus and potassium contents in shoots of the tea plant (Bagyalakshmi et al. 2012). Arbuscular mycorrhizal fungi are basically involved in phosphorus nutrition (Whitman 2009). These fungi improved the macro- and micronutrients uptake and enhanced water uptake (Kumar 2018).

9.9 Methods of Biofertilizers Application

There are four methods of biofertilizers application which are:

- Seed application.
- Set application.
- Seedling application.
- Field application.

9.9.1 Seed Application

The most extensively used method for biofertilizers application is seed treatment. First of all, to make the slurry, one packet of 200 g is mixed with double amount of water (1:2) ratio, or for better results, rice glu or Kenji can be used. For one acre seed, keep them on clean cemented floor or gunny bag. This amount is sufficient to treat 10 kg seeds. Spray the prepared slurry on seeds, and mix it uniformly by hands for thin coating. Keep the seeds under shade for 30 min at least but should be sown within 24 h. This method can be applied to cereals like wheat, rice, maize, sorghum and oil seed crops like sunflower, safflower, groundnut, mustard, gram and soybean.

9.9.2 Set Application

In this method, crops which are sown in sets or pieces like sugarcane, potato and banana are treated with culture suspensions. To prepare culture suspension, 1 kg of biofertilizers bag is mixed with 50 l of water (1:50) ratio. Seeds of crop to be sown should be kept immersed in the suspension culture for at least 30 min. Then bring out the seeds from suspension and dry them under shade for 1 h, and then sow them in the field immediately for good results. Field should be irrigated within 24 h after sowing.

9.10 Seedling Application

This method is most favourable for transplanted crops like rice, onion, cabbage, cauliflower, tomato and brinjal. Dose-wise diluted formulation is required for seedling treatment. To prepare the solution, one part of inoculant is mixed with ten parts of water. For example, 400 g of biofertilizer is mixed in 40 l of water. The roots of the seedling to be transplanted are dipped in the mixture for 15–30 min. After treatment, seedlings are immediately planted in the field without drying.

9.11 Field Application

Different crops required different amount of biofertilizers depending upon its duration. Normally, a crop completes its life cycle in 6 months; 2–3 kg of inoculant is mixed with 50–60 kg of farm yard manure, compost or rice husk for one acre land. This mixture can be applied directly into the soil or sprayed or through fertigation method. For long duration crops, double amount of biofertilizers should be applied for better results.

9.12 Constraints in Biofertilizers

Although biofertilizer technology is cost-effective and environment-friendly, there are some limitations to its implementation within the field in a broad way. There are different constraints which affect it on one way or another impacting its technique in production, marketing, or practicality. First of all, the most significant limitation of biofertilizer technology is their concentration of nutrients as compared to chemical fertilizers. But this can be cured by the addition of wood ash which is rich in potash or bone meal rich in phosphorus. Second, there are no suitable facilities for biofertilizers production, resulting in the production of low-quality and less efficient inoculants without understanding the basic techniques of microbiology. Third, the availability of skilled staff is limited for the production unit, and inoculants have short shelf life. Fourth, there is lack of storage facilities for inoculant packets and also space for testing laboratory. Fifth is nonavailability of sufficient funds and bank loan schemes, and there is also less profit in smaller production units. Sixth, the demand of biofertilizers is seasonal based because of the microorganism's activity. Finally, soil characteristics also affect its efficiency to a greater extent (Chen 2006).

9.13 Precautionary Measures in the Use of Biofertilizers

- Do not mix nitrogenous fertilizers with biofertilizers.
- Do not apply fungicides with biofertilizers.
- Do not mix nitrogenous fertilizers with biofertilizers.
- Avoid direct sunlight exposure to biofertilizers.
- Storage of biofertilizers should not be below 0 °C and above 35 °C.
- Do not keep the used solution of biofertilizers over night (Gupta 2004).

9.14 Conclusion

Our dependency on chemical fertilization has encouraged the flourishing of industries that are producing and marketing the dangerous chemicals which are life-threatening. These chemical fertilizers are not only harmful to human but also damaging the ecological balance. However now farmers are motivated on large scale to shift from chemical fertilization to organic fertilization due to destructive effects on human health when consumed. Use of biofertilizers can be helpful in solving these problems of food need and ever-increasing global population. So, there is dire need to understand the beneficial aspects of biofertilizers to apply it in advanced agricultural practices. The use of biofertilizers can promote the crop productivity in larger scale and could play a key role in soil sustainability by protecting the environment.

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Organic Manuring for Agronomic Crops

10

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Abstract

Organic farming is emerging as a popular way of growing healthy, safe, and nutritious food worldwide in a long-term sustainable way that cut the indiscriminate use of agrochemicals being used globally on the cost of environmental health and safety. Nevertheless, the growing population of the world requires increased food production for that use of chemical fertilizers become inevitable. However, there might be opportunities in some crops where organic fertilizers can be encouraged to get enough food production. Keeping in view the importance of organic farming, this chapter covers the current scenario of organic farming in Pakistan and the world and its importance and effects on quality of foods and soil sustainability. Different types of amendments that can be used under organic farming system are examined and compared. Shifting toward the organic farming system is encouraged by describing its benefits with reference to plant, soil, and human health. As agronomic crops are too important in providing raw materials for food, clothes, and shelter, impact of organic farming system on quality and quantity of agronomic crops is addressed in the chapter.

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Organic manuring · Agronomic crops · Farm yard manure · Compost · Organic agriculture · Carbon sequestration

Abbreviations

CEC	Cation exchange capacity
DAS	Days after sowing
FAI	Fertilizer Association of India
FYM	Farm yard manure
GMOs	Genetically modified organisms
INM	Integrated nutrient management
Mha	Million hectare
N	Nitrogen
NAAS	National Academy of Agricultural Sciences
OARDF	Organic Agriculture and Rural Development Foundation
PGS	Participatory Guarantee Systems
USA	United States of America
WTO	World Trade Organization

10.1 Introduction

Organic agriculture is the integrated use of numerous approaches for sustainable agricultural production and development which is being adopted worldwide as it is economically viable, ecologically safe, and socially acceptable. It is the complete production management system which is widely accepted and stresses upon the adoption of all the approaches based on the use of agronomic, mechanical, physical, and biological methods in preference to off-farm inputs. Further, it opposes and discourages the use of chemical and synthetic materials which are unsafe for the environment and human health. Moreover, this system gives the central importance to soil with the basic aim to optimize the productivity of crops and health of ecological communities of humans, animals, plants, and soil. As population is increasing rapidly and requires more and more food production, food production globally is intensified by the indiscriminate use of agrochemicals (e.g., pesticides and fertilizers) to meet the increasing food demand of the multiplying population. Indiscriminate usage of agrochemicals like pesticides creates several problems like pest resistance, resurgence of pests, contamination of food, and social and economic problems. Understanding the realities, organic farming is getting popularity, and a number of countries are trying to expand organic farming system because of its importance irrespective of their stage of development. As a result, farming system model and practices are now shifting from indefinite enlarged production and yield to product quality, system's sustainability, and eco-friendly production techniques. The traditional agriculture system merely concerns with increased production to meet the rising food demand of growing population and pay less attention to consistent and sustainable utilization of indigenous resources both natural and human. Consequently, practice of flimsy techniques and intensified application of agrochemicals are resulting in overall decreased production to the destruction of soil and depletion of soil fertility. Moreover, agricultural lands are continuously shrinking in area, water availability is declining, and whole agricultural production system is leading toward unpredictability and pollution. Concurrently, these conventional chemical-based practices are disturbing and upsetting the natural resources and local knowledge system making the agriculture system inadequate and unsustainable.

In several ways, the organic farming system promotes and boosts up healthy and safe ecosystem by regulating biological life and biodiversity. Organic agriculture is a sustainable and reliable structure which mainly focused tomorrow's ecology rather than today's economy. Over the last four decades, dependency upon artificial substances like fertilizer, pesticides, growth hormones, modern farming system, etc. has been increasing manifold. Due to which, soil health, human health imbalance in natural habitat, and other hazards like erosion problems and contamination of drinking and irrigation water are more common. Ultimately it causes higher cost of cultivation with poor-quality food. Therefore, it is a dire need of the day to shift from the conventional artificial product-dependent farming system to a sustainable organic farming system. Keeping this in view, this chapter reviews the worldwide current scenario of organic food production with special context to Pakistan (Sect. 10.2); Sect. 10.3 elaborates its importance for quality of food and human health. Section 10.4 discusses the effects of organic forming on soil fertility, soil biota, soil structure, and plants' root growth and health. Further, carbon sequestration and sustainable soil productivity was also discussed in this section. In Sect. 10.5, different sources and types of organic amendments are elaborated. Different types of organic amendments and their importance is compared with special reference to sustainable food production. Section 10.6 discusses the organic food production system and its impact on soil characteristics (physical, chemical, and biological). Further, how organic amendments can suppress plant diseases are also described in this section. Section 10.7 of this chapter describes the influences of organic farming on improved crop yield and quality and its attributes, and the last section addresses the different challenges and barriers for adopting the organic farming system in a sustainable way.

10.2 World Status of Organic Farming

Organic food demand is increasing rapidly not only in developing but also in developed countries, but adaptation of organic farming is very slow even in the developed countries like the USA (0.2%) and in many European countries (6–10%), which is

Table 10.1 Percentage of area under organic farming in the total cultivated area of different countries of the world

Nations	Organic farming area (%)
USA	0.23
UK	4.22
Germany	4.10
Argentina	1.70
Austria	8.40
Australia	2.20
Japan	0.10
Switzerland	7.04
South Africa	1.05
Italy	3.70
India	0.03
Pakistan	0.08
Sri Lanka	0.05

Source: FiBL-IFOAM Survey 2012

1% of the world's cropped area. According to estimation, the concept of organic agriculture is emerging at a high rate. Organic food demand is also increasing rapidly, and this is the reason that almost 170 nations are growing organic food on commercial basis. Asia (36%) is the largest organic food producer followed by Africa (29%) and Europe (17%). In Asia, organic agriculture is flourishing day by day, and most of the developing countries (65%) are focusing to grow organically. Latin America, Australia, Argentina, Brazil, Europe, and Oceania produced organic food on a larger scale. According to a survey in year 2007, globally 32.3 Mha of organic food was produced by 1.2 m growers/farmers; even small landholders also participated in this figure. About 0.4 Mha of agricultural land is certified organic aquaculture. According to year 2006 and 2008 comparison, more than 1.5 Mha of land area was grown organically in year 2008.

According to a report in Latin America, more than 1.4 Mha (28%) of agricultural land is under organic farming, and in Brazil 0.9Mha of area is under conversion, but data is unavailable. So an increase in organic farming has been observed in Europe and Africa (+4%, 0.33 Mha and +27%, 0.18 Mha, respectively) (Willer and Klicher 2009). Austria is the leading country which produces organic food by adopting organic agriculture (8.4%), followed by Switzerland (7.04%), the UK (4.22%), and Germany (4.10%). While only minor area about 0.03% is under organic farming in India, which is very less than the scope (Table 10.1).

Internationally, organic farming system increased 6 Mha in 2013 than in 2012, as 5 Mha rangeland came into organic cultivation just in Australia. Globally, $25 billion were marketed by organic food in 2002 and $12 billion in the USA. In 2013, earing from organic product was reached to peak (US $72 billion), indicating almost five times more increased since 1999. Cuba is a more prominent and leading organic food producer by using low inputs and indigenous renewable resources. Organic agriculture is flourishing rapidly and providing organic food to the nations with eco-friendly techniques on sustainable basis. Though contribution of organic farming is very less, consumer of organic food is increasing day by day predominantly in the USA and Europe (Willer and Lernoud 2015).

Currently, organic agriculture has set certain standards and protocol for health and safe food production. Laws (almost more than 80 national laws) have been developed, and 16 nations are in the development of drafting legislation. Furthermore, alternative organic food certification protocol has been devised by 38 countries, focusing quality assurance Participatory Guarantee Systems (PGS) on local level, while 17 countries are under development under this system. Approximately, in US and European markets, consumption of organic food is about 80%; however, 75% of organic food production is not produced in these chief marketplaces.

10.3 Organic Farming in Pakistan

World Trade Organization set up food standards and followed strict policy to produce healthy and safe food. Pakistan also signed WTO memo and categorically present Euro Good Agricultural Practice (Euro GAP) to the farmers by upgrading its farming standards according to the international standards to enhance their export.

Pakistan is among those countries, which Allah has blessed with diverse and ideal growing conditions not only for crops but also for animal husbandry too. Pakistan is an excellent place for growing of organic food, and there is a huge scope for organic farming. A vast area is highly fertile and productive which can easily be brought under organic agriculture. Surveys should be made to initiate organic farming, and potential of agriculture land should be identified to convert it from unfertile to fertile and productive land. Farmers and local enterprisers should be educated about the huge income returns by growing organic foods.

Pakistan Organic Farms (POF) is one of the leading rice exporters in Pakistan certified by Control Union Certifications, Zwolle, the Netherlands, for organic production of organic basmati rice, sesame seeds, cotton, and wheat. This organization is also affiliated to "Organic Agriculture and Rural Development Foundation (OARDF)," a nongovernmental organization working for organic agriculture and ruvral development. This foundation is introducing latest advanced techniques for growing of organic foods in Pakistan.

The Ministry of Food, Agriculture and Livestock made an agreement with an American company to import organic cotton (50,000 bales) from Pakistan. The meeting was chaired by the Federal Secretary of Agriculture. During this meeting experts recognized that area of Baluchistan has a great potential for growing of organic crops especially cotton. Because the agriculture area of Baluchistan is free from pest pressure and uses synthetic chemicals minorly if compared with the other parts of Pakistan, its production of cotton during 1998–1999 was around 28,000 bales.

It was concluded that the quality of chemically grown cotton in province Baluchistan is better than the rest of the provinces. So, quality of the cotton will further improve by introducing organic farming.

During 1997–1998, supporting price of seed cotton by using chemical was around Rs. 620 per 40 kg. Although organically produced cotton might have less yield, there is a need to introduce premium price for farmers to motivate them to grow more and more organic crops. According to estimate, prices of chemically grown seed cotton (50,000 bales) would be around Rs. 132 million, while it was expected that organic cotton would be two to three times more to motivate farmers.

10.4 Importance of Organic Farming

Organic farming may be defined as production of safe and healthy food to compensate bad impacts of the green revolution on air, topography, soil, water, and humans globally. This kind of cultivation is considered to be eco-friendly due to the elimination of all kinds of synthetic inputs for crop production. For organic agriculture, specific areas are defined and all kinds of inorganic substances like fertilizers, pesticides, veterinary drugs, hormones, additives, preservatives, etc. and genetically modified seeds (GM seeds) and breeds forbidden in organic crop production system. All these substances are replaced by site-specific farm management system to enhance soil fertility and soil productivity and to prevent pests by applying organic and on-farm substances. Inorganic fertilizers are prohibited, and the success of system is based on good soil management, and progressively enhanced soil organic matter and microorganism community ultimately build up soil carbon (Hodges 1991).

Organic agriculture can be adopted and developed to fulfill the world's food demand on sustainable basis. Organic farming is not only providing and ensuring food safety but also showing a significant part in land and soil degradation managing; solving atmospheric issues; minimizing poverty, hunger, and health issues; and biodiversity. Organic agriculture also provides employment to the rural people by diversifying economy by gaining foreign exchange. Organic farming can be extra gainful (22–35%) and have more 20–24% benefit/cost ratios as compared with conventional agriculture; actual payments are applied. Economically, organic agriculture might be chosen for lesser ecological prices and boosted environment facilities from the acceptance of respectable agricultural practices (Crowder and Reganold 2015).

Worldwide, farmers, researchers, and scientists are continuously adopting organic farming. In organic farming on farm and local resources like FYM, crop management and indigenous seed protection measures are the major elements for efficient use.

Organic farming follows a route to promote self-regulation and natural resistance in plants and animals by making them strong against adverse environmental conditions. In this farming system, appropriate new and traditional technologies used in a wise manner named as sustainable farming. The main principles of organic farming are as follows (Manivannan et al. 2015; Yuda et al. 2016):

1. To use local resources as much as possible within a closed system.
2. To use soil wisely so the soil fertility remains intact for a long time.
3. To keep the atmosphere safe from any type of pollution due to agricultural methods.
4. To grow food with adequate quantity and high dietary value.
5. To diminish the practice of fossil energy in agriculture.
6. To provide suitable livestock living conditions to confirm their physical desires.
7. To provide all the benefits and suitable conditions for agriculture producers so that they may explore their maximum potential for the people.

Organic farming provides the following services.

10.4.1 Greater, Deeper Root System

A few aspects of organic farming surge the level of roots in the soil and also result in the roots extending more deeply into the soil, where less mineralization takes place. This may be an important contributor to the soil carbon levels. Roots are also key contributors of the carbon in the subsoil, where the soil carbon is much more stable. There is a large increase in age of carbon with soil depth. Therefore, any increase in the subsoil carbon store is very significant for long-term carbon sequestration. Organic farming provides 72% more root biomass carbon per hectare than nonorganic farming (Soussana 2008).

10.4.2 Higher Level of Living Soil Organisms

Organic farming promotes the soil life. It is revealed that organic farming supports a greater abundance of organisms in cultivated soils, including more earthworms, mycorrhizal fungi, and bacteria. Evidence is growing that this may be one of the main reasons for higher soil carbon levels of organic farming. The greater level of soil microorganisms does not itself account for the higher soil carbon levels of organic farming. Soil microbes commonly constitute only 1–2% of the soil carbon store in arable land. But the activities of soil organisms are highly influential in the stabilization of soil carbon input and thus the accumulation of soil carbon. The polysaccharide gums produced by microorganisms and the network of hyphae of fungal mycorrhizae bind the soil's mineral particles into aggregates which then encapsulate and protect humus against degradation. Larger populations of earthworms might also help distribute more soil carbon to the deeper layers where the soil carbon is longer-lasting. Arbuscular mycorrhizal fungi have been shown to enhance soil aggregation, and recently a major portion of soil carbon store has been recognized which is produced by hyphae of mycorrhizal fungi in the form of glycoproteins. Higher levels of mycorrhizal fungi are not just a by-product of organic practices but are fundamental to the organic farming system. The agronomic crops supply fungi with sugars, and in response crops receive minerals and water through hyphae of fungi, which acts as crop's own root system.

10.4.3 Nonuse of Inorganic N Fertilizer

The replacement of inorganic N fertilizers by biological N fertilization methods in organic farming avoids the negative knock-on effects of relying on inorganic fertilizers and also avoids any more direct effects. Several long-term trials around the world have shown that inorganic N fertilizers do not raise soil carbon levels and the levels remain low in the absence of positive soil management practices (Heidmann et al. 2002).

10.4.4 Better Soil Structure and Winter Vegetation Cover

Soils with higher organic matter contents have particles in more aggregated form that gives it a healthy crumb structure which is less susceptible to erosion. This is because, in such a condition, the soil particles are more stable and the soil surface is more open, enabling water to percolate instead of passing over the surface and causing erosion. In organic farming, some cereals are undersown with legumes which then remain after the cereals are harvested and act as a winter cover crop. Winter cover crops guard the soil from destruction by avoiding the development of rills and small gullies and by providing food for earthworms, fungi, and other soil microorganisms whose by-products increase soil particle aggregation (Mader et al. 2002).

10.4.5 Carbon Sequestration Potential of Organic Farming

In recent years, increasing amounts of atmospheric CO_2 and methane (CH_4) emission have raised an interest to study the soil dynamics of organic matter and carbon sequestration potential and understand capacity of soil as source or sink role on global basis (Van-Camp et al. 2004). Organic substances like compost and other carbon containing materials mixed into the soil, organic carbon decomposition starts by producing CO_2 and another part of compiled in the soil. Carbon sequestration term is used first time by Lal (2007) which describes transformation of atmospheric CO_2 into soil C pool through:

(i) To form humus by adding crop residues and other waste materials in the soil.
(ii) In arid and semiarid areas, carbonate leaching or secondary carbonate formation may take place.
(iii) Carbon attached with organo-mineral complexes formation, and it is less affected by the microbes.
(iv) Organic carbon is translocated in the subsoil and by plowing, and agronomic practices can transfer it away from the root zone, diminishing the hazards of being detached by erosion.

CO_2 sequestration in cultivated soils promotes sustainable cropping methods through organic farming by reducing soil disturbance and optimizing water-use efficiency. However, C dynamics is also influenced by incorporation of organic material in the soil. Carbon sequestration is good to enhance soil organic carbon reservoir and helpful to reduce the global warming. Triberti et al. (2008) conducted a series of experiments about 29 years in which comparison was made among manure and slurry of cattle and residues of crops mixed with synthetic fertilizer and found that the quickest carbon sequestration (0.26 t ha^{-1} $year^{-1}$) was built up through cattle manure which contains 33.1% of organic C and 27 kg C ha^{-1} is compiled in the 0–40 cm soil layer. This rise is linked to maximum sequestration efficiency equal to 8.1% incorporated C, because of its minimum degradability, than the cases of cattle slurry and cereal crop residues with 3.8% and 3.7% C addition, respectively. Carbon residues of incorporated manure and compost remained up to 25% and 36%, respectively, showing higher sequestration with composted as compared to non-composted manure. It has been reported by Sodhi et al. (2009) that application of rice straw compost for 10 years with or without the combination of inorganic fertilizers resulted in carbon sequestration in the form of macroaggregates.

10.5 Sources and Types of Organic Amendments

Soil quality and fertility may be improved by adding organic substances as history told that Greeks and Romans used to do organic amendments in the soil. Animal manure and human sewage were the most common organic materials applied to the soil during cultivation. They also knew the advantage of growing wheat after legume crops. Various organic substances like farm yard manures, crop residues, sea shell thrashes, etc. were used to enhance crop growth and development. These days, compost and animal dung are the most common organic amendments which are being used for the betterment of soil. Five categories have been made for essential organic materials (Goss et al. 2013).

Organic matter amendments are made in the soil to enhance the nutrient supply to the soil. Most of the nutrients like K in the organic manures are water soluble and more available to crop. Manures from the animal sources like FYM and slurry contain 60–80% inorganic phosphate as compared to the total P content in the manure and act as same as P from the inorganic sources like phosphatic fertilizers. With the usage of nitrogenous fertilizers, production of food is doubled since the 1950s, and ultimate source of N for soil and plant was organic manures. However, nitrogen mineralization is proceeded in spring season but often higher rate of mineralization in autumn when crops needed a small amount of it and there is a lot of chances of its loss in the form of nitrate.

Mineralization boosts up due to favorable soil and atmospheric conditions by increasing microbial activity in the soil and provides energy source from incorporated crop residues. Properties of different manures are shown in Table 10.2.

Organic manures are classified mainly into two types as shown in Fig. 10.1.

Table 10.2 Properties of some manures

	Physical properties			
Manure	Color	Solubility	State	Nutrient content
Cow dung	Blackish	Water soluble	Solid	% N = 0.5–1.5% P_2O_5 = 0.4–0.8% K_2O = 0.5–1.9
Compost	Blackish	Water soluble	Solid	% N = 0.4–0.8% P_2O_5 = 0.3–0.6% K_2O = 0.7–1.0
Farm yard manure	Light green or blackish	Water soluble	Solid	% N = 0.5–1.5% P_2O_5 = 0.4–0.8% K_2O = 0.5–1.9
Mustard oil cake	Brownish	Water soluble	Solid	% N = 5.1–5.2% P_2O_5 = 1.8–1.9% K_2O = 1.1–1.3
Sesame oil cake	Blackish	Water soluble	Solid	% N = 6.2–6.3% P_2O_5 = 2.0–2.1% K_2O = 1.2–1.3

Source: Knott's handbook for vegetable growers (1997)

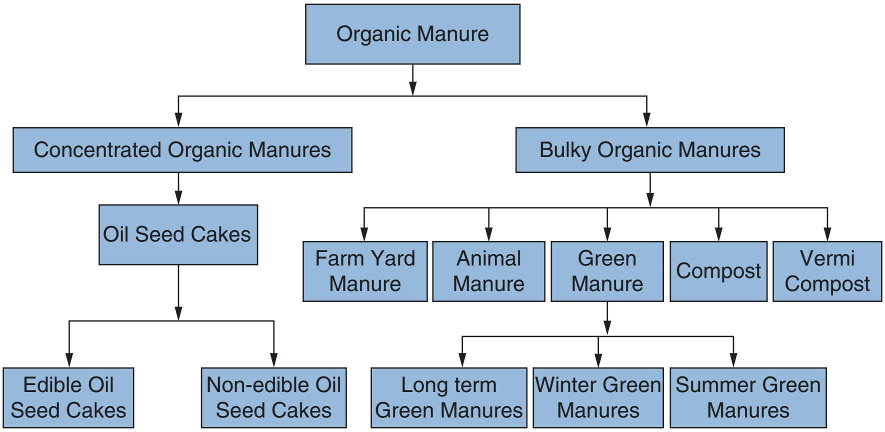

Fig. 10.1 Classification of organic manure

10.5.1 Bulky Organic Manures

Bulky organic manure includes FYM, BYM, green manure, compost, and vermin compost having less nutrients in comparison to concentrated organic manure. These manures have the following benefits:

1. They provide growth nutrients for plants.
2. They enhance soil physical characteristics.
3. They enhance the accessibility of growth substances for plants.
4. CO_2 liberated during decay functions as a CO_2 enricher.
5. Microbial activity enhanced due to regulation of plant parasitic nematodes and fungi in the soil.

Table 10.3 Nutritional status of FYM (%)

Nutrients	(%)
N	0.50
P	0.25
P	0.40
Ca	0.08
S	0.02
Zi	0.0040
Cu	0.0003
Mn	0.0070
Fe	0.45
H2O	76

Source: FAI (2012)

10.5.1.1 Farm Yard Manure (FYM)

Farm yard manure (FYM) is the most significant reservoir of growth substances for plants and refers to the finely decomposed excreta of farm animals including litter and plant residues or remaining or wastage of fodder. Uncovered storage of farm yard manure for a long time causes loss of nitrogen in the form of ammonia. The dung must be stored in 1.0-meter-deep pits, and surface is sealed with mud slurry to avoid and overcome such kinds of losses. Microorganisms play a vital role in decomposition, and manure is ready after 4–5 months. The chemical constituents present in FYM are given in Table 10.3.

10.5.1.2 Animal Manure

Animal manure is composed of feces, urine, and animal bedding stacked and turned up to finely decomposed end product. It is obtained from beef, dairy, pork, and poultry farms and its constitution based on its source, the time when urine and feces are excreted and mixed, and the storage time before being added to soil. Manure provides essential nutrients and organic matter to crops thus enhancing soil fertility. Cow dung is an excellent source of nitrogen and phosphorus (Boller and Hani 2004; Goss et al. 2013). The sheep and goats manure hold more nutrients than FYM and compost. It is employed to the agricultural farms by two different methods. The droppings of sheep or goats are kept in the pits till decomposition, and then it is used in the fields. This method results in wastage of nutrients from urine. The other process is sheep penning in which sheep and goats are kept for a night in the agricultural farms. In this way, urine as well as fecal stuff is mixed in the soil directly to workable depth through mechanical means. Application of animal manure will add important micro- and macronutrients to the soil that will be slowly released over time and construct good soil structure and texture and enhance the soil aeration as well as water retention potentials. Animal manures vary from each other based on source, age, storing method (piled, spread, turned over or not), and the animal bedding stuff that may be merged in. The general knowledge about nutrient contents of different animal manures is given (Table 10.4) which describes the approximate

Table 10.4 Animal manure type and approximate NPK percentage

Manure type	Nitrogen (N %)	Phosphorus (P %)	Potassium (K %)
Chicken	1.1	0.8	0.5
Cow	0.6	0.2	0.5
Duck	0.6	1.4	0.5
Horse	0.7	0.3	0.6
Pig	0.5	0.3	0.5
Rabbit	2.4	1.4	0.6
Sheep	0.7	0.3	0.9
Steer	0.7	0.3	0.4
Swine	3.0	0.4	0.5

Source: FAI (2012)

Table 10.5 Plants used as green manure

English name	Botanical name
Sunn hemp	*Crotalaria juncea*
Lentil	*Lens esculenta*
Egyptian clover	*Trifolium alexandrinum*
Sesbania	*Sesbania aculeata*
Cluster bean	*Cyamopsis tetragonoloba*
Cowpea	*Vigna sinensis*
Horse gram	*Macrotyloma uniflorum*
Senj	*Melilotus parviflora*

Source: FAI (2012)

levels of total nitrogen, phosphate, and potassium. FYM is basically excreta of farm animals mixed with a bit of plant residues like husk, leaves, or hay, while animal manures include animal waste (urine and dung) mixed along with a bit of soil.

10.5.1.3 Green Manures

Green manures also called as fertility-building crops can be considered as crops grown for the interest of soil. Green manures include different plants grown to feed the soil. Green manuring is a developing method to improve the soil productivity (Haynes 2004). They are low cost than chemical fertilizers and can be applied with animal manures. Application of green manure for crop production may improve economic viability, while decreasing the environmental impacts of agriculture (Cherr et al. 2006). The plants commonly used as green manure are given in Table 10.5.

Green manure crops are mostly cultivated into the soil at growing plant stage, before they flower. They are developed due to their green leafy material that contains high level of nutrients and preserves the soil. The plants are kept buried for about 1–2 months for total decomposition. The soil is then tilled, and then the next food crop is sown. By altering the green manure crop with food crop, both the nitrogen and organic matter of the soil are sustained. Green manuring is the method to

Table 10.6 Nutrient content of green manure crops and green leaf manures

Plant	Nutrient content (% on dry weight basis)		
	N	P	K
Green manure crops			
Sesbania aculeata	3.3	0.7	1.3
Crotalaria juncea	2.6	0.6	2.0
Sesbania speciosa	2.7	0.5	2.2
Tephrosia purpurea	2.4	0.3	0.8
Phaseolus trilobus	2.1	0.5	–
Green leaf manures			
Pongamia glabra	3.2	0.3	1.3
Gliricidia maculata	2.9	0.5	2.8
Azadirachta indica	2.8	0.3	0.4
Calotropis gigantea	2.1	0.7	3.6

Source: FAI (2012)

decompose plant materials into the soil for promoting the soil health by increasing organic matter and nitrogen, mainly if it is a legume crop that has potential to fix nitrogen from the air by its root nodule bacteria (Fageria 2007). The nutrient contents of green manure crops and green leaf manure are shown in Table 10.6.

The ideal green manures should have the following characteristics:

1. Have a fast growth rate.
2. Have the potential to tolerate unfavorable climatic conditions, pests, and diseases.
3. Have sufficient *Rhizobium* nodulation capability and must be a potent nitrogen fixer.
4. Should accumulate adequate fixed N in 4–6 weeks and be easy to integrate and rapidly decomposable.
5. Should produce abundant and succulent tops.

10.5.1.3.1 Process and Classification of Green Manure Crops

There are two kinds of procedures to produce green manure.

(i) **In situ green manuring crops**

In this method, undecomposed green manure crop is added into the soil of the similar agricultural farm where the crop was cultivated (e.g., sunn hemp, *Sesbania*).

(ii) **Ex situ green leaf manuring crops**

This process includes converting green leaves and tender green twigs accumulated from different sources into fine organic material. The most common beneficial plant species used for this process include sunn hemp and *Sesbania*.

Green manures are classified into the following three types:

(i) **Long-term green manures**

Leys, generally grown for 2–3 years, are essential for most of organic arable rotations. When animals are present on the farm, then leys will be grazed or cut for silage, but in stockless setup, they are cut monthly in the summer season, and the mowings are kept on the top layer as mulch. Such leys may be pure clover (when nitrogen fixation is important) or a grass/clover mixture (when organic matter buildup is also important).

(ii) **Winter green manures**

Winter green manures are normally cultivated in the autumn and integrated in the subsequent spring. They can be used as fertility-building crop in a rotation. They may be legumes (e.g., vetch), but they are mainly used (even in traditional agriculture) to reduce the nitrogen leaching; when employed for this reason, they are termed as winter cover crops.

(iii) **Summer green manures**

Summer green manures are typically legumes cultivated to enhance nitrogen in mid rotation. They can be cultivated for the full season (April to September) or for a short duration between two cash crops. These short-term manures can include nonlegumes like mustard and phacelia.

10.5.1.3.2 Objectives, Advantages, and Disadvantages of Green Manures

Green manure crops can be grown separately or in combination with crops. Generally, green manure crops are considered for the following purposes:

1. To provide soil cover with no tillage, thus minimizing water evaporation and soil temperature and improving water infiltration.
2. To save the soil from erosion.
3. To minimize weed invasion.
4. To enhance biomass in the soil (for accumulation of soil organic matter and addition of nutrients).
5. To develop soil structure.
6. To improve biological soil properties.
7. To diminish pest and disease invasion.

By performing the abovementioned functions, green manure/cover crops provide the subsequent advantages:

1. **Maintenance and/or accumulation of organic matter**

The main role of green manures is the inclusion of organic matter to the soil. Organic matter is the most important for soil health in cultivated areas as it conducts various physical, chemical, and biological activities as organic matter is the reservoir for essential plant growth substances. Once introduced, the green manure supplies abundant fresh organic matter, and there are several examples where application of green manures rises soil organic matter as compared to experiments where only chemical fertilizers are used (e.g., Shepherd et al. 2002). Crop residues in traditional agricultural practices are not sufficient to counterbalance the loss of organic matter, as a result of high mineralization in tropical and subtropical climates. In agricultural system, the cost-effective way to sustain or increase the soil organic matter is the application of green manure crops that have a high capacity for biomass production. The different plant species provide different levels of organic carbon.

2. **Soil structural improvement**

Green manures can enhance the soil structure by different mechanisms. The widespread root network of some plants like rye grass trapped the soil particles, helps to stabilize aggregates, and increases pore size and hence improves the seedbed structure. Some species with deep taproots support to break up the compressed soil. Soil consists of different size units that can be detached by rain washing from the soil, causing impenetrable layers or pans (Breland 1995). By covering the exposed soil surface, it can be protected from heavy rain.

3. **Minimizing nitrate leaching**

If soil is left bare overwinter, then large levels of nitrate can be lost from soil, because nitrate is not firmly bound to soil particles. Leaching also reduces the nitrate that is a serious problem for organic farmers as it is very difficult for them to substitute the lost nitrogen.

The best way to prevent the nitrate leaching is to establish a dynamically growing crop during the winter season. Winter green manures can eliminate excess nitrate from the soil during the autumn. Green manures differ in their potential to minimize the leaching. Rye grass is mostly effective due to its huge leafy growth during cold weather (MAFF 1998).

4. **Loosens the soil**

Deep rooting green manures can be beneficial to loose and ventilate the soil up to greater depths; this progresses the drainage and increases the organic matter that advances the environment conducive for survival, multiplication, and functioning of valuable microorganisms.

5. **Improves the fertility of soil by adding nitrogen**

Legume family plants capture N from the air and with the help of *Rhizobia* species converts it into a form that plants can use. These plants have the potential to add large concentrations of nitrogen into the soil through biological fixation by *Rhizobium* bacteria on their roots. This nitrogen is beneficial for succeeding crops.

6. **Locks up soil fertility**

Readily available essential nutrients are washed out from bare soil in winter season during the time period of heavy rain. Green manuring crops when used as cover crop provide all the essential growth nutrients to the soil reservoir. These essential growth substances are being stored in the plant cell and released when crops die back, cut, or dug into the soil.

7. **Rests soil**

Soil that has been intensely used for agriculture requires time to improve its structure and fertility. Cultivating green manure is an effective way to protect the soil during the recovery period with all the advantages given above. Clover is a principally good crop for resting soil as it fixes the N.

8. **Pest, disease, and weed control effects**

The green manures can be helpful to control pests, weeds, and diseases. This depends on the kind of green manure employed and the succeeding crops cultivated. They may function as a habitat for predatory insects to decrease the pest pressure, but they can also develop the pests like wireworms or slugs in succeeding crops. Hence careful attention is required for cropping sequences. Green manures have a suppressive effect on diseases but some green manures like *Brassica* green manures in horticultural rotations can favor the diseases. Weed suppression can be one of the crucial advantages of green manures. However, poor control of weeds in green manure can cause harmful effects because green manure itself can become a weed for the following crops.

Green manures can also have the following disadvantages:

1. Costs of seed and extra cultivations.
2. Lost prospects for cash cropping.
3. More work at busy times of the year.
4. Intensified pest and disease problems (due to the "green bridge" effect).
5. Possibility for the green manures to become weeds.

10.5.1.4 Compost

Compost is formulated from waste vegetables and other refuse combined with cow dung, urine, town waste, and night soil. Night soil is human excreta enriched with growth substances more than FYM and compost. Night soil consists of 5.5% N, 4.0% P_2O_5, and 2.0% K_2O. Compost is applied by similar mechanism as by FYM, and its application is beneficial for different types of soils and crops. The application of compost provides both agricultural and waste management benefits. Compost is rich in nutrients and can also be used for garden, landscaping, and horticulture purposes (Perez-Piqueres et al. 2006).

Table 10.7 Typical nutrients of finished compost

Nutrient	Dry weight
Nitrogen (N)	<1% up to 4.5%
Potassium (K_2O)	0.5–1%
Phosphorus (P_2O_5)	0.8–1%
Calcium (Ca)	2–3%
Magnesium (Mg)	2–3%

Source: B.C. Agriculture Composting Handbook (1998)

The procedure of formulating the compost is called as composting. It is mainly a biological method in which both aerobic and anaerobic microbes involve in breakdown of organic substances and lower the C:N ratio of the refuse. The compost becomes ready in 3–4 months without any further attention. Composting is a cost-effective and useful way to process the animal manure for land utilization because in this method the pathogens and weed seeds are devastated and the heterogeneous solid organic material is converted into stable humic material by the action of microbes. Moreover, nitrogen level of original waste is minimized during composting process, and nitrogen is converted into a stable form (N_2) (Guo et al. 2012). Level of nutrients in finished compost will differ on the basis of type of manure, plant residue, or biosolids used. Nutrient concentration of finished compost is given in Table 10.7.

10.5.1.4.1 Types and Benefits of Compost

Composts are of the following two kinds with different composition.

(i) **Rural/village compost**

This compost is prepared from farm wastes such as straws, crop stubbles, crop residues, weeds, waste fodder, urine-soaked earth, litter from cowshed, and hedge clippings. This kind of compost comprises 0.4–0.8% N, 0.3–0.6% P_2O_5, and 0.7–1.0% K_2O.

(ii) **Urban compost or town compost**

This form of compost is formulated from town waste and night soil and contains 1.0–2.0% N, 1.0% P_2O_5, and 1.5% K_2O.

Numerous benefits obtained from the application of compost as fertilizer include (Donn et al. 2014; Scotti et al. 2015):

1. Rise in organic C and microbial activity of soil as compost has potential to stimulate the soil microbial population by inhibiting soilborne pathogen diseases like *Pythium*, *Phytophthora*, and *Fusarium* spp.
2. A huge level of plant nutrients such as N, P, K, and Mg addition.
3. The intensification of soil porosity with resultant upsurge in available water for plants.

4. Rise in cation exchange capacity (CEC).
5. Compost reduced the mineralization rates that minimize the nitrate leaching by slowing the transformation of organic N to mobile nitrate.

10.5.1.5 Vermicompost

Vermicompost (biofertilizer) is an organic manure formulated by earthworms and microorganisms as they feed on organic waste materials. The compost thus formed is mostly worm excreta and finely ground soil. Organic materials from different sources can be fed on by worms so that the wastes are converted into decomposed end product. The biologically degradable nontoxic organic matter is employed in vermin-composting process. Normally used composting feedstocks are animal dung, agricultural waste, forestry waste, and nontoxic industrial waste of organic nature. Worm casting (excreta) in the vermin compost contains nutrients that are 97% utilizable by plants. Apart from supplying plant nutrients, worms also upturn the soil and make the soil lighter. Vermicompost has been used for flowering plants for a long time. Earthworm community has hormonelike effect, stimulating the development and precociousness of plants. Vermicomposted larval litter meaningfully enhanced the length and weight of shoot and root, shoot-root ratio, and N, P, and K uptake (Garhwal et al. 2007). Vermiculture technology is being implemented for low-cost treatment of nontoxic wastes from different sources. The end product of vermiculture technology that is vermicompost is high in quality nutrients and is being progressively implemented for sustainable organic farming.

Advantages of Vermicompost

1. Earthworms present in organic matter containing soils function as natural bioreactors, stimulate the advantageous soil microbial population, suppress soil pathogens, and transform organic matter into precious product like biofertilizers, growth hormones, and tenacious worm biomass.
2. Earthworms present in the soil are involved in the modification of physical, chemical, and biological characteristics of the soil and stimulate the nutrient cycling by ingestion of soil and humus and transforming it into nutrient-enriched cast.
3. The early accessibility of different nutrients like P, Ca, Na, Mg, K, etc. is increased in earthworm cast than in the nearby soil.
4. Two to four hundred thousand worms per ha can develop pertinacious structurally stable holes in the soil that permit water infiltration up to 120 mm depth.
5. Each burrow behaves as a mini dam and avoids runoff losses and facilitates the soil to hold the moisture for long duration.
6. The earthworm casting are stable and do not break into smaller fragments, hence avoiding the soil erosion.
7. It is an eco-friendly, nontoxic, and recycled biological product.
8. This compost is an odorless and clean organic matter with different essential nutrients.

Table 10.8 General nutrient contents of oil cakes

Oil cake	Nutrient content (%) N	P_2O_5	K_2O
Nonedible oil cakes			
Castor cake	4.3	1.8	1.3
Cotton seed cake (undecorticated)	3.9	1.8	1.6
Karanj cake	3.9	0.9	1.2
Mahua cake	2.5	0.8	1.2
Safflower cake (undecorticated)	4.9	1.4	1.2
Edible oil cakes			
Coconut cake	3.0	1.9	1.8
Cotton seed cake (decorticated)	6.4	2.9	2.2
Groundnut cake	7.3	1.5	1.3
Lin seed cake	4.9	1.4	1.3
Niger cake	4.7	1.8	1.3
Rape seed cake	5.2	1.8	1.2
Safflower cake (decorticated)	7.9	2.2	1.9
Sesame cake	6.2	2.0	1.2

Source: FAI (2012)

10.5.2 Concentrated Organic Manures

Concentrated organic manures include raw materials of animal or plant origin like oil seed cakes, blood meal, fish meal, meat meal, and horn and hoof meal that contain higher level of essential plant nutrients like N, P, and K in contrast to bulky organic manures.

10.5.2.1 Oil Seed Cakes

Oil seed cakes are the by-products of oil seed crops. After the removal of oil from seeds, the residual material is dehydrated as cake that can be implemented as manure. Oil cakes are the imperative and organic nitrogenous manure. It also contains low levels of P and K. The general nutrient contents of oil cakes are shown in Table 10.8. There are two kinds of oil cakes.

10.5.2.1.1 Edible Oil Seed Cakes

This sort of oil cakes is exercised as feed for cattle and includes mustard oil, groundnut, sesame, linseed, cotton oil seed, and coconut cakes.

10.5.2.1.2 Nonedible Oil Seed Cakes

This form of oil cake is not appropriate for feeding the cattle and mostly utilized for manuring crops like castor, neem cakes, etc. The nonedible oil cakes consist of toxic material that makes them inappropriate for feeding the cattle. However, these are excellent sources of N-containing manure. The level of N differs with the nature of oil cake. It varies from 2.5% to 7.9%. Besides N, all oil cakes have low levels of H_3PO_4 (0.8–2.9%) and potash (1.1–2.2%). Oil cakes are not soluble in H_2O. However, their N becomes readily accessible after 10 days of its application to crops.

10.6 Benefits of Organic Manuring in Intensive Agriculture

Application of organic material to crop land can affect soil characteristics. However, the effects usually may not be evident in short-term applications. The easiest way to check the agronomic worth of fine decomposed organic manures is the estimation of supply of organic content and plant growth nutrients. The prolong supply of essential growth substances is important to enhance the crop yields in the succeeding years. However, it is important to generalize the outcomes of organic manures utilization on the soil-plant network.

10.6.1 Effects on Soil Biological, Chemical, and Physical Fertility

There are general standards for physical and chemical characteristics of good (fertile) soil which are also applicable to different types of soils. However, standards for biological characteristics of good soil are difficult to establish. Moreover, as compared to chemical fertility, limited techniques are available to farmers to analyze the soil physical and biological fertility. In organic farming more attention is paid on biological processes because chemical fertility depends on biological processes. Organic amendments influence the physical, chemical, and biological features of soil and thus enhance the crop production described (Abbott and Murphy 2007).

10.6.1.1 Biological Fertility

Soil biological fertility depends on those soil mechanisms that involve direct or indirect microorganism's activity. Root nodulation by bacteria and mycorrhiza fungi directly enhance the plant growth. However, growth may be indirectly influenced by enhancing soil chemical fertility through organic compound mineralization and mineral dissolution and physical fertility like soil aggregation. Soil biological fertility can be counted by determining the size, diversity, and activities of microbial populations. Small changes in management practices affect the microbiological and biochemical soil characteristics to a greater degree. Microorganisms such as bacteria, fungi, actinomycetes, and microalgae significantly contribute to breakdown of organic compounds, nutrient cycle, and other chemical changes in soil. Decomposing microorganisms require organic C as a source of energy; hence organic C should either be assimilated into their cells, discharged as metabolic compounds, or dissipated as CO_2. The growth nutrients N, P, and S existing in the organic compounds are transformed into inorganic form. Afterward, they are either immobilized and utilized in microbial metabolism or mineralized and discharged into the soil nutrient reservoir (Murphy et al. 2007). For the assimilation of decomposed organic deposits, microorganisms require the optimum concentration of N that depends on the C:N ratio of the microbial biomass. The optimum concentration of N essential for microbes is 20 times less as compared to C. In the presence of low level of readily decomposable C compounds and high level of N as compared to that required by the microbial population, the rate of N mineralization will be higher that releases inorganic N. It is problematic to differentiate between the direct and indirect outcomes of an organic amendment on the activities of soil microflora. The activity and growth of autochthonous plants can be enhanced by amending the soil with compost or other organic compounds containing mineral N fertilizer. Different long-term field trials have proved that soil biological characteristics like microbial biomass C and respiration and certain enzymatic activities are exceptionally enhanced by compost amendments mostly in the surface layers of the soil. As decomposition rate of composts is slow in the soil, the persistent supply of nutrients can support microorganisms for longer periods, in contrast to chemical fertilizers (Ros et al. 2006). Generally, the concentration and quality of organic amendment added to soils are the main aspects that control the activity and strength of different microbial population involved in nutrient cycling. It may be recommended that application of organic matter to crop land improves the biological properties of soil, based on the concentration and nature of materials added.

10.6.1.2 Chemical Fertility

The chemical fertility of soil demonstrates its potential to deliver an appropriate chemical and nutritional environment to plants and to assist biological and physical activities. In organic farming, the preservation of soil chemical fertility depends on the processes that convert the nutrients from fixed to soluble forms like mineralization of organic matter and dissolution of minerals. These mechanisms also occur in traditional farming systems, but they are more important in organic farms. Several long-term field experiments demonstrated that application of organic material to soil improved the organic C level and thus improved the cation exchange potential. This outcome can be attributed to negative surface charges of organic matter that is imperative to keep the nutrients and their supply to plants. Soil application of compost and manure for many years result in both increasing and decreasing the pH of soils, depending on their original pH and organic deposits. Soil pH raised by 0.5 units by increasing quantity of dairy manure compost from 11.2 to 179.2 t ha^{-1} (Butler and Muir 2006). Residual effects of long-term application of compost on crop yield and soil characteristics can exist for many years, because the N and other growth substances become available for plants in the first year after application. Numerous microbes transform organic N into inorganic form through mineralization process. N mineralization from compost is inadequate in the short term. However, long-term application of compost has significant effect on N availability and crop yields. Consistent application of manures to soil for many years enhanced the soil N in the surface layers of soil by providing the protection to this nutrient within macroaggregates. The C:N ratio of organic matter is a good sign of nutrient supply. It is acknowledged that when compost having high C:N ratio (more than 30:1) is applied to the soil, then microorganisms compete with plants for soil N, consequently immobilizing it. The application of organic material to soil for many years derived from household wastes and yard trimmings increases the concentration of available K in the soil, because these organic sources are rich in K. In context of P from organic amendments, the application of beef cattle manures to soil also increase the plant available P in the soil (Sodhi et al. 2009). It can be established that long-lasting applications of several organic materials enhance the soil K, P, and organic C and result in prolonged N supply.

10.6.1.3 Physical Fertility

Physical processes and properties influence soil fertility by fluctuating the movement of water through the soil pores, waterlogging, and root penetration of soil. Soil structure and texture are important physical properties of soil that affect soil fertility. Structure depicts the natural aggregation of soil particle and pores in the soil, while texture is the ratio of sand, silt, and clay particle in the soil. Erosion is a physical process that takes away the fertile layer of the soil thus declines the soil fertility. Poor soil structure and loose texture augment the severity of water erosion and waterlogging. Soil salinity also affects the soil physical fertility. But soil salinity is a chemical property which affects the physical fertility by declining the water movement through the soil. Physical fertility of soil promotes the sustainable organic farming by supporting the system in which biological and chemical mechanisms provide essential growth substances to plants and minimize the threat of soil erosion. In organic farming practices, the soil physical fertility is enhanced as compared to traditional practices due to the advantageous effects of added organic material on soil microbes and soil structure. Organic matter improves soil aggregation through enhanced activities of soil organisms. Enhanced soil structure and root development are important in organic farming for efficiently using the growth substances and for preventing N leaching from mineralizing legume deposits. Aggregate stability in soil can be enhanced with organic amendments that can support an appropriate soil structure by improving pore spaces for gas exchange, water holding, and root and microbial growth. Soils in arid and semiarid zones are vulnerable to erosion due to low level of organic matter. Organic matter improves the soil structure by two distinct methods, by enhancing the interparticle cohesion within soil aggregates and by promoting their hydrophobicity, hence reducing their disintegration. Enhanced activity of microbes in the soil due to application of composted material is responsible to increase the stability of soil structure. Various biological binding agents are responsible for aggregate stability. Polysaccharides released by microbes most importantly at the start of organic matter decomposition adsorb the mineral nutrients and improve their intercohesion. Organic materials rich in humic compounds also increase aggregate hydrophobicity of clays. Tejada et al. (2009) documented that application of compost increased the soil structural stability by providing greater levels of humic substances to the soil that is mainly important in formation of clay-organic complex compounds. Long-term application of compost, FYM, and digested sewage sludge decreases the soil bulk density and increases the soil porosity. Excessive C level in the soil promotes the water-holding potential due to the effect of organic compounds on soil aggregation. This rise results in more availability of water to plants and also improves the resistance to drought. It can be concluded that constant applications of organic manure can improve soil physical fertility by boosting aggregate stability.

10.7 Compost and Plant Disease Suppression

Soilborne pathogens involving fungi and oomycetes are the main aspects that restrain the yield of agricultural farms, and it is difficult to suppress them by conventional methods like the use of resistant cultivars and chemical fungicides. Plant diseases due to soilborne pathogens can be suppressed by application of organic manures. However, in some cases the application of compost in soil has increased the incidence of diseases. Bonanomi et al. (2010) reported that organic amendments suppressed the diseases in 45% cases, no significant in 35%, but promote the disease incidence in 20%. Unreliable results enormously impede the practical use of compost for disease suppression in organic farming culture. Compost is produced from different plant and animal sources that result in massive variation in the chemical and microbiological characteristics of the final compost and hence in its disease suppressiveness. Actually, compost is formulated by heterogeneous materials due to the diversity of composting methods, feedstock origin, application rate, and level of maturity. The complicated relationships among these aspects make problematic to calculate the suppressive potential of compost. Significant efforts have been done during the last 10 years to understand the mechanism and indicators of organic amendment suppressiveness. Anyhow, very limited knowledge exists about the associations between the chemical and microbiological properties of compost and disease suppression for different plant-pathogens combinations. An established factor to calculate compost suppressiveness is fluorescein diacetate hydrolases (FDA) activity that includes the esterases, proteases, and lipases, soil enzymes related to organic C cycle (Bonanomi et al. 2010). The problem of disease-causing potential of compost can be minimized by disinfecting the compost material. In disinfection process only pathogens are killed but no damage to the beneficial microbes. Disinfection can be performed by exposure to UV light and sunlight.

10.8 Organic Manuring and Agronomic Crops

10.8.1 Crop Productivity

Organic matter is an essential and crucial element, as it improves soil fertility and crop productivity. In Asian countries, addition of organic matter is most common practice to increase crop yield. Addition of organic matter increases crop yield by increasing FYM rates. Significant increase in the yield of rice and chickpea grain through *Sesbania aculeata* L. incorporation in the growing field has been reported (Singh et al. 2002). Organic farming is beneficial for both developed and developing countries because it is eco-friendly, increases biodiversity, minimizes energy use, uses resources economically, and ultimately increases crop yields without reliance on costly inputs. Microbial activity can be enhanced by adding organic matter and composts in the low productive soils. Organic matter enriched with microbes speeds up biodegradation process. Microbes and earthworms mostly work in a combined manner to produce vermin compost and provide essential macroelements like nitrogen, phosphorus, and potassium as macroelements while calcium, magnesium, iron, molybdenum, zinc, and copper as microelements (Amir and Fouzia 2011). Maize grain yield can be improved up to 17% through combination of compost and manure foliar application respect to conventional maize production system where organic fertilizer and artificial fertilizers were applied in combination (Onduru et al. 2002). Although organic input rates are higher than conventional or synthetic substances, rates of organically produced food are more than the foods produced under traditional crop production system.

In an experiment Chan et al. (2008) compared organic farming with conventional farming system. He observed that use of organic inputs at three different regions was higher (46%, 25%, and 22%) as compared to the conventional crop system and the yield difference was more (55%, 94%, and 82%) between organic and traditional rice-growing systems, respectively. Though organic product's yield is less with more inputs, internationally it is sold at higher prices. It was observed that vegetables have shown maximum potential and responsiveness to organic fertilizers and provide more profit to the farmers. In glass house experiment, tomatoes were grown under medium Metro-Mix 360 (control) in combination with animal manure and vermicompost at various concentrations as (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%). Atiyeh et al. (2000) revealed that substitution of Metro-Mix 360 with vermicompost (20%) gives higher rates in the market as compared to the rest of the treatments by producing ideal size of fruits. So, it is concluded that organic matter has momentous influence on root and fruit weights of tomato.

Hashemimajd et al. (2004) found that organic manure from dairy animals along with rice hull and treated sewage sludge improve tomato quality and yield by increasing shoot and root dry matter as compared with control (sand and soil mixture). Quality of potato improves when it is grown organically by increasing concentration of dry matter accumulation (up to 23%) without impairing its texture, while potato textures and quality fell down after combined application of commercial N and K fertilizers (Haase et al. 2007). Organic matter responsiveness also depends upon crop varieties. Organically grown potato produced more yield (66% and 46%, respectively) treated with organic matter as compared with conventionally grown potato crop (Mourao et al. 2008). More nitrogen uptake was observed by Virgo and Raja (50.5 and 37.0 kg/ha, respectively) as compared with conventional/mineral fertilizers (27.8% and 21.1%, respectively) application of organic crop (tubers and foliage).

Organic crop production not only improves soil fertility but also improves crop productivity by controlling crop diseases in peas, mustard, and chickpea. Vermicompost also influenced the availability of essential minerals like N, P, K, Ca, and Mg (Tripathi et al. 1999). Vermicompost application at 3 t ha^{-1} to chickpea improves total dry mass accumulation, protein content, and grain yield. Soil microbial activity enhanced nitrogen and phosphorus availability and also increased the succeeding maize crop yield (Jat and Ahlawat 2006). Organic substances like biogas slurry, etc. increased the enzymatic activity and protein contents of crops as maize, gram, and sunflower. More nitrogen concentration was observed during all growth stages of maize gram and sunflower by applying biogas slurry with panchagavya (Somasundaram et al. 2007). Organic materials like FYM, BYM, or poultry manures benefit the soil for a long time as they enhance the productivity and yield of intercrops (maize-bean intercrop) for farmers possessing low landholdings in Eastern Cape of South Africa (Silwana et al. 2007). *Rhizobium leguminosarum* bv. *phaseoli* seed inoculation and farm yard manure mixing in soil improve the rajmash (*Phaseolus vulgaris* L.) yield by enhancing nitrogen fixation (Datta et al. 2006). A 4-year research trial showed no marketable yield differences of various vegetable crops (tomato, bean, cabbage, and zucchini) between organic and conventional farming systems. Differences between yield of organic farming and conventional farming were 10% and 3%, respectively. Described that bean yield was increased (53 g/pot–228 g/pot) by applying urban well-decomposed waste having (0.58–1.9%) nitrogen, (0.45–0.67%) phosphorus, and (1.4–1.8%) potash. Maximum bean growth and yield (228 g/pot) response was recorded with well-decomposed and enriched vermin culture waste.

10.8.2 Crop Quality Attributes

Organic matter increases the yield of crops by improving quality parameters like protein, starch, and oil contents. Vermicomposted vegetable waste was used to assess its influence on biochemical characters of chilies. Protein content (113 mg g^{-1} and 79 mg g^{-1}) at 60 and 90 DAS, respectively, carbohydrate content (15.34 mg g^{-1}) at 60 DAS, and chlorophyll (2.61 mg g^{-1}) and total chlorophyll (3.62 mg g^{-1}) at 60 DAS were found to be maximum with vegetable vermin-composted waste. Higher chlorophyll a contents (1.01 mg g^{-1}) were found at 90 DAS with commercial fertilizer application (Yadav and Vijayakumari 2004). Quality of potato is improved when it is grown organically by increasing concentration of dry matter accumulation (up to 23%) without impairing its texture, while potato textures and quality fell down after combined application of commercial N and K fertilizers (Haase et al. 2007). More nitrogen uptake was observed by Virgo and Raja (50.5 and 37.0 kg/ha, respectively) as compared with conventional/mineral fertilizers (27.8% and 21.1%, respectively) application of organic matter. Maheswari et al. (2004) observed that quality of chili increased by adding organic material in the field and it also increased the rate of the chilies in the market.

10.8.3 Soil Fertility

Soil fertility and productivity can be enhanced by adding organic material in the soil. Organic matter in fully decomposed form is more beneficial for good and better soil fertility; also, rotten and fully decomposed farm yard manure releases essential micro- and macronutrients to the soil solution, which become accessible to the root with more concentrations. For sustainable and higher crop production, organic farming should be adopted which improves the quality and productivity of soil by deploying soil properties on sustainable (Minhas and Sood 1994). Organic farming improves the soil fertility by enhancing soil microbial activity, organic carbon, available phosphorus and potassium, soil pH, and soil porosity, maintaining soil EC level, and also acting as a nutrient reservoir for succeeding crops (Gaur et al. 2002).

Changes in soil pH influence the growing vegetation in the soil. Mixing or incorporation of compost in the soil changed the pH from 6.5 to 6, which reduced the population of broad leaf and grassy weeds by 29% and 78%, respectively (Bulluck et al. 2002). Addition of carbon-containing organic material like rice straw, wood, saw dust, sugarcane trash, and corn cobs improves the soil physicochemical characteristics by enhancing decomposition process of manures, reducing water contents, and increasing C:N ratio. In rice-wheat cropping system, addition of farm yard manure along with green manure maintains the Zn, Fe, Cu, and Mn in higher concentrations (Singh et al. 2002). It was observed that green manuring reduced soil reactions by producing humus and organic acids at initial decomposition stage (Laxminarayana and Patiram 2006).

Urkurkar et al. (2010) stated that nitrogen (100%) for rice (120 kg/ha) and for potato (150 kg/ha) in rice-potato cropping system comes 1/3 each from cow dung, neem cake, and decomposed crop residues and increases 6.3 g kg^{-1} organic carbon over preliminary 5.8 g kg^{-1} as compared to the synthetic fertilizers alone. Nevertheless, accessibility of phosphorus and potassium did not display any noticeable modification subsequently accomplishment of five cropping cycles under organic as well as integrated nutrient approaches.

10.8.4 Soil Biotic Characteristics

Organic matter enhances the microbial activity within the soil profile which ultimately leads toward good crop productivity. Microbes like bacteria, fungi, and actinomycetes present in the compost provide humic acid by stimulating microorganisms in the soil (Gaur et al. 1973). In addition, activity of soil nematodes also controlled by organic compost and played an important in mitigating the pesticides influence by important soil organic and pesticide interaction called sorption. Sorption confines deprivation in addition to mineral transportation in soil. Applied insecticides attached to the soil organic matter or clay particles. These are more persistent due to low mobility and less accessible to microbial degradation (Prasad et al. 1972; Gaur 1975). Activity of heterotrophic bacteria and fungi increased due to the addition of more organic matter in the soil thus activates the soil enzyme responsible for nutrient availability by conversion from unavailable form to available form. Farming practices influence soil's biological, physical, and chemical properties. Soils where organic farming is practiced harbored the dense populations of arthropods, nematodes, protozoa, and bacteria as compared to the soils under conventional farming.

To enhance the soil fertility and bioactive agents, addition of organic matter in the soil is the crucial amendment as it increases the beneficial microorganisms; decreases pathogen population, total soil carbon, and CEC; decreases soil bulk density; and ultimately increases soil fertility by improving soil quality (Bulluck et al. 2002). The National Academy of Agricultural Sciences (NAAS) endorsed a general tactic to enhance efficiency of applied inputs. According to NAAS farmers should adopt integrated nutrient management (INM) and integrated pest management (IPM) approach in cropping systems as an alternative organic farming strategy. Prices of organically produced crops give more income return showed an increased microbial population in rice-pea-gram as compared with rice-wheat cropping system. Crops like wheat, rice, and cowpea showed significant increase in yield when P solubilizers like *Aspergillus awamori*, *Pseudomonas striata*, and *Bacillus polymyxa* are used in field experiments. In general, it is observed that vegetables are more responsive to azotobacterial inoculation than the other crops. Nonetheless, wheat, maize, sorghum, cotton, and *Brassica* crops when grown by using *Azotobacter chrooccocum* culture showed increase in yield which was 0–31% as compared to control.

Growth-enhancing substances produced by *Azotobacter* inoculation gave more seed germination due to extensive root growth. Soil structure improved due to the formation of polysaccharides in the soil (Gaur 2006).

10.9 Challenges for Organic Agriculture

Organic farming is facing several issues regarding adaptation, although it is environment friendly, justifiable, but still not achieving its goal. Most common issues in organic agriculture are:

(i) Tillage practices in organic agriculture.
(ii) Industrialization of organic production system.

In organic agriculture system, some common questions are asked about yield, sustainability, and productivity which depend upon many factors like farmer's interest, farmer background, resources of farmer, and indigenous and state sustenance mechanism. The opposite response could be: does conservative cultivation fulfill the world's food demand? Because more input means more yield, agriculture structures are at present waning to feed the world due to problems with productivity and food distribution, public organization, and thoughtful worries such as poverty, discrimination, and masculinity inequity. Since the 1980s, debates have been started among the researchers to compare organic and traditional agriculture. Yield comparisons were made among crop considering the environmental factors. Publication was made on the basis of research trials as comparison of organic and traditional farming (Mader et al. 2002). Same or more production may be achieved in organic farming as follows:

(i) Yield reduction through adaptation nevertheless recovers later.
(ii) Biodiversity and microbial activity found to be higher in organic agriculture system.
(iii) Yield reduction due to weeds, pests, and diseases. They damage the host crop and animals.
(iv) Accumulation of more nutrients may affect the crop growth by utilizing nutrient resource.
(v) Pesticide infection in organic products, public, and the atmosphere found to be less in organic agriculture.
(vi) True benefits of organic farming are still to be exposed.

Appreciated information about agricultural productivity and performance may be gained after farming system comparison over several years. To expand the conventional farming system, huge government and commercial support has been given for several years for plant and animal germplasm optimization, soil fertility, and pest management system to enhance the crop productivity. For conventional and organic farming comparison system, research has been continuously conducted for agricultural, environmental, and also for social and statistical problems (Powell 2002).

Organic food producers should adopt good and better techniques by keeping in mind the market trend and economics of the farmers. Social, economic, and atmospheric restriction may influence the organic production system. Wes Giblett who is a progressive dairy farmer in Western Australia, recently, explained organic farming as "the aim is to grow topsoil." He highlighted that organic farming can be achieved by adopting good agricultural management techniques as zero tillage, manuring (FYM, BYM, crop residues, etc.), crop rotation, and less use of artificial substances. By adopting organic dairy farming, he supplied to Western Australia in an area of Western Australia 2.5 m sq. km, and it was ten times larger than Germany – with a population of almost 1.5 million. Even though he runs this business in a very successful way, the primary objective of Wes Giblett was to cultivate the topsoil for farming to make organic farming successful and more economical for the poor and small farmers.

Adaptation of organic agriculture depends upon by distinguishing the advantages and disadvantages of organic system, so that farmers can make improvements and transfer valuable knowledge regarding organic farming issues when compared with the conventional farming system. On the other hand, organic agriculture is a beneficial and charming option of many farmers and consumers for improving the productivity and ecological influence of organic cultivation. Generally, success of organic farming depends on the region and demand of the people living in that region. In organic farming, weeds, soil fertility, and health of the living species are major concerns. Besides these, marketing and price regularity of organic food is also a big issue, that's why farmers and growers are looking reluctant to adopt organic agriculture. Government policies are also inadequate. Government policies, research, and extension services in this matter should be inline, and they cooperate themselves.

In conclusion, organic farming is a good and better option for the future generation to make them healthy and more intelligent than the existing ones. Organic farming is more economic and environment friendly for the growers and farmers.

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Nitrogen Fixation in Nutrient Management

11

Asif Tanveer, Hafiz Haider Ali, and Rao Muhammad Ikram

Abstract

The rapid population increase per annum forces over-exploitation of natural resources, including soil. Both the sustainability of agricultural systems and environmental protection are of serious concern for most of the countries. As a result of rapidly increasing population, there is pressure on the limited soil resources. Intensified and diversified cropping per unit of land or time has depleted the soil fertility. One of the major factors limiting soil productivity on sustained basis is depletion of soil fertility. Due to low organic matter content in soil, the inherent nutrient supply capacity is poor. Moreover, the current jumping up prices of inorganic fertilizers and sometimes their non-availability could not withstand the fertilization demand of different crops.

Ultimately, low yield is obtained even with the high intensity and diversity in the cropping system. Sustainability in the context of soil fertility can be obtained if the farmers should be able to operate within such a cycle that nutrients extracted from the soil should be returned back in order to avoid depletion leading to poor fertility and low yields, a real and immediate threat to food security and economic development. About 78% nitrogen is present in the air over every hectare of land, waiting to be trapped by legumes. Rates of symbiotic nitrogen fixation in legumes vary with plant species, cultivar, growing season, and soil fertility. Benefit of including legumes in crop rotation is that nitrogen fixed by them is almost as effective in promoting growth and development of plants as nitrogen applied as fertilizer.

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Keywords
Fertility · Legume · Soil · Development · Resources

11.1 Introduction

The rapid population increase per annum forces overexploitation of natural resources, including soil. Both the sustainability of agricultural systems and environmental protection are of serious concern for most of the countries. As a result of rapidly increasing population, there is pressure on the limited soil resources.

The agricultural land meant for crop production is shrinking as a result of fragmentation of landholdings and rapid use of agriculturally productive land for residential and industrial purposes. Thus, the future food and fiber requirements are to be met by intensifying cultivation on more less fixed land resource base.

Intensified and diversified cropping per unit of land or time has depleted the soil fertility. One of the major factors limiting soil productivity on sustained basis is depletion of soil fertility. Due to low organic matter content in soil, the inherent nutrient supply capacity is poor. Moreover, the current jumping up prices of inorganic fertilizers and sometimes their nonavailability could not withstand the fertilization demand of different crops. Ultimately, low yield is obtained even with the high intensity and diversity in the cropping system.

Sustainability in the context of soil fertility can be obtained if the farmers should be able to operate within such a cycle that nutrients extracted from the soil should be returned back in order to avoid depletion leading to poor fertility and low yields, a real and immediate threat to food security and economic development.

The cost of chemical fertilizer has increased manifold. One possibility of partial substitution of mineral fertilizers is through including legumes in crop rotation or cropping system. Legumes are plants of Fabaceae (leguminosae) family which produce seeds in pods and are characterized by five-petalled flowers and root nodules capable of nitrogen fixation, moong, mash, masoor, gram, and soybean. Cowpeas, arhar, Indian clover, berseem, lucerne, guar bean, dhaincha, and groundnut are the important legume crops. Legumes provide a potential source of N to increase the yield of standing and subsequent crop. Nitrogen is the most abundant element on the planet. Production of high-quality, protein-rich food is extremely dependent on the availability of sufficient nitrogen (Table 11.1).

About 78% nitrogen is present in the air over every hectare of land, waiting to be trapped by legumes. It means about 90 thousand tonnes of nitrogen is present over every hectare at every time which is equal to 195 thousand metric tonnes urea fertilizer. But plants are unable to use it directly. Plants obtain their nitrogen either by mineralization of endogenous organic matter or through symbiotic nitrogen fixation. God has bestowed special property to legumes for utilization of atmospheric nitrogen. Legume nodules contain bacteria (*Rhizobium* spp.) which take free nitrogen from the soil air and synthesize it into $NH^{+}{}_{4}$ which may be converted either into

Table 11.1 Major cross-inoculation groups with inoculants and host plant

Cross-inoculation group	*Rhizobium* species	Legume host
Pea group	*R. leguminosarum*	Pea, sweet pea
Alfalfa group	*R. meliloti*	Sweet clover
Clover group	*R. trifoli*	Clover/berseem
Bean group	*R. phaseoli*	All beans
Soybean group	*R. japonicum*	Soybean
Lupine group	*R. lupini*	Lupins
Cow pea group	*R.* Species	Cowpea, gram, arahar, urd, mung, groundnut

Table 11.2 Average nitrogen remaining (N-credit) in the soil after legume crops

Legume	N credit (kg/ha)	Legume	N-credit (kg/ha)
Alfalfa	90	Cowpeas	34
Sweet clover	67	Vetch	45
Red clover	45	Winter peas	45
White clover	22	Peanuts	22
Soybeans	22	Beans	22

plant protein or NO_3^- in the soil. In many countries of the world, legumes are often grown as a break between cereal crops to enrich the nitrogen in soil. Amount of nitrogen fixed by different legume crops is given in Table 11.2. The amount of nitrogen fixed by legume crops depends on soil aeration, drainage, moisture, pH, amount of active calcium, host plant, and strain of bacteria.

Rates of symbiotic nitrogen fixation in legumes vary with plant species, cultivar, growing season, and soil fertility. Some forage legumes can fix 600 kilograms per hectare per year, but more common values are 100–300 kilograms per hectare per year. Rates for grain legumes are often lower. Inclusion of legumes in crop rotations is generally thought to improve soil nitrogen levels, but benefits depend on the level of nitrogen fixed and the amount of nitrogen removed in grain or forage. A good soybean crop might fix 180 kilograms per hectare but remove 210 kilograms per hectare in the grain.

Benefit of including legumes in crop rotation is that nitrogen fixed by them is almost as effective in promoting growth and development of plants as nitrogen applied as fertilizer. It also cut short required chemical nitrogen fertilizer. The nitrogen compounds produced are not subjected to wastage due to soil erosion or leaching as is the case with chemical fertilizer.

The nitrogen fixed may go in three directions:

1. Used by the host.
2. Used by the nonlegumes growing in close association.
3. Left in the soil when the nodules slough off and decompose.

11.2 Nitrogen Fixation

Additions to soil nitrogen are made as a result of atmospheric, biological, or industrial fixation of atmospheric nitrogen (N_2). These processes are responsible for transforming nitrogen from the atmosphere to either ammonium or nitrate nitrogen that can be used by plants. These types of nitrogen fixation contribute significant quantities of NH_3 to different natural ecosystems, but not to most cropping systems, with the exception of flooded rice. The atmosphere contains an inexhaustible amount (78%) of nitrogen. Approximately 35,000 tons of nitrogen is present in the atmosphere above every acre of the earth's surface. Before its incorporation into plants, N_2 must first be "fixed" (combined) in the form of ammonium (NH_4) or nitrate (NO_3) ions. This process of reduction of N_2 is commonly known as "nitrogen fixation" (N-fixation).

11.3 Biological Nitrogen Fixation

It is the conversion of molecular nitrogen of atmosphere (N_2) to organic combinations or to form useable in biological process by microorganisms.

Biological N_2 fixation is carried out by:

11.4 Free-Living or Asymbiotic Microorganisms (i.e., Capable of Independent Existence)

Certain nitrogen-fixing bacteria can grow on root surfaces or to some extent within root tissues or area immediately adjacent to the roots which are high in energy-rich materials because of their exudation of organic compounds and their sloughing off tissues. These bacteria are also known as associative bacteria. Asymbiotic systems generally fix no more N_2 than can be used by the microorganisms themselves. This fixed nitrogen becomes available to higher plants only on death and decay of the free-living microorganisms that fixed it.

Major types of free-living nitrogen-fixing bacteria include:

11.4.1 Azotobacter

It is a free-living (nonsymbiotic) aerobic nitrogen-fixing bacteria commonly used on a limited scale found in close association with vegetable crops. Besides vegetables it is also effective for cereals, millets, cotton, and sugarcane. It can fix about 15–25 kg N/ha/season and causes about 10–15% increases in yield. Azotobacter is reported to synthesize growth-promoting substances like IAA, IBA, NAA, cytokines, GA, and B-vitamins which help in plant growth promotion. Azotobacter synthesizes antibiotic substances which control or suppress various fungal (*Alternaria* and *Fusarium*), bacterial, and viral diseases of crop plants. It mineralizes tricalcium phosphate and thus increases uptake of P in plant. Besides, it also increases the activity of beneficial rhizosphere bacteria such as ammonifiers, nitrifiers, nitrogen fixers, phosphate solubilizers, and cellulose decomposers. It has been reported that rice and wheat yields were increased by 5–31 and 16–30%, respectively, with azotobacter culture. This can be applied in the fields either by seed inoculation, seedling inoculation, pelleted seeds, preinoculated seed, or granular soil inoculants. Of these, seed and seedling inoculation are common, effective, and easy. In seed inoculation, carrier-based culture as per requirement is mixed with a minimum of water (500 ml/packet) to form slurry adding 10% sugar and 40% Arabica gum. Required quantity of seed is then mixed with slurry to form uniform coating of seed with inoculants. Two kilograms of carrier-based culture is mixed with 25 kg FYM and broadcasted in the field uniformly before sowing. The roots of seedlings can be dipped in azotobacter slurry prior to transplantation.

11.4.2 Azospirillum

It is noncrop specific and is mainly used for cereal crops. The crops responding to azospirillum are maize, barley, wheat, rice, oats, sorghum, pearl millet, and forages. Roots of these crops excrete organic substances (exudates) which are good source of carbon and energy for azospirillum and stimulate its multiplication. It can enhance crop yield by 14–20%. It can fix about 20–25 kg N/ha/season. Application procedure is same as for azotobacter.

11.4.3 Blue-Green Algae

They are also called cyanobacteria and are free-living organisms. They are photosynthetic nitrogen fixers (they use energy derived from photosynthesis to fix atmospheric N). They consist of chains of cells in branched or unbranched long filaments. Cells which are capable of fixing nitrogen are known as heterocysts. The BGA *Anabaena* inhabits cavities in the leaves of floating fern *Azolla* and fix nitrogen in lowland rice. The *Azolla-Anabaena* complex is a significant nonsymbiotic system without nodule formation. The common *Azolla* species is *Azolla pinnata*.

This association is most suitable for rice production. During the period when water stands in the paddies, a heavy pellicle (a very thin film) of BGA develops and fixes N_2 in the presence of light captured by host surface (azolla). BGA is located in cavities in leaves of water fern and is protected from external adverse conditions. BGA species responsible for nitrogen fixation is *Anabaena*. Fixed nitrogen (i.e., NH_3) leaks out of the fern plant and thereby supplies the nitrogen needs of the rice plants or with the evaporation of water, the pellicle of BGA settles to the soil where it decomposes and liberates fixed nitrogen. In rice field it is active only in the early growth stages before closure of crop canopies which results in shortage of light.

Blue-green algae occur under a wide range of environmental conditions, including rock surfaces and barren wastelands. Their numbers are normally far greater in flooded ditches or stagnant water than in well-drained soils. It forms green mat over water surface which often becomes reddish due to accumulation of anthocyanin pigment. About 40 species of BGA are capable of fixing nitrogen. They are mainly important in wet tropical soils. The algae that are generally used for field application are species of *Aulosira, Tolypothrix, Scytonema, Nostoc, Anabaena*, and *Plectonema* as a mixture. In submerged rice field soil, biological nitrogen fixation is essential and the algal process contributes about 30 kg N/ha/year. Values ranging from 40 to 80 kg N/ha/year have been recorded at the International Rice Research Institute, Philippines.

The BGA can be cultured in small pits and used as an inoculum in rice fields at 12–15 kg ha^{-1} or mass multiplied in the main field and incorporated into the soil before planting. Blue-green algae increase rice yield (up to 50%) under flooded conditions by fixing atmospheric nitrogen and release of growth-promoting substances for crop, improve soil texture by addition of organic matter and amino acids, and produce organic acids that solubilize P precipitates and Ca which ameliorate soil. Blue-green algae also produce growth-promoting substances and vitamins for rice and oxygenate the field impounded water to prevent accumulation of reduced iron and sulfates which are injurious to root growth. In soil, BGA conserve organic carbon and N and immobilize sodium converting the sodium clay into calcium clay. BGA produce the compounds responsible for “Earthy” odors detected in soil. Some BGA secrete mucilaginous substances which bind soil particles into soil aggregates.

Field trials indicate that one third of the recommended nitrogen fertilizer could be conserved without affecting crop productivity through algal inoculation. Algae are the living systems, and once they establish, their biological activity will be continuing in the inoculated fields. Normally, continuous inoculation for 3–4 consecutive cropping seasons results in an appreciable population buildup without further inoculation unless some unfavorable ecological conditions occur.

Azolla is applied in rice field at the rate of 7.5 kg/ha as a green manure, and it is allowed to grow on the flooded field for 2–3 weeks before transplanting; later on water is drained and *Azolla* is incorporated by plowing. As a dual crop 10–50 q/ha of *Azolla* (hybrid *Azolla* at 60 kg/ha) is applied in the field 1 week after transplanting of rice. It forms a thick mat on water. *Azolla* can double its biomass in 3–5 days and assimilate 30–80 kg N/ha.

11.4.4 Nonvascular Plants and BGA Association

Certain nonvascular plants like lichens (fungi) growing on the surfaces of trunks and branches of forest trees are able to fix N_2 with BGA. Filaments of BGA spread throughout the fungal mycelium. Nitrogen fixed may be leached down to the forest floor by rain. In addition, weathering and aging of the bark will cause the lichen to fall to the forest floor, where it decomposes and releases fixed nitrogen to trees.

11.5 Symbiotic Nitrogen Fixation by Nodulated Legumes through Rhizobia Bacteria

Rhizobium is a crop-specific bacterium and used to inoculate legumes. It has the ability to fix atmospheric N in symbiosis with legumes from which they receive energy and convert molecular nitrogen into nitrogenous compounds, act on grain legumes like mash, moong, arhar, pea, lentil, chickpea and others like soybean, groundnut, berseem, lucerne, etc. *Rhizobium* can fix 50–150 kg N/ha/season and increase yield 10–30%. It is needed in areas where a particular legume crop has not grown earlier or is being grown after 3–4 years. Twenty grams of culture is required to inoculate 1 kg seed of grain legume crop.

Rhizobia are collective common name for the genus *Rhizobium*. The symbiotic bacteria rhizobia (from the Greek words *Riza* = Root and *Bios* = Life) are soil bacteria that fix nitrogen after becoming established inside root nodules of legumes. Strains of bacteria which form nodules are usually naturally present in the soil. These bacteria are also introduced into the soil by treating seed with rhizobia culture.

From the agricultural point of view, symbiotic N_2 fixation by plants of the leguminous family is the most important. The infecting microorganisms are several species of bacteria of the genus *Rhizobium*. Different species of *Rhizobium* require specific host legume plants, e.g., the bacteria that live symbiotically with soybean will not do so with alfalfa. Symbiotic N_2 fixation occurs only in legume nodules (swellings or lumps on the roots of leguminous plants containing bacteria, living symbiotically with the root tissues) containing viable bacteria, present on roots. Leguminous plants themselves do not have the ability to fix N_2 and grow very well without the bacterium, provided that a source of fixed nitrogen (e.g., nitrate) is supplied. In the symbiotic association (mutual beneficial relationship between two dissimilar organisms, e.g., the association of nitrogen-fixing bacteria with leguminous plants in their root nodules) of legume host and invading rhizobium, the bacterium obtains carbon-containing substances from the host, and the host obtains fixed nitrogen through the agency of the bacterium. Thus the symbiotic association of the host and the bacterium is mutually beneficial to both organisms. Symbiotic N_2 fixation by root nodules of legumes contributes far more to the nitrogen economy of natural communities and to the fertility of soils than the asymbiotic systems. Nitrogen-fixing root nodules can fix 100–200 times more N_2 than free-living microorganisms, primarily because of the ability of nodules to continue to fix N_2 for long periods of time, perhaps for 30–40 days. Almost all of the nitrogen fixed goes directly into the plant. Little leaks into the soil for a neighboring nonlegume plant. However, nitrogen eventually returns to the soil for a neighboring plant when vegetation (roots, leaves, fruits) of the legume die and decompose. A perennial or forage legume crop only adds significant nitrogen for the following crop if the entire biomass (stems, leaves, roots) is incorporated into the soil. Poor nitrogen fixation in the field can be easily corrected by inoculation, fertilization, irrigation, or other management practices.

11.6 Nodule Formation

Steps involved in the initial process of infection of the roots and establishment of nodules are:

- The rhizobia cluster around the root hairs.
- Contact between rhizobia and root hair stimulates the root to secrete certain organic compounds like "lectin" protein into the soil. Function of "lectin" is to recognize and permit the entrance of the correct type of rhizobia that colonize root.
- The root hairs curl at their tips.
- The rhizobia then invade the root hairs at the site of curling, the rhizobia (bacteria) invade the root tissue, and an infection thread is produced.
- Rhizobia proliferate and pass through the infection thread to the cortical cells (portion of the stem or root lying between the epidermis and the stele) and pericycle (the layer of cells (of stele) just within endodermis) of the root.
- Cells in the inner cortex are stimulated to divide, possibly as a result of secretion of growth-promoting substances cytokinins (type of plant hormone) by infected host cells.
- A mass of host cells, some infected, some not, develop into a young nodule.
- The nodule thus formed establishes a direct vascular connection with the host for the exchange of nutrients.
- Vascular tissue of the root establishes continuity with newly differentiated vascular tissue in the nodule.

Bacterial cells inside infected host cells multiply rapidly and are transformed into swollen forms called bacteroids. The bacteroids are able to fix nitrogen into ammonia, which can subsequently be utilized by the plant. Enzymes necessary for nitrogen fixation are present in bacteroids. Bacteroids have a full complement of enzymes (TCA cycle, oxidative phosphorylation) which enable them to convert photosynthates obtained from the host plant to ammonia. Ammonia is excreted into the cortical tissue of the nodule converted there to organic form (e.g., asparagines) and then translocated via the xylem to the shoot system of host plant.

Legume nodules, function in an oxygen limited environment, which are required to protect nitrogenase disintegration by oxygen. These microaerobic conditions are maintained through an oxygen-binding compound leghemoglobin, synthesized jointly by *Rhizobium* and legumes, which regulates the supply of oxygen to bacteroids.

The heme (oxygen-binding) portion is produced by the bacterium, while the globin (protein) portion is produced by the host plant, again showing the closeness of the symbiotic relationship. Ammonia formed as a result of nitrogenase is transferred from microbe to the plant.

11.7 Nodulation

The production of nodules on the roots of legumes by specialized legume bacteria is called nodulation. The presence of nodules on the root system of legumes is no guarantee of nitrogen fixation, as it is important that the strain of rhizobia present in the nodules be of high nitrogen-fixing capacity. Mature effective nodules are larger, are few in number, often cluster on the primary roots, and have pink to red centers. The pink or red color is caused by leghemoglobin (similar to hemoglobin in blood). Ineffective nodules are small, are usually numerous and are scattered over the entire root systems, and have white or pale green centers. Nodules are clubbed shaped, lobed structure (clovers), branched and longer (lucerne), and spherical (cowpeas)**.** Nodule life is very limited. Nodules on many perennial legumes such as alfalfa and clover are fingerlike in shape.

Nodules on annual legumes are short-lived and will be replaced constantly during the growing season. At the time of pod fill, nodules on annual legumes generally lose their ability to fix atmospheric nitrogen because the plant feeds the developing seed rather than the nodules. Beans will generally have less than 100 nodules per plant, soybeans will have several hundred per plant, and peanuts may have 1000 or more nodules on a well-developed plant.

Nodules on perennials are long-lived and will fix nitrogen through the entire growing season, as long as conditions are favorable for their growth. A change from pink to greenish-brown coloration is first sign of senescence. In the field, small nodules can be seen 2–3 weeks after planting, depending on legume species and conditions necessary for seedling emergence.

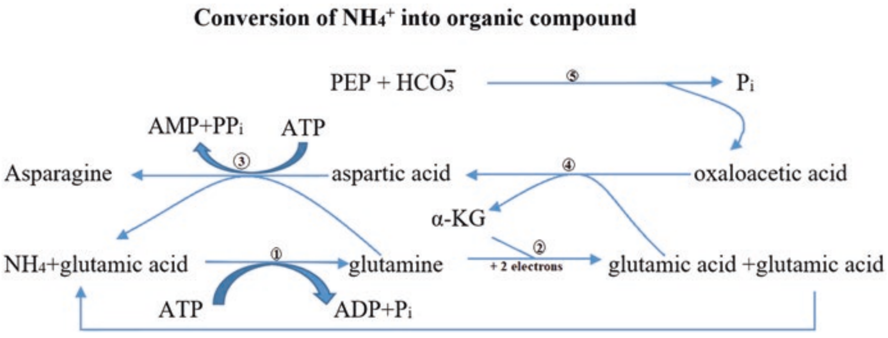
11.8 Biochemistry of Nitrogen Fixation

The overall chemical reaction for nitrogen fixation which results in the synthesis of ammonia is

$$\mathrm{N}_2 + 6\mathrm{e} + 6\mathrm{H} + ATP \rightarrow 2NH_3$$

Although ammonia (NH_3) is the direct product of this reaction, it is quickly ionized to ammonium (NH_4^+). The enzyme that catalyzes the reduction of N_2 is called nitrogenase. Nitrogenase is the only enzyme that can split nitrogen molecule for nitrogen. The reduction of N_2 to NH_3 by nitrogenase in bacteroides depends on a continuous supply of both ATP and reduced substrate capable of donating hydrogen atoms (i.e., protons and electrons) to N_2. Reduced substrate is obtained from photosynthate (glucose) supplied by the host plant.

Ammonia is excreted into the cortical tissue of the nodule, converted there to organic form and then translocated via the xylem to the shoot system of the host plant. Various organic forms are asparagines, glutamine, and glutamic acid in berseem, shaftal, and lucerne, whereas soybean, cowpeas, chickpea, moong, mash, and lentil export allantoin and allantoic acid from their nodules.



1. Glutamine is formed by the addition of NH_2 group from NH_4^+ to glutamic acid (glutamate) in the presence of glutamine synthetase. Hydrolysis of ATP to ADP and P_i occurs which is essential to derive the reaction forward.
2. Glutamate synthetase transfers NH_2 group of glutamine to α-ketoglutaric acid, thereby forming two molecules of glutamic acid. In this reaction ferredoxin (two molecules) acts as reducing agent to provide two electrons. In one of the two glutamic acids (glutamates) formed in the reaction, two goes back to maintain reaction, but the other can be converted directly into proteins or into other amino acids necessary for synthesis of proteins, nucleic acid, chlorophyll, and so on.
3. Besides forming two molecules of glutamic acid (glutamates), glutamine can donate its amide (NH_2) group to aspartic acid to form asparagine in the presence of asparagine synthetase. Hydrolysis of ATP to AMP and PP_i occurs to derive the reaction forward.
4. A continuous supply of aspartic acid must be present to maintain asparagine synthesis. The N in aspartic acid (asparate) can come from glutamic acid (glutamate), but its four carbons probably arise from oxaloacetic acid.
5. Oxaloacetic acid (oxaloacetate) is formed from phosphoenolpyruvate (PEP) and HCO_3^- by the action of PEP carboxylase.

11.9 Factors Affecting Nitrogen Fixation

11.9.1 Environmental Factors

11.9.1.1 Temperature

Temperatures ranging between 15–25 °C and 25–35 °C enhance nitrogen fixation in temperature (berseem, shaftal, lucerne, peas, beans) and tropical (moong, mash, lentil, gram, cowpeas, soybean) legumes, respectively, by increasing photosynthetic activity, nodule formation, and increased nitrogenase activity.

11.9.1.2 Light

Nodules increase in size due to cell enlargement in high light than low light. Nitrogen fixation is usually maximum in early afternoon when translocation of sugar from leaves to nodules is occurring rapidly. At that time high transpiration stream also helps in removal of organic compounds from nodules.

11.9.1.3 CO_2

High CO_2 level enhances nitrogen fixation.

11.9.2 Soil Factors

11.9.2.1 Organic Matter

Addition of farmyard manure enhances the number of nodules, the weight of nodules, and population of rhizobia and chances of rhizobia infection.

11.9.2.2 Nutrients

The application of nitrogen suppresses both nodulation and nitrogen fixation by reducing root hair and their curling. But these are improved by phosphorus. Potassium stimulates nodule activity by improving carbohydrate supply. Fixed nitrogen in excessive amount reduces synthesis of leghemoglobin which leads to lower nodule activity. When large amounts of nitrogen are applied, the plant literally slows or shuts down the nitrogen fixation process. It is easier and less energy consuming for the plant to absorb nitrogen from the soil than to fix it from the air. Deficiency of Fe and Mo decreases the formation of nitrogenase and leghemoglobin.

11.9.2.3 Chemicals

Residues of some insecticide and weedicides in soil cause reduction in the number of rhizobia and may lead to poor nodulation and nitrogen fixation.

11.9.2.4 Moisture

Adequate moisture enhances nitrogen fixation. Shortage of water may seriously reduce nitrogen fixation by inhibiting roots and root hair growth, rhizobia infection, stomata closure, and photosynthetic limitation. Water shortage after infection retard nodule development and nitrogen fixation and increases the nodule senescence.

11.9.2.5 Water Logging

It inhibits nitrogen fixation by reducing oxygen supply to the nodules. Nodules formed are of small size with less vascular tissue.

11.9.2.6 Salinity

Generally modulated plants do not like saline conditions. At low salt levels, they compensate by producing larger but lesser number of nodules. High salt concentration in soil results in withdrawal of water from nodules, and function of nitrogenase is inhibited.

11.9.2.7 pH

Maximum activity of nitrogenase occurs at 7 pH. At low pH, deficiency of Ca, Mo and excess of Al, Mn, decrease nodulation and rhizobia multiplication.

11.9.3 Biological Factors

Ineffective strains of rhizobium compete with the effective strains and thus reduce nodulation (e.g., soybean). The ineffective strains cause nodulation but do not fix nitrogen.

Frankia species of actinomycetes live in symbiotic association with certain non-leguminous plants, especially trees and shrubs. Nodules are formed on roots from pericycle cells. Nitrogen-fixing structure is known as endophyte vesicles. Nodules are pink color due to anthocyanin/tannins and are perennial. Alnus (alder) and casuarina are well-known host plants.

The favorable condition for nitrogen fixation are presence of enzymes nitrogenase and hydrogenase in the nitrogen-fixing cells or organisms, presence of leghemoglobin, ferredoxin which supplies electrons for this process, a source of hydrogen (strong reducing agent) like NADPH or $FMNH_2$, constant supply of ATP to transfer hydrogen atoms to dinitrogen, presence of coenzymes and cofactors, and compounds for trapping ammonia formed by the reduction of dinitrogen (N_2).

12

Weed Seed Bank: Impacts and Management for Future Crop Production

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Abstract

The seed bank is the resting place of weed seeds and forms an important component of the life cycle of weeds. Weed seed banks are the only source of future weed populations of annual and some perennial weed species that reproduce by seed only. Therefore, understanding of the weed seeds in the seed bank can be an important component of overall weed control. When weed seeds enter the seed bank, several factors influence the duration for which weed seeds persist. Seeds can sense the surrounding environment in the seed bank and use these stimuli to become dormant or initiate germination. Soil and crop management practices can directly influence the environment of seeds in the seed bank and can thus be used to manage seed longevity and germination behaviour. The weed seed bank serves as a physical history of the past successes and failures of cropping systems, and knowledge of its content (size and species composition) can help producers both anticipate and ameliorate potential impacts of crop-weed competition on crop yield and quality. Eliminating "deposits" to the weed seed bank (also called seed rain) is the best approach to ease future weed management. In the agroecosystems, the soil seed bank is related to weeds, and the knowledge of its size and composition in terms of species can be used in the prediction of future infestations, to build simulation models of population establishment through time and also the definition of soil and cultural management programs, in order to have a rational use of weed control practices.

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12.1 Introduction

Weeds are any plants that are objectionable or interfere with the activity or welfare of humans. They are competitive in nature, persistent, and pernicious; hence they are one of the major limiting factors to an efficient crop production. Weeds are undesirable and considered as pests like insects and diseases. High weed densities reduce the yield and quality through competition with crop plants for space, light, moisture, and plant nutrients as well as also exhaust the soil (Herren 2011). Although the weed management practices have developed more influential over time, weeds still exist in cropping systems. Weed control was conventionally accomplished by mechanical means (hoe, plow, hand weeding). The establishment of herbicides provided an alternative control method. However, the extensive use of herbicides has led to pervasive herbicide resistance in weeds. The recent observation made by the International Survey of Herbicide Resistant Weeds, USA has placed the number of herbicide-resistant weeds to a total of 217 species (129 dicots and 88 monocots).

There is an old adage that “One Year’s Seeding – Seven Years’ Weeding.” The importance of this adage has increased with the advent of herbicide resistance in weeds and is much anticipated that the herbicide-resistant weeds produce seeds which will germinate and produce the plants that are also herbicide-resistant (Shrestha 2004). Incidentally, we keep eliminating the susceptible weed plants, the densities of the resistant weed plants will increase, and they modify the volume and diversity of the weed seed bank and thus demand for a modification in our present weed management policies. As a value of operational issues, the ethnic state of the soil declines and weeds thrive; numerous species are difficult to eliminate. While herbicide-resistant weeds are not a big problem to the farmers who do not rely on chemical weed control (Farkas 2006), however, it is correspondingly important for all the growers to understand weed seed banks because it is the most important source of weed plants in agricultural fields. Most of the weeds start their life cycle from a single seed in the soil, and if the weeds escape control strategies, they will grow and produce thousands of seeds, and ultimately these weed seeds are returned to the soil seed bank and become the source of future weed populations (Zimdahl 2013). For instance, *Amaranthus spinosus* produces 2,35,000 seeds from a single plant, while other weeds like *Eleusine indica* 50,000–1,35,000, *Chenopodium album* 72,000, *Striga asiatica* 90,000, and *Orobanche cernua* 1,00,000 seeds per plant.

12.2 Weed Seed Bank

The term “seed bank” denotes to the place where the weed seeds accumulate and remain until germination. It is the reserve of viable weed seeds existing on the soil surface and spread in the soil profile. In other words, the seed bank is the resting place of weed seeds and forms an important element of the life cycle of weeds. The seed bank is an indicator of past and present weed populations. Thus, the seed bank comprises of massive numbers of new seeds recently shed by a weed plant and older seeds that have continued in the soil for several years.

Agricultural soils can contain thousands of weed seeds per square meter of which many seeds die within a few years or are removed from the seed bank by other processes (Mahesh and Robert 2007). Nevertheless, some weed seeds remain viable for decades and produce new plants as well as new seeds. Viable seeds in the soil reserve are the first guess of actual weed infestation (Dvořák and Smutný 2003). It has been assessed that about 1–9% of the viable seeds produced in a given year develop into seedlings and the rest remain viable or will germinate in subsequent years depending on the depth of their burial (Swanton et al. 2000). Seeds are dispersed both horizontally and vertically in the soil profile. The greatest seed reserves were in the surface layer (0–5 cm) of the soil (Janicka 2006), and the majority (about 95%) of the seeds entering the seed bank are from annual weeds. The seed densities in agricultural soils have been reported from near 0 to as much as one million seeds per square meter. Although seed banks and the resulting weed populations are composed of many species, a few dominant species generally comprise 70–90% of the total seed bank (Gselman and Kramberger 2004). These dominant species are the primary pests because they are resistant to control measures and are adapted to the cropping system (Buhler et al. 2001). Thus, the understanding of the factors impacting on the dynamics of weed seed banks can help us for the development of integrated weed management (IWM) programs.

12.3 Purpose and Characteristics of Weed Seed Bank

Weed seeds are a vital constituent of the weed life cycle as they are the beginning of future populations and are mainly important in annual and perennial weed species (*Taraxacum officinale*, *Sorghum halepense*, *Saccharum spontaneum*, etc.) which reproduce by seed only. The perennial weed species usually depend on the seeds to commence the new colonies some distance away from the mother plant, while the colony expansion near the mother plant is the result of vegetative reproduction. Thus, the weed seed bank is the viable reservoir in the upper part of the soil profile, which determines the composition of weed flora in the concrete region (Caetano et al. 2001). Species composition and density are influenced by farming practices and vary from field to field and among areas within fields.

Weed seed banks serve many purposes viz. enhances the survival of a weed species throughout time by buffering against harsh environmental conditions, tolerating high and low temperatures, dry and humid environments and variation in the oxygen supply or highly effective control methods as well as allow them to germinate over a period of many years. The significant fact in the success of weed survival is their persistence capability. This ability is a significance of a great number of seeds produced, long-term viability, continuous germination, and phenotypic and genetic plasticity. Thus, this potential decelerates the genetic shift of a weed population exposed to severe selection pressures by confirming that all the seedlings that germinate in any 1 year are not all from similar genetic backgrounds. Thus, the above considerations clearly give attention toward the existence of aerial seed banks which is most common in all the arable lands. Aerial seed banks are the seeds remain on the mother plant for erstwhile after maturity and allowing them for different dispersal mechanisms.

Some of these mechanisms consist of weed seeds dispersal by clinging to the fur of animals (*Arctium minus*, *Xanthium strumarium*, *Lappa minor*, *Torilis arvensis*, *Bidens frondosa*, etc.), or depending on passage through the digestive tract as in the case for many fruit-bearing weeds, or agitation of the mother plant as seeds are blown away from its point of origin by wind (*Kochia scoparia*, *Carthamus oxycantha*, *Salsola kali*, *Amaranthus graecizans*). Other weeds have a variety of mechanisms for short- and long-distance dissemination of seeds mainly blown by wind. Thus, the aerial seed banks are of greater significance in pastures or orchards than in agricultural fields. Weed seed banks are typically categorized by their prolonged existence and are determined by how long an individual seed may exist within it in a viable state. The structure of seed bank is unpredictable, which contains a fewer species to a large number of species with different growth habits, and is classified as temporary or persistent, when modifying the regeneration of the vegetation during different times of the year. Temporary or transient seed banks are composed of seeds of those species (*Avena fatua*, *Alopecurus myosuroides*, *Galium aparine*, *Kochia scoparia*, *Lapsana communis*, *Matricaria perforata*, *Taraxacum officinale*, etc.) having short life, which do not show any type of dormancy and are dispersed in time for short periods during the year (Grillas et al. 2004). The rate of decrease of these temporary seed banks is around 80%. Persistent seed banks are composed of seeds of those species whose seeds are generally buried into the soil and have more than 1 year of age and seed reserves remain in the soil year after year. *Chenopodium album*, *Sinapis arvensis*, *Aethusa cynapium*, *Papaver rhoeas*, *Viola arvensis*, and *Amaranthus retroflexus* are examples of persistent soil seed banks. Thus, the success of a seed bank relies on the seed population ready to germinate, when replacement is necessary and environmental conditions are favorable.

12.4 Persistence of Weed Seeds in the Seed Bank

The viability and longevity of seeds represent a major mechanism of survival of the weed species, and it in the soil varies among species, characteristics of the seeds (intrinsic dormancy), burial depth, climatic conditions (e.g., light, temperature, moisture), and biological processes (e.g., predation, allelopathy, microbial decay, aging, and senescence). The longevity of weed seeds mainly depends on variable dormancy of the seeds, presence of the seeds at various depths of soils experiencing different edaphic conditions, and variable viability of the seeds.

Although, the researches on weed seed banks have shown that agricultural weed seeds of some species have variable and long dormancy and remain dormant and viable for several years together. It is considered that grassy weeds, in general, remain dormant and viable for 10 years, whereas, broad-leaved weeds for 50 years. Despite the fact that most of the weed seeds will either germinate or die shortly after being dispersed from the parent plant (Table 12.1, 12.2, and 12.3). In a field study conducted, wild oat seeds were incorporated into the top four inches of a wheat-fallow field and approximately 80 percent of them died during the first winter.

An experiment on the longevity of different weeds seeds was done by Freitas (1990) which were buried and placed to germinate in different times of the year. The result showed that the weed species like *Amaranthus retroflexus*, *Ambrosia eliator*, *Lepidium virginucu*, *Plantago major*, *Portulaca oleracea* and *Rumex crispus* originated their seedlings after 40 years of burial. Broadleaf weed seeds tend

Table 12.1 Number of years required for 99% reduction in seed number in the seedbank of nine common agricultural weeds (Davis et al. 2005)

Species	Years required for 99% reduction
Chenopodium album	78
Thlaspi arvense	38
Xanthium strumarium	37
Setaria glauca	30
Polygonum aviculare	30
Capsella bursa-pastoris	11
Setaria faberi	5
Helianthus annuus	2
Kochia scoparia	2

Table 12.2 Life span of some weed seeds in soils (Kurth 1975)

Weeds species	Life span (years)
Agropyron repens	<10
Agrostemma githago	1–2
Avena fatua	3–8
Chenopodium album	<39
Cirsium arvense	<21
Echinochloa crus-galli	<15
Polygonum aviculare	<50
Portulaca oleracea	30–40
Rumex crispus	<70
Setaria viridis	<39
Sinapis arvensis	>40

Table 12.3 Seed density, seed production, and maximum longevity for some of the noxious weeds

Species	Seedbank density (viable seed yard^{-2})	Seed production (seed plant^{-1})	Longevity (years)	References
Cirsium arvense	–	Up to 12,000	22	Sheley and Petroff (1999)
Hypericum perforatum	–	15,000 to 33,000	10	-do-
Linaria dalmatica	–	Up to 500,000	10	-do-
Centaurea diffusa	–	10,000	12	-do-
Isatis tinctorial	–	500 to 10,000	10	-do-
Euphorbia esula	>16,000	Hundreds	10	-do-
Salvia aethiopis	–	Up to 100,000	10	-do-
Taeniatherum caput-medusae	Up to 10,000	Tens to hundreds	2	-do-
Carduus nutans	–	10,000	10	-do-
Lythrum salicaria	–	Up to 2,700,000	15	-do-
Chondrilla juncea	–	Up to 10,000	2	-do-
Acroptilon repens	–	1200	8	-do-
Onopordum acanthium	–	7000 to 40,000	16	-do-
Centaurea solstitialis	–	Up to 100,000	10	-do-
Linaria vulgaris	–	15,000 to 30,000	10	-do-
Cardaria spp.	–	1200 to 4800	3	Di Tomaso and Healy (2007)
Aegilops cylindrica	–	Up to 3000	5	-do-
Solanum elaeagnifolium	>24,000	4500+	15	-do-
Anthemis cotula	–	550 to 7000	25	Kay (1971)
Lepidium latifolium	>1.3 million	Tens of thousands	–	Young et al. (1998)
Tamarix ramosissima	–	500,000+	1	Di Tomaso (1998)
Centaurea biebersteinii	25 to 480	1000 to 30,000	8	Davis et al. (1993)

to last longer in the soil than grassy weed seed since they usually have tougher seed coats. In most cases, the majority of seeds only exist in the soil for a few years due to germination, decomposition, predator feeding, or other factors. However, with the large number of seeds produced, a small percentage may remain viable for long-term survival.

12.5 Seed Dormancy

The seed dormancy is another characteristic that affects the seed bank reservoir. Seed dormancy could be considered as a block to the completion of germination of an intact viable seed under favorable conditions, but earlier reviews concluded that it is one of the least understood phenomena in the field of seed biology (Hilhorst 1995; Bewley 1997; Finch-Savage and Leubner-Merzger 2006).

Dormancy prevents germination of the weed seeds during the condition that would otherwise be ideal for germination. The seeds of various weed species behave in different ways regarding germination, and there are several internal and external factors which prevent germination. Baskin and Baskin (2004) suggested internationally acceptable hierarchical system of classification for seed dormancy. The modified system includes three (hierarchical layers – class, level, and type); thus, a class may contain levels and types, and a level may contain only types. The system includes five classes of dormancy: physiological dormancy (PD), morphological dormancy (MD), morph physiological dormancy (MPD), physical dormancy (PY), and combinational dormancy (PY + PD). This modified system of classification helps us in thorough understanding of different types of dormancy and ways to overcome these dormancy types for better germination. Among the internal factors, the presence of a seed coat is important, which is a barrier to the penetration of water and oxygen, presence of a biochemical inhibitor in the seed, and immature embryo. Among the external factors, the most common are soil water content and temperature (Fernández-Quintanilla and Saavedra 1991).

Carmona (1992) used the term innate dormancy (primary) and induced dormancy (secondary) to characterize the development of the dormancy in the mother plant and after the dissemination in space, respectively. Most weed seeds are dormant at the time of maturity which is referred to as primary dormancy. However, seeds can set in and out of a dormant state because of environmental conditions and the process is referred as secondary dormancy; hence, regulates seasonal germination in weed seeds (Baskin and Baskin 1998). The secondary seed dormancy averts germination at a time of the year when the life cycle of a plant could not be completed, and this ensures that summer annual species germinate primarily in the spring and winter annual weeds germinate primarily in the fall. This process is regulated by seasonal changes in soil temperatures. Most of the summer annual weeds *viz*. *Amaranthus retroflexus*, *Chenopodium album*, *Digitaria* sp. and others can germinate in the spring because the cold of winter will break the dormancy and allow the seed to germinate in the spring. While on the other hand, winter annual weeds such as *Ailanthus altissima*, *Capsellabursa pastoris*, etc. require the heat of summer to break their dormancy and thus, germinate in the early fall and form a rosette before winter (Gulden and Shirtliffe 2009). The inability of the seeds to germinate due to an environmental restriction, like water deficit, low temperature, and poor aeration, is termed as enforced dormancy.

The dormancy represents a main mechanism of species preservation in the seed bank, distributing the germination through the year. It can guarantee the species survival in the form of seeds, under adverse conditions, even when the population of plants is completely eliminated (Carmona 1992). However, some seed physiologists do not consider the induced dormancy as an actual dormancy since the seed does not germinate because of the absence of environmental conditions and characteristics of the seed and since the seed does not need break dormancy but responds only to favorable conditions for germination. This situation is more conveniently referred as a case of dormant seeds.

The studies on population dynamics have the objective to determine their size throughout time and factors that influence their size (Saavedra 1994). In agroecosystems, where the soil is disturbed frequently, the soil seed bank acts to stabilize and ensure species survival (Roberts 1981). The dynamics of a seed bank involves a series of events of and of seeds from the bank, in relation to time (Simpson et al. 1989). The input is determined by the seed "rain." This way of dispersion includes passive forms, mechanical ejection of seeds, fire, wind, water, and animals. This way of dispersion includes passive forms, mechanical ejection of seeds, fire, wind, water and animals; and thus, results from physiological answer of plants to environmental factors, which induces the germination, seed burial or redispersion of the seeds, and predation of the seeds.

12.6 Topographical Tetrazolium Test

The tetrazolium test is a measure of seed viability and also provides quick estimation of seed viability. Tetrazolium testing originated in Germany during the early 1940s. George Lakon and colleagues discovered that embryonic tissues had to be alive and respiring in order for the seed to germinate normally. The early experiments used toxic chemicals such as selenium and tellurium to indicate viability, which limited their usefulness in seed testing. In 1942, Lakon developed a method using less-toxic tetrazolium as the viability indicator (source: Tetrazolium Testing Handbook, Contribution No. 29, Revised 2009).

12.7 Fate of Seeds in the Seed Bank

The weed seeds under continuous dynamism indicate the loss and replenishment of the seed reservoir through various means. The potential ways through which weed seeds may be distributed into the field depict that few weed seeds can germinate, emerge, grow, and produce more seeds; a large proportion of them will germinate and die (also known as fatal germination), or decay in the soil, or fall to physical damage by implements, pathogens, or fungi; predation by rodents, insects, birds, or mammals; or an unfavorable environment for growth; and thus, the losses/withdrawals of weed seeds occur in the soil.

Weed seeds have many fortunes for their distribution into the field (Fig. 12.1). Many weed seeds will remain dormant in the soil and not germinate under any set of the favorable environmental conditions. This state of dormancy is not permanent,

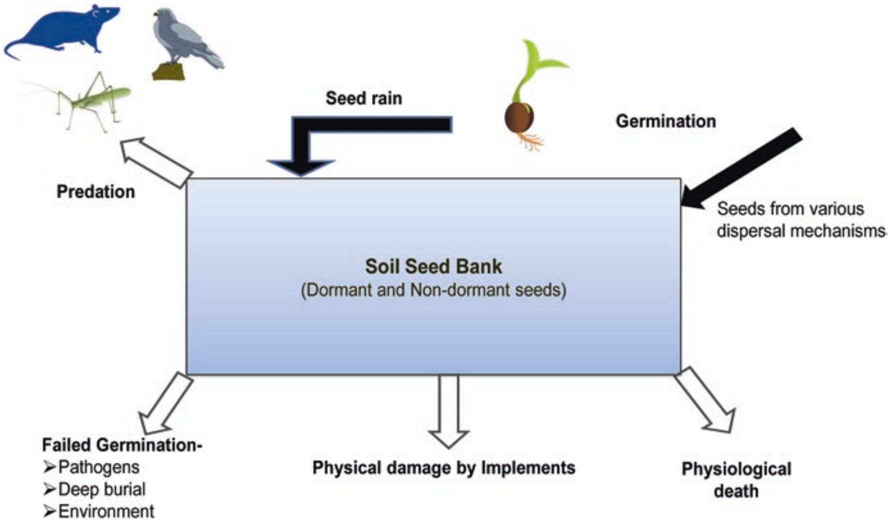

Fig. 12.1 Seed bank cycle (Anil Shrestha 2004)

and weed seeds can change from a state of dormant to nondormant, wherever they can germinate over a wide range of environmental conditions. When inputs of weed seeds exceed losses, the seed bank becomes larger and results in the potential for a large weed population. Successful weed management programs focus on reducing the seed bank by reducing inputs and/or increasing losses so they exceed inputs.

Weed seeds can spread on the soil surface after shedding and become the part of the soil seed bank through several avenues. The main source of weed seeds in the seedbank is from local matured weeds that set seed. Agricultural weed seeds can also be dispersed in a field by wind, water, animals, vehicle, and human activities. The dissemination of weed seeds depends on the dispersal process and the weed species (Fig. 12.2). Understanding the importance of these dispersal mechanisms is vital in the development of preventive weed management strategies.

Ball (1992) stated that there are two primary agricultural practices, land preparation and crop rotation, which create the impact on weed seed banks. Land preparation is done with the aim to control weeds, break soil surface hardness, and increase aeration so as to provide an optimum condition favorable for growth and development of crop as well as weed seeds. Thus, after attaining the favorable condition, weed seed germination is stimulated because light, alternated temperature, water, and nitrate ions break the weed seed dormancy (Cavers and Benoit 1989). The weed seeds dispersal in the soil profile is influenced by the kind of land preparation and the management at same depth favoring a uniform supply of the seeds in the soil profile and thus resulting in the lower seed populations at deeper layer of the soil (Dessaint et al. 1990). The stimulus of land preparation types over the seed bank was studied by Clements et al. (1996), and he observed that >70% of the weed seeds were present in the layer of 0–5 cm where no mechanical method was used, while

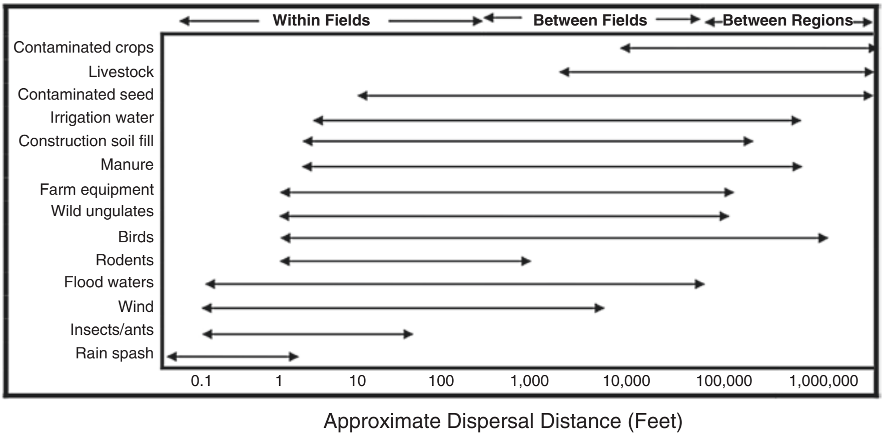

Fig. 12.2 Agricultural weed seeds travelling over a range of distances depending on the method of transport and the weed species (Mohler 2001)

the weed seeds were distributed up to 30 cm in the case of plowed fields (Yenish et al. 1992). Some of the weed species may exhibit higher intensity of emergence in zero tillage than in the conventional tillage (Fig. 12.2).

Carmona (1992) quantified that zero and minimum tillage tends to diminish the quantity of weed seeds at the soil surface shed by plants because of initiation in the germination or loss of viability of the weed seeds. The existence of weed seeds at upper soil layer and recurrent cultivation are the main factors which reduce the seed bank rapidly. This condition can simplify seed predation by exposure of seeds to variations in temperature and humidity and/or by breaking the seed dormancy. Nevertheless, the speed of soil seed bank depletion depends on the seed production of the weed species (Yenish et al. 1992; Fernández-Quintanilla 1988).

The species composition of the weed seed bank is also influenced by the use of herbicides, as it may increase or decrease the composition depending upon the chemicals used (Ball 1992) and can also cause species shifting (Roberts 1968). Overall, it can be determined that the interaction of herbicides, land preparation, and cultural practice have altered the size and nature of seed banks (Roberts 1981). Murphy et al. (2006) stated that the seedbank declined in no-tillage systems from 41,000 to 8000 seeds m^{-3} over 6 years of rotation (corn-soybean-winter wheat) and the crop yields were not affected by tillage or crop rotation. Schweizer and Zimdahl (1984) observed that there was 98% reduction in the seed bank after application of atrazine in a corn field during 6 years of cultivation. The continuous use of triazines in corn in Ontario, Canada, altered the species composition and resulted in an increase in resistant plants to the products (Cavers and Benoit 1989). In practical terms, reduced tillage in combination with a good crop rotation and cultural practices may reduce weed density and expenditures on weed management. Thus, the seed bank reflects the historical process of the plant life cycle, from its establishment in the environment to the distribution in time and space (Fig. 12.3).

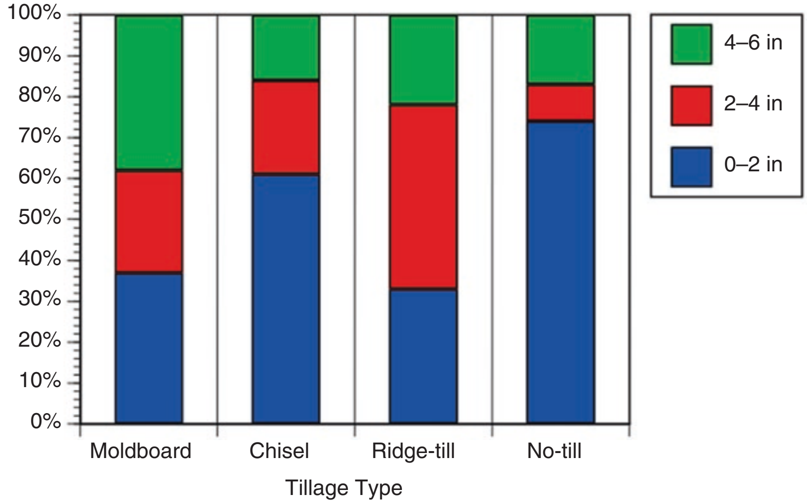

Fig. 12.3 Vertical position of the seedbank with respect to different types of tillage practices being adopted (Clements et al. 1996)

12.8 Distribution of Weed Seed in the Soil Profile

Weed seeds disperse both horizontally and vertically in the soil profile. The horizontal distribution of weed seeds in the seed bank generally follows the direction of crop rows, while type of tillage is the main factor determining the vertical distribution of weed seeds within the soil profile. In plowed fields, the majority of weed seeds are buried 10 to 15 centimeters below the surface. Under reduced tillage systems such as chisel plowing, approximately 80–90% of the weed seeds are distributed in the top 10 centimeters of the soil profile. In no-till fields, the majority of weed seeds remain at or near the soil surface. Although very few studies have assessed the effect of tillage systems on the vertical distribution of weed seeds in different soil types, evidence exists that soil characteristics influence weed seed distribution (Fig. 12.4).

Therefore, understanding the effect of management practices on the vertical distribution of seeds is important as it can help us predict the weed emergence patterns, e.g., in most soils small-seeded weeds like *Amaranthus retroflexus*, *Digitaria* sp., *Bassia scoparia*, *Cirsium arvense*, *Chenopodium album*, etc. germinate at very shallow depths (less than 2 cm), while large-seeded weeds such as common sunflower (*Helianthus* spp.) have more seed reserves and may germinate from deeper depths.

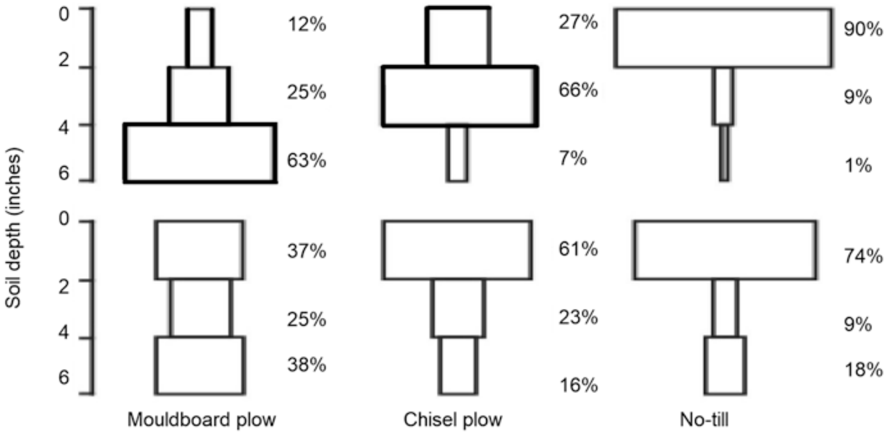

Fig. 12.4 Vertical distribution of weed seeds in a loamy sand (top) and silty loam soil (bottom) (Clements et al. 1996)

12.9 Management of Weed Seeds

Management of weed seed offers the most practical long-term management of hard to control weeds, including wild oats (*Avena* spp.), wild radish (*Raphanus raphanistrum*), and annual ryegrass (*Lolium* spp.). The decrement in the input of seeds into seed bank is the most apparent way to reduce the weed seed bank. Any method which diminishes the magnitude and number of weeds producing seeds will also lessen the quantity of seeds dropped into the seed bank. Obviously, the weed seed bank can be accomplished by using other methods that surge the death of the seeds in seed bank or encourage germination when the weeds can be easily controlled.

Even though most of the agronomic practices have an indirect consequence on the weed seed bank, a few important methods can directly affect the input of weed seeds, seed bank persistence, and germination from the seed bank. Control strategies include destroying or burying set seeds, encouraging germination, and tactical herbicide use and crop agronomy. There is not a single weed management program ideal for all conditions. The set of strategies selected to reduce weed seeds depends on the soil type, rainfall pattern, crop rotation, equipment available, and budget and farmer preference. The initial phase is to recognize the problematic weeds and develop a multi-year approach to their management. The subsequent step is to control the weeds that undergo early weed control or germinate in-crop and seed-set reinfesting the seed bank.

When the weed seed bank has been diminished, the use of crop competition is one of the best tools to combat weed germination and seed-set. Strong crop competition combined with rotation of herbicides having different modes of action and the use of suitable agronomic practices for crop nutrition and disease management are the best approaches of keeping seedbank low. Wherever the weed populations are high or seed bank life span is extended, multi-year approaches are required to control the seed-set and to drive populations down. Therefore, efforts to control the seed bank must be sustained for years to be successful. The research with lamb's quarters (*Chenopodium album*) found that a 6-year effort to control the weeds reduced the seed bank 94–99%, whereas after 1 year without control, the seedbank increased to 90% of its pre-control size (Di Tomaso and Healy 2007). In another experiment conducted in Canada for 6 years, Beckie et al. (2005) observed that weed patches expanded in size by 35% when standard weed management practices were combined with weed seed shed prevention, while when only standard weed management approaches were applied, the weed patch expansion reached 330%. The best tactic to ease the forthcoming weed management is to limit present contributions to the weed seed bank. In a 5-year period experiment conducted at Nebraska, broadleaf and grass weed seed bank was reduced to 5% of their original density when weeds were not allowed to produce seeds. However, in the sixth year, weeds were not controlled, and the seedbank density increased to 90% of the original level (Burnside et al. 1986).

12.9.1 Weed Resistance

The resistance in different weed species develop as a result of overuse of any single strategy is called weed resistance. Herbicides experience the least risky option for weed control and are used by most of the farmers. Rotating the herbicide with different modes of action and tumbling the dependence on herbicide control by the use of physical and biological control methods will aid to curb the development of herbicide resistance. Integrated weed management is not a replacement for herbicides but adds other control strategies throughout the season in order to create a system that maintains weeds at low levels while minimizing current and future financial risks.

12.9.2 Prevention

The most efficient approach to reduce weed seed banks is to not allow weeds to set seed in the field. Care should be taken to avoid bringing new weed seeds into a field through irrigation, equipment, or animals. This can be achieved by screening irrigation water, washing equipment before bringing it into the field, and keeping grazing animals in quarantine before moving them from a weedy field to a clean one.

12.9.3 Reducing Seed Inputs into the Soil Seed Bank

Reduction not only minimizes future weed problems, it also reduces the speed at which weed patches expand across crop fields. Increasing crop interference by increasing seeding rate and filling empty niches with cover crops helps minimize weed seed inputs into the seed bank. Other approaches include mowing weeds prior to seed production and controlling weeds with herbicides or cultivation.

12.9.4 Herbicides

Herbicides have, and continue to be, the most effective weed management tool of the twenty-first century because of their ability in reducing weed populations very effectively as well as at the same time reduces the number of seeds added to the seed bank. Weed seed bank densities lean to be greater in organic management systems than in systems reliant on herbicides, although this is not always the case as other factors such as crop rotation also strongly influence weed seed production. In production systems that use herbicides as the principal tool to manage weeds, seed bank densities are typically between 1000 and 4000 seeds m^{-2} (Blackshaw et al. 2004; Clements et al. 1996). When herbicide-tolerant crops are used extensively in cropping systems, weed seed banks will be near the low end of this range; however, despite lower weed seed bank densities in these systems, weed seedling emergence still remains significant in following years. Preharvest applications of glyphosate can decrease seed production and impact seed viability in late-flowering weeds. However, the slow action of glyphosate means that weeds must be managed well before the plant sheds its seed near maturity.

12.9.5 Crop Rotation

Crop rotation is also an effective means of managing the weed seed bank. Introducing perennial crops in annual cropping systems tends to deplete the soil seed bank of annual species over time. This method is more effective on weed species which have low levels of longevity such as kochia and many of the grassy weeds like wild oat and green foxtail. Likewise, crop competition is also important for decreasing weed seeds being recruited to the seed bank. Studies near Saskatoon, SK, conducted in the late 1970s showed that seed bank populations were greatest in summer fallow (about 1600 seeds m^{-2}) versus wheat stubble (about 500 viable seeds m^{-2}) (Archibold 1981). Weed seed bank additions are high in fallow fields impart due to incomplete weed control by tillage and the absence of a competitive crop (Archibold and Hume 1983).

12.9.6 Chaff Collection

Chaff collection is an effective method for reducing inputs into the weed seed bank. Weed seeds generally weigh less than crop seeds and therefore end up in the chaff fraction which is typically spread evenly across the field. Even for large weed seeds such as wild oat, chaff collection can prevent upward of 90% of the weed seed numbers added to the seed bank during the harvest operation (Shirtliffe and Entz 2005).

12.9.7 Seed Longevity

While burying weed seeds by tilling increases the longevity of the seeds in the seedbank, leaving weed seeds on the soil surface exposes them to predation, reducing their abundance in the seed bank.

12.9.8 Manure

Composting manure reduces the viability of weed seeds, minimizing weed seed inputs into the seed bank.

12.10 Conclusion

Weed seed banks are a vital constituent of the weed life cycle. There are many fates and processes that occur in the weed seed bank, many of which are not very well understood. The absolute difficulty of monitoring a process that occurs mostly underground has deterred weed scientists from gaining a full understanding of the weed seed bank. Nevertheless, current knowledge about weed seed banks has shown some potential management options. Reducing inputs to the seed bank is an important component of seed bank management, while other strategies like using a no-till cropping system can be used to directly affect germination, persistence, and mortality of weed seeds. Managing weed seed banks should be an important component of integrated weed management, but more often than not, seed bank management is not being exploited to its fullest potential.

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Weed Management for Healthy Crop Production

13

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Abstract

This chapter deals with the potential, limitation, and impacts of the recent trend of changing agricultural practices induced by predicated climatic changes on weed management in crop production systems. Change in the agricultural practices from conventional to conservation agriculture has to some extent compromised the sustainability and productivity of cropping systems through the evolution of herbicide-resistant (HR) weed species, a shift in weed populations, and human and environmental hazards. The chapter assesses the potential challenges faced by regarding the overreliance of herbicides, with the introduction of herbicide-tolerant (HT) crops and possible recommendation of how healthy crop production can be achieved through sustainable weed management. The first section deals with the potential constraints associated with weed management in cropping system focusing the main driving factors, such as changing agricultural practices and climate change, socio-economic constraints. Possible strategies to improve weed management, focusing on the importance of promoting IWM strategies and best management practices for HT crops, have been discussed in the second section. The third section shares a series of recommendation for future research directions for sustainable and profitable weed management.

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Keywords
Cropping production · Sustainable weed management · Changing agricultural practices · Climate change · Herbicide resistance

Abbreviations

A	ACCase inhibitors
B	ALS inhibitors
BMP	Best management practices BMP
C1	Photosystem II inhibitors
C2	PSII inhibitor (ureas and amides)
C3	PSII inhibitors (nitriles)
CO_2	Carbon dioxide
D	PSI electron diverter
E	PPO inhibitors
EPTC	Eptam
F1	Carotenoid biosynthesis inhibitors
F2	HPPD inhibitors
F3	Carotenoid biosynthesis (unknown target)
F4	DOXP inhibitors
FAO	Food and Agriculture Organization
G	EPSP synthase inhibitors
GM	Genetically modified
GMHT	Genetically modified herbicide-tolerant crops
GRDC	Grains Research & Development Corporation
H	Glutamine synthase inhibitors
HR	Herbicide-resistant
HT	Herbicide-tolerant
IWM	Integrated weed management
K1	Microtubule inhibitors
K2	Mitosis inhibitors
K3	Long-chain fatty acid inhibitors
L	Cellulose inhibitors
MOAs	Mode of actions
N	Lipid inhibitors
non-GM	Non-genetically modified
NSCT	Nonselective crop topping
O	Synthetic auxins
pK_a	Vapour pressure
SOA	Site of actions
SST	Selective spray-topping
Z	Antimicrotubule mitotic disrupter
Z1	Unknown
Z2	Cell elongation inhibitors
Z3	Nucleic acid inhibitors

13.1 Introduction

Food demands have doubled in recent times due to an ever-increasing world population and overconsumption. This increasing need for more food production is at its greatest in the least developed countries where the most dramatic expansion of population is occurring. The clear majority of the world's most hungry people belong to these developing countries, where about 13% of the population is undernourished with approximately 281 million of these people in Southern Asia. In addition, more recent projections suggest a rate of undernourishment of almost 23% in sub-Saharan African countries. For the next decade, more sustainable food production will be essential if these ever-growing demands on food production are to be met and for this to be done with judicious use of natural resources whilst moderating the deleterious impacts of an intensified agriculture on the environment (Yaduraju and Rao 2013).

Agriculture, the world's largest employer, provides a livelihood for 40% of the global population and is the largest generator of jobs and income for poor rural households. Available figures suggest that half a billion smallholder farmers globally produce up to 80% of the food consumed in developing countries (FAO 2018a). Another concern is that since the 1900s, about 75% of the diversity of crops planted has been lost from farmer's fields (FAO 2018b). Furthermore, climate change is putting pressure on the normally dependable resources required for agriculture, with the outcome being degraded soils, unstable supply of freshwater resources and biodiversity losses, etc., thus, increasing the susceptibility of agricultural systems to unfavourable events, such as drought, fire, and flood. Because of such changes, a profound change needs to follow in the global food and agricultural systems that we use to nourish the already 815 million hungry people and the additional 2 billion population expected by 2050. Better use of agricultural biodiversity would be one way to help create more nutritious diets and to enhance farmers' livelihoods, leading towards more resilient and sustainable farming systems.

Weeds are the main threat to world agriculture production, reducing crop and pasture yields and quality, interfering with crop harvesting and postharvest handling, affecting animal health, and hindering irrigation (Abouziena and Haggag 2016). According to a study, the annual world losses due to weeds are approximately 10–15% of the potential production of all the major food commodities or approximately USD $40 billion per year (Monaco et al. 2002). Despite the tremendous improvement in the way weeds are chemically controlled, especially with the advancement of genetically engineered crops with tolerance, both in the developed and developing countries, weeds remain an unmanageable threat to crop productivity and profitability (Nawaz et al. 2017; Banerjee et al. 2018). As one example, the cost of not managing agricultural weeds in maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) is estimated to be USD $43 billion per year in North America (Peter 2018).

Numerous socio-environmental constraints as the impact upon the damage weeds cause and impact the strategies employed for their control. For example, herbicide use worldwide has now risen 12-fold over that used in the period 1995 to

2014 (both in agricultural and nonagricultural applications), leading towards serious environmental and public health concerns (Drzyzga and Lipok 2018). In addition, the acute shortage of labour during peak periods and the absence of economically feasible and effective weed management techniques adapted for local conditions, all have influenced weed control in crop production systems (Sengxua et al. 2018). Thus, changes in land use, climate change factors, increasing food production demands, and the public-demanded increased environmental protection have all necessitated the move towards a more effective and reliable weed management approach. It is believed that by diversifying the weed management strategies used, the current and future challenges in weed control may be addressed more effectively (Liebman et al. 2016). These socio-environmental constraints have allowed the damage caused by weeds to become unchecked and have limited the kind of strategy that can be used to manage them. Therefore, new diversified ways of weed control are needed to manage weeds effectively under the growing demands for greater food production, to help counter the rapid shifts in land use and climate, and to meet the future expectations of environmental protection (Ehrenfeld 2010; Liebman et al. 2016).

In the next section (Sect. 13.2), several of the greatest challenges to food production are reviewed, and that when considered together will help in the development of an improved weed management approach that can support healthy and sustainable crop production. In the subsequent section (Sect. 13.3), further development of the components of the approach will be discussed, which will make the agricultural production system sustainable in the longer term by creating a healthful food supply that reduces the impact on natural resources and farmers' health without compromising crop yields.

13.2 Constraints Associated with Weed Management in Crop Production

13.2.1 The Results of Human-Induced Changing Agricultural Practices

13.2.1.1 Overuse of Herbicide: The Evolution of Herbicide-Resistant (HR) Weeds

Overuse of the same herbicide year after year, especially by farmers with less awareness, has dramatically increased the occurrence of herbicide-resistant (HR) weed populations, with the result that herbicide resistance has now become one of the major threats to global food security (Pacanoski 2017). Selection pressure due to the continuous use of the same herbicide or herbicides mode of action group is the main reason for this development (Manalil et al. 2011; Vencill et al. 2012; McElroy 2014). In addition, the increased use of herbicides, in general, has resulted in cases of multiple resistance developing, leaving limited or no herbicide options for farmers to control weeds in the future (Peterson et al. 2018).

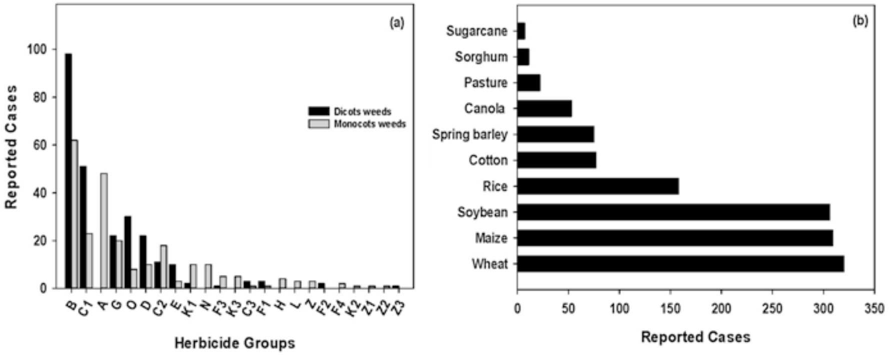

Fig. 13.1 Globally reported case of herbicide-resistant weeds on the basis of mode of action group (**a**) and crops (**b**). (Reference Heap 2018)

Of the 26 known herbicide mode of action groups, weeds have developed resistance to 23 of these, including resistance to 161 herbicide formulations (Fig. 13.1; Heap 2018). Currently, 495 unique cases of HR weed populations have been reported in 255 species (148 dicot and 107 monocot species) found in 92 crops grown in 70 countries, including all continents apart from Antarctica (Figure 13.1a, b; Heap 2018). Countries such as Australia and the USA have the highest number of HR cases, whereas many fewer have been reported from Asia and South America. Similarly, fewer cases have been reported from Africa, but this may be due to the limited area that is under intensive agriculture and where herbicides are routinely used. Based on the number of reported cases, HR is a problem of the developed countries (Peterson et al. 2018).

In countries with developing economies, significant human migration from rural to urban areas has taken place, and rural agriculture is already experiencing a shortage of labour due to this migration. This trend, if continued, will increase farmer's dependence on herbicides, leading to a greater selection pressure which will result in more HR weed populations and more cases of multiple resistance. Consequently, the evolution of HR weed populations will outpace those of the development of new herbicides with new sites of action (SOA), making it critical for farmers to employ diverse weed management option to maintain sustainable crop production (Peterson et al. 2018). It is highly likely that some countries will lose the use of certain herbicides to control particular weed species if the present trend in increasing HR continues. In developed countries, if the appearance of HR populations continues, this will result in the use of alternative herbicides and mixtures, and this may also result in the use of higher application rates (Peterson et al. 2018). For example, results from a national grower survey in Australia estimated that HR costs growers an additional AUD $135 million annually in addition to herbicide costs (Llewellyn et al. 2018).

The continued evolution of HR weed populations will reduce crop yield and the flexibility of cropping systems, thus restricting farmers to operate only certain kinds of cropping system in those areas that have become affected. Additionally, in cases where HR weed populations are present, a proactive approach that moves towards using a greater range of crops and tillage in combination with herbicides might result in a net profitability loss of between 4 and 24% as compared to cropping systems without resistance (Gerhards et al. 2016). In recent surveys in the USA, the proportion of respondent indicated that weed control costs of USD $50 per acre nearly doubled following the emergence of HR weeds on cotton farmers (Zhou et al. 2015). There have been reported yield losses of 15%, whilst in extreme cases, farmers have abandoned farming land entirely (100% yield losses; Carpenter and Gianessi 2010; Culpepper et al. 2010). Despite these costs due to HR weed populations, farmer's adoption of resistance management practices has been poor and insufficient to restrict the further development of HR weed populations (Lamichhane et al. 2017).

13.2.1.2 Introduction of Herbicide-Tolerant (HT) Crops

The introduction of genetically modified herbicide-tolerant (HT) crops has offered numerous benefits to farmers; however, this technology has reduced the diversity of herbicides used, resulting in the evolution of more HR weed populations and HT volunteers (HT crop plants emerging in the following season) as well as resulting in weed population shifts. The marketing of these HT crops, designed to tolerate specific broad-spectrum herbicides, has encouraged farmers to use more herbicide, thus increasing the chances of HR development in weed species (Fig. 13.2). For example, the high predominance of glyphosate-tolerant (GT) crops has greatly increased the development of glyphosate resistance (GR) in weed species, since their introduction in 1996. Ineffectiveness in the control of HR weed species in HT crops has called into question the long-term sustainability of these GMHT crops (Livingston et al. 2015). Promoters and supporters describe HT crops to be revolutionizing farming and to be bringing about considerable agro-economic and environmental

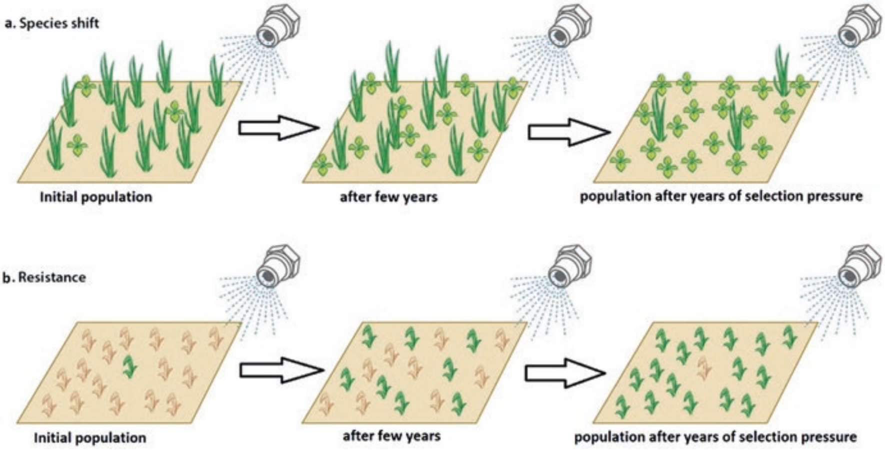

Fig. 13.2 Repeated herbicide uses impose selection pressure leading towards weed species shift (**a**) resulting in more tolerant/resistant species (**b**). (Adapted and modified from Orloff et al. 2009 with permission)

benefits. However, sceptics challenge this by citing the considerable rise of more HR weed populations (Bonny 2016).

Increased adoption of HT crops, particularly GT crops, has increased the use of glyphosate for weed control (Benbrook 2016). In addition, this has promoted the adoption of conservation tillage practices, which in turn reduced further the use of other herbicides and facilitated glyphosate overreliance (Travlos and Chachalis 2010). The widespread use of glyphosate has now resulted in heavy selection pressure linked to the adoption of GT crops and the concomitant reduction in the tillage, thus contributing to weed species shifts. Studies have demonstrated that an increase in the annual grassy and perennial weed species has been associated with the use of reduced tillage practices and are now becoming the predominant weeds in conservation tillage production systems (Buhler 2002). Though the use of reduced tillage practices, there has been a change in weed species present, their distribution, densities, as well as weed community composition, and these different weed communities respond differently in conservation tillage systems and need to be treated accordingly (Bajwa 2014).

HT crops are reported to exert significant influence on growth and yield in many crops as HT volunteers in succeeding crops (Lopez-Ovejero et al. 2016). These HT crop volunteers are emerging as a major threat due to their seed characteristics (i.e. production, dormancy, and persistence), resulting in depletion of available resources, interfere with weed management, and reduced herbicide efficacy, as herbicide fails to manage HT volunteer with same herbicide tolerance profile (Alms et al. 2016; Lopez-Ovejero et al. 2016). In addition, the flow of gene to GM or other non-GM cultivars result in adventitious presence or contamination of seed lots, exerting economic consequences or repercussions in the marketplace (Warwick et al. 2009; Dong et al. 2014). The potential of gene or pollen flow from GM HR crops to non-GM to other GM crop and to weedy relatives is seen to be a real risk in transgenic crops with a high degree of outcrossing, particularly with a large number of weedy relatives (Fig. 13.3; Warwick et al. 2009). The prevailing environmental conditions and agronomic technologies, most importantly the weed management strategies, harvest efficacies, and postharvest handling, significantly influence the pace at which the volunteer plants can acquire the status of major weeds in coming years, like herbicide-resistant weeds (Graef et al. 2007; Bond and Walker 2009).

13.2.1.3 Intensification of Agriculture: Impact on Human Health and Environment

Commercial crop production is highly dependent on the utilization of agricultural pesticides; in the top 25 pesticides used in the agricultural sector, 13 are herbicides, predominantly glyphosate (Grube et al. 2011). Exposure to the herbicide, either contact or inhalation, type of herbicide, duration of exposure, and the individual health status determined the possible health outcome. More emphasis is given widely to glyphosate, which is closely related to current agriculture (Baylis 2000). Continuous exposure from frequent use resulted in increased levels of this herbicide in foods, drinking water, and the atmosphere (Chang et al. 2011), although research

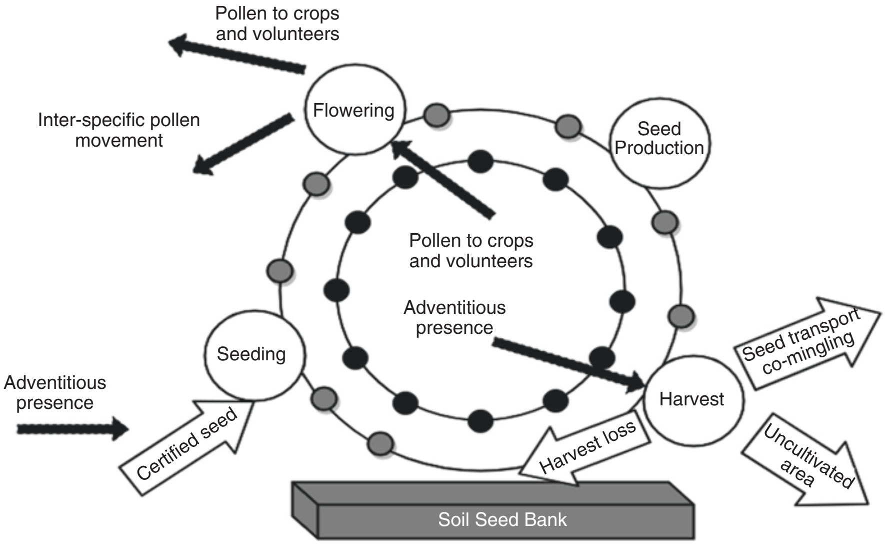

Fig. 13.3 Seed- and pollen-mediated gene flow in crop plants (○) and volunteers (●) through the annual crop cycle. (Reproduced from: Warwick et al. 2009)

on the risk assessment identifies glyphosate as one of the safest herbicides on human health.

In recent years, the World Health Organization's International Agency for Research on Cancer concluded that glyphosate is probably carcinogenic to humans. The half-life of glyphosate in water and soil is longer than previously recognized, and human exposure to this herbicide is rising; thus glyphosate is now authoritatively classified as a probable human carcinogen (Myers et al. 2016). Moreover, certain herbicides like acetochlor, imazaquin, imazethapyr, and pendimethalin have also been reported for causing lung cancer, bladder cancer, colon cancer, and asthma, respectively, in humans (Lerro et al. 2015; Koutros et al. 2015).

Besides intensifying problems of herbicide-resistant weeds, excessive use of herbicides has raised public concerns about their adverse impact on the soil and groundwater contamination (Kumar et al. 2013). One of the major drawbacks associated with chemical weed control is the excessive accumulation of residues in the soil, a serious environmental concern (Bzour et al. 2018). Soil enzymes, phosphates, and microorganisms mediate organic matter decomposition and organic chemical degradation, promote organic phosphorus mineralization, and improve soil quality and health (Abbas et al. 2015).

Herbicide contamination of the soil ecosystem leads to imbalances in the equilibrium between soil chemistry and microbes involved in nutrient cycling. Soil-applied herbicides adsorb to clay minerals, soil organic matter, and organoclay complexes, enhancing their concentration in the topsoil and affecting crops grown in the subsequent season (El-Nahhal and Hamdona 2015). Herbicides inhibit extra- and intracellular protein-synthesizing enzymes, leading to imbalances in the production of plant growth regulators (Abbas et al. 2014). Baboo et al. (2013) stated that herbicides, butachlor, pyrazosulfuron, paraquat, and glyphosate, at recommended field doses, caused a transient impact on the microbial population and enzymatic activities in agricultural soils of Burla, India.

13.2.2 The Results of Climate Change on Weed Management in Crop Production

Over the past few decades, significant transformations have been induced by changing climate in the weed flora of agroecosystems, worldwide (Peters et al. 2014; Varanasi et al. 2016), allowing thermophile, late-emerging weeds, and some opportunistic weeds to become more abundant in some cropping systems (Peters et al. 2014). These climatic variables, particularly precipitation and temperature, have ruled the composition of arable weed species directly or indirectly by enforcing adaptations of altered agronomic practices (Fleming and Vanclay 2010). In order to persist in a local habitat, arable weed species have responded to the change in climatic conditions, leading towards shifts at distinctive scales (Fig. 13.4; see Peters et al. 2014 for details).

Being principal determinants of species distribution, changing climate variables may increase the distribution range of weed species or might allow non-potential weed to dominate weed abundance in cropping systems (see Ramesh et al. 2017). It is believed that perennial weed species are more likely to take advantage in terms of their abundance and survival with the rise in CO_2 due to stimulated tuber and rhizome growth (Chandrasena 2009). On the other hand, weeds with less phenotypic plasticity will experience population decline under frequent extreme weather events, drought or cold spells (Peters et al. 2014). In addition, lack of vegetation cover and bare ground due to limited growth of crops and pastures as the result of a decline in

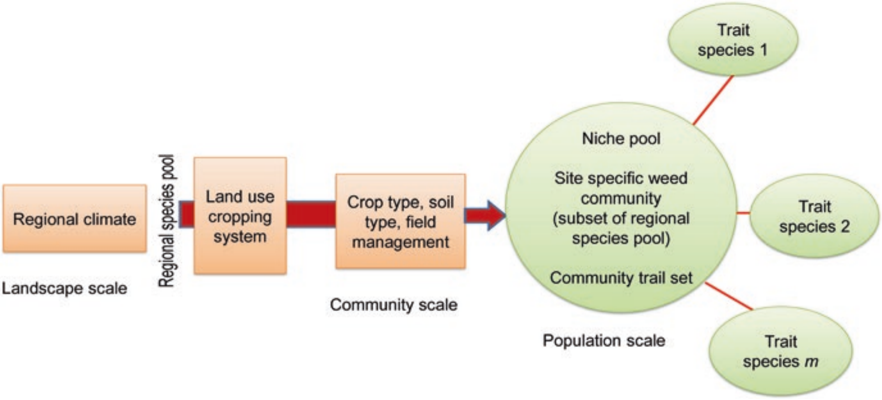

Fig. 13.4 Factors determining the species composition of the arable weed community in a particular area. (Adapted from Peters et al. 2014)

rainfall and prolonged drought will allow invasion of more resilient drought-tolerant weeds.

Due to the diverse genetic pool and great physiological diversity, weeds are more likely to show greater resilience and better adaptation to changes in climatic condition in competition with crops (Varanasi et al. 2016). However, weed with C_3 and C_4 photosynthetic pathways might exhibit a differential response to rising CO_2 and associated changes in global temperature and precipitation (Varanasi et al. 2016). In addition, reduced water availability, associated with unpredicted droughts, might alter the competitive balance between crops and some weeds, thus intensifying weed-crop competition, which will threaten to crop production (Ramesh et al. 2017). However, the interactive effect of this variable will affect weed-crop competition simultaneously or sequentially in a more complex and quite differential manner.

Despite affecting weed growth positively, changes in climatic conditions could influence the efficacy of many herbicides, making it a great challenge for farmers to manage weed effectively for sustainable crop production (Ziska 2016). Changes in environmental factors, such as CO_2 concentration, temperature, precipitation, light, and relative humidity, either alone or in combination, differentially affect the uptake, translocation, and activity of different herbicide chemistries (Varanasi et al. 2016). Morpho-physiological and anatomical changes in C_3 plants, such as a decrease in stomata number and conductance, increase in leaf thickness and starch accumulation on leaf surface under elevated CO_2, interfere with the foliar uptake of herbicides. Thus, stimulated vegetative growth to turn weeds into more noxious due to increased photosynthesis, which is expected to reduce herbicide efficacy due to dilution effect (Manea et al. 2011).

Unpredicted rainfall and drought spell also have an adverse effect on the persistence activity of soil-applied herbicides (Rodenburg et al. 2011). Prolonged drought spells to increase the volatilization of many herbicides thus reduce their rain-safe period available for herbicide application in the soil. For example, trifluralin and pendimethalin will be lost if remain on the soil surface for an extended period without rainfall (Curran 2016). Increased rainfall frequency and intensity promote leaching of many soil-applied herbicides, subsequently cause groundwater contamination, and lead towards additional weed pressure. Impact of these climatic changes on the efficacy or performance might be unpredictable among herbicides belonging from same MOA or within herbicide MOAs, thus making difficult to draw generalized assumptions for each MOA (see Ziska 2016; Varanasi et al. 2016).

The fate of pesticide, including herbicides, is more likely to be affected by changing climatic variables, such as temperature and precipitation (Lewan et al. 2009). These factors usually increase the volatilization of herbicide; thus, most volatile herbicides are incorporated into the soil to avoid losses (Table 13.1). Generally, an increase in temperature and soil moisture increased the degradation of herbicide due to chemical and microbial activity. In years following a drought, the carryover problems are always high, whereas if winter and spring receive mild to high rainfall following a previous dry summer, then the likelihood of herbicide carryover is low (Curran 2016).

Table 13.1 Soil and climatic conditions to increase the persistence of herbicide families

	Importance		
Herbicide families	Very important	Important	Less important
Clomazone	Low rainfall	High clay/organic matter	High or low soil pH
Dinitroanilines	Low rainfall	High clay/organic matter	High or low soil pH
Imidazolinones	Low rainfall	High clay/organic matter	Low soil pH
Pyridines	Low rainfall	High clay/organic matter	High or low soil pH
Sulfonylureas	High pH	High clay/organic matter	Low rainfall

Curran (2016)

13.2.3 Socio-economic Constraints: Inputs Unavailability to Farmer's Unawareness

Weed Dynamics and Uncertainty Current trends suggest that weed problems will worsen in the next 10–20 years, becoming an even more intractable barrier in efforts towards the sustainable intensification of agricultural production and the preservation of natural habitats (Neve et al. 2018). The uncertainties associated with the variations in demographic traits, weed impacts, and efficacy of control methods are highly relevant to weeds in agroecosystems. In general, some field held many weeds of a single species spread throughout the field in a diffuse, consistent pattern, whereas other fields show tight patches of multiple weed species. The difference among weed species in herbicide tolerance, life history, competitive ability, and other factors affects the relative abundance of individual species when management practices changes (Gibson et al. 2005).

For practical perspective, variations in seed production, dispersal, and persistence as well as weed recruitment and survival remain the sources of unpredictable variation in demographic traits under field conditions. Moreover, the uncertainty of occurrence of species and the uncertainty of their spread might result in irreversible crop losses. Recruitment of weeds from natural into agricultural ecosystems can be highly episodic due to possible associated risks, such as lack of effective control measures. It will take time for farmers to understand the sources of the diversity of weeds in their agricultural fields to develop successful long-term weed management approaches.

Herbicide Ban In recent years, there has been a call to limit the use of herbicides at national levels either through reducing application rates, restricting product ranges, or using alternative weed management strategies. In Europe, the proposed measure comprises banning specific herbicides (i.e. glyphosate) or introducing pesticide taxes (Finger et al. 2017). In most countries, farmers and researchers have expressed strong concerns with regard to potential negative impacts of the partial herbicide ban on the crop potential yield and food security (Wilson and Tisdell 2001; Foley et al. 2011). Herbicides are implicitly thought to improve crop yield by reducing weed biomass so reducing herbicide use would indirectly reduce the crop production (Gaba et al. 2016).

For example, ban on glyphosate use will stop farmers from growing GMHT crops, resulting in a significant effect on crop production as it will influence the production of major HT crops, such as cotton, soybean, corn (maize), rapeseed, and sugar beet (Table 13.2; Brookes et al. 2017). Globally, production of soybeans and rapeseed falls by 9.7 million tonnes and 0.45 million tonnes, respectively, but it will increase the production of oil palms and other oilseeds by 1.6 million tonnes and 2.3 million tonnes, respectively (Brookes et al. 2017). More likely, this ban on glyphosate use will increase the prices of rice, wheat, sugar crops, and other crops by 0.5%, worldwide. In short, cultivation of GMHT crops will no longer shock the cost of chemical, labour capital, and productivity of land, which will directly affect the costs of affected crops, will alter relative prices and will derive changes in the global economy (Brookes et al. 2017).

Table 13.2 Impact of the ban on glyphosate use on crop production

Data item	Crop	USA	EU	Brazil	Canada	South America	Others	World
Percent change	Rice	0.2	0.2	−0.1	0.5	−0.6	0.0	0.0
	Wheat	0.4	0.1	−0.4	0.6	−1.1	0.0	0.1
	Coarse grains	−2.3	0.1	−0.8	0.8	−1.6	0.2	−0.6
	Soybeans	−1.9	7.5	2.7	−5.6	−17.1	1.4	−3.7
	Palm fruit	6.8	3.1	3.6	9.8	4.8	0.5	0.7
	Rapeseed	−0.1	1.7	2.9	−5.6	1.6	0.0	−0.7
	Other oilseeds	3.3	2.3	2.7	2.8	2.5	1.1	1.4
	Sugar crops	0.0	0.0	−0.2	−0.6	0.0	0.0	−0.1
	Other crops	0.2	0.1	−0.5	0.4	−1.1	0.0	0.0
Change in 1000 metric tons	Rice	18.9	5.5	−18.1	0.0	−73.7	−2.9	−70.2
	Wheat	226.2	73.9	−19.9	143.2	−213.6	223.0	432.8
	Coarse grains	−7518.4	140.8	−482.3	170.3	−751.3	1258.9	−7182.0
	Soybeans	−1604.5	82.4	1988.3	−236.2	−10497.9	528.7	−9739.2
	Palm fruit	0.0	0.0	46.4	0.0	319.6	1272.1	1638.2
	Rapeseed	−0.6	330.0	1.5	−795.3	3.3	10.4	−450.6
	Other oilseeds	93.6	519.3	94.4	14.7	142.4	1484.0	2348.4
	Sugar crops	11.2	−56.5	−1812.1	−4.6	−45.3	−221.8	−2129.1
	Other crops	1605.8	498.1	−458.2	183.8	−2312.6	952.2	469.1

Brookes et al. (2017)

Weak Adoption of Integrated Weed Management (IWM) Practices Despite several decades of promotion, farmers have relatively weak adoption of integrated weed management (IWM) practices due to their complexity in contrast to the simplicity of regular pesticide application. Factors identified to act negatively upon the decision by farmers to invest in adopting IWM practices include the preference for returns in the short term over the long terms, expectations of new herbicide technology, and uncertainty as for whether weed problems will be prevented or delayed by adopting the practices. In addition, system's profitability and sustainability, heterogeneity of farm situations, time of benefits and costs, and social or institutional issues also influenced the adoption of new technology (Pannell et al. 2006).

Education programmes intended to promote IWM practices rely primarily on innovation diffusion methodology. This methodology has proven to be ineffective for the promotions regarding the adoption of prevention practices, which do not address farmers weed management problems in the short term. Though some of the members of the society lag behind for a considerable time before adopting the new practices and some will never change but this methodology has successfully been used to diffuse agricultural technologies to the farming communities (Rogers 2003). Instead, IWM tends to be a deterrent to adoption due to associated short-term complexities and learning costs (Swanton et al. 2008). In addition, the unintentional patronizing attitude of the researchers and extension educators towards influences the farmer's decision-making, contributing to a failure to adopt IWM practices.

Many IWM practices are perceived to be costly and unreliable relative to major selective herbicides; some of the extensively used practices do not offer high weed control efficacy (Llewellyn et al. 2004). In most cases, less attention has been paid to farmers' perceptions related to the efficacy and economic values of the IWM practices. The perceived value of the practice and subsequent adoption decisions are greatly influenced by the farmers' perception of various attributes of a practice.

Inappropriate Herbicide Use Herbicide application is considered a key factor in optimizing herbicide efficacy through maximizing herbicide deposition and minimizing spray drift (Kudsk 2017). It should be according to the three E's of spray application: economic, effective, and environment-friendly (Wolf 2009). Series of stages starting from the nozzle with droplet formation, travelling to plant surfaces, impacting the leaf surface, the formation of a deposit, uptake by the plant, and other biological responses are involved in the spraying process, which influences the herbicide use and performance (Ebert and Downer 2008). Spray performance can be affected if a change occurs at any stage interacts with the other application factors and subsequent stages (Creech et al. 2015).

Most common mistake associated with the inappropriate use of herbicide is the incorrect identification of weeds and using inappropriate herbicide product. Similarly, incorrect rate and/or water volume can frequently result in poor weed control and crop damage, causing a waste of money and time. Herbicide application below label rate or when the plant is stressed also result in application failure. In addition, if the chemical is not stored under the recommended conditions or maybe too old, it might also influences herbicide efficacy.

Farmers' Perceptions and Technical Unawareness Due to diversity and dispersal, the issues facing farmer communities with weed management are complex and varied. In most cases, farmers' perception "it would cause significant losses" or not considering it the main priority prevent them from controlling the overwhelming infestation, i.e. lack of motivation to spend money on controlling weeds. In other words, not everyone is aware of their responsibilities related to weed control, which resulted in continual seed rain from uncontrolled infestations. Some of the farmers are not fully aware of the consequences of not managing weed populations or may not have the knowledge or equipment to properly control weeds.

In the developing countries, lack of awareness in farmers and government organization is the major constraint limiting the implementation of efficient weed management causing significant losses caused by weeds and the methods to control them. Lack of information from agricultural extension services about weeds and their problems, ineffective links between agricultural research units and extension services and inappropriate or limited research on weed management are the possible reasons for the lack of technical awareness. In most of the countries, there is no adequate agricultural weed research programme due to lack of funds or lack proper research activities and are too weak, if exist, which results in the deficiency of well-trained weed scientists.

13.3 Weed Management Options for Healthy Crop Production

13.3.1 Planning Weed Control

The outcomes of weed management in cropping systems can substantially be improved by approaching the task with an efficient plan. A well-thought-out strategic plan can make weed management tasks much easier and more achievable and can result in significant savings of resources (time, effort, and money). Therefore, weed strategies must be built on a solid foundation of good agronomy in order to be effective enough to contribute to profitable and sustainable cropping systems. In addition, it should avoid heavy reliance on one or two control methods, especially herbicide with same MOA to avoid selection pressure. Overall steps involved in the development of the strategic plan are (see Fig. 13.5):

(i) Developing an effective plan is to be familiar with the weed species present and another management issue in the fields. Many resources are available to assist you in understanding how to identify and understand the behaviour of the weed species.

Fig. 13.5 The five-step process of on-farm weed management plan

(ii) The range of skills that are useful to define management zones, describing the current extent of weeds and identifying key land management practices, helps in preparing a property-wide weed management plan.
(iii) Prioritize the weed management options (i.e. herbicide, cultural, etc.) to ensure a high impact within the available resources.
(iv) Implement the plan taking into account the seasonal and weather patterns, weed emergence, potential impact, and increased efficacy.
(v) Monitor and review the results to realize at the outset that the plant will need to change as you progress, and these changes are based on the evidence gained whilst monitoring your results.

13.3.2 Preventing Weed Introduction

Globalization and World Trade Organization (WTO) regime resulted in a free flow of food grains another commodity across the borders that enhance the possibilities of movement of weed seeds along with grains to other countries (Duary 2014). Human-induced mechanisms seem to be more important in the rapid spread of weed seeds than the natural mechanisms (i.e. water, wind, or animals). Globally, human-induced mechanisms are now considered to be the main reason for new weed incursions (Adkins 2013). Survival of any weed species depends on the production of sufficient numbers of viable seeds, and therefore, prevention of entry of weeds seed is the key to eliminate future weed problems (Duary 2014).

Preventing weed establishment is the most effective way to minimize weed problems in crop fields (GRDC 2018). Farmers need to implement strategies to reduce and avoid the unnecessary introduction of weeds and their spread in order to reduce the likelihood of new weed species and also the risks of importing herbicide-resistant weeds. Following approaches will be helpful in preventing weed seed introduction:

- Preventing introduction through contaminated seed and feed through sowing weed-free seeds. If possible, seed lot sample should be analysed for both weed seed contamination and germination, the herbicide resistance status of weeds present on the source farm should be determined, and seeds should be graded to reduce weed.
- Restricting the movement of machinery to prevent weed seed introduction from one field to another field. Prior to entry on the farm, ensure machinery and vehicles are cleaned or are cleaned at a specially designed wash station.
- Avoid livestock grazing in weed-infested areas during flowering and seeding time period. If grazed, and then their movement should be restricted for 10 to 14 days before moving to weed-free ranges.
- Use well-decomposed farmyard manure/compost, otherwise many seeds of annual weeds will germinate and aggravate the weed problem.
- Cleaning the wastelands, public places, and irrigation channels.
- Avoid soil transplant from an area highly infested with weeds.
- Use appropriate weed control measures in the nurseries of rice and vegetables.
- Inspect farm on a frequent bases for any strange looking weed, and such patches should be destroyed by digging deep or by using suitable herbicides.
- Isolation of an area where a serious weed has established and prevented further movement of weeds into non-infested areas.
- Legal and quarantine measures should be followed whilst importing crop seeds, food grains, seedlings, etc.

13.3.3 Stopping Weed Seed Set

As an important weed management principle, prevention of weed seed production can dramatically reduce the number of seeds present in an area (GRDC 2018). Research has reported many cases in which a single weed plant can produce more than one million seed, which is eventually deposited either onto the soil adjacent to parent plant or transported to another area (Norris 2007). Therefore, preventing weed seed production provides an opportunity to control weed seed in the pasture, late fallow, late stubble, and in-crop phases. Techniques such as herbicide-topping, pasture spray-topping, crop desiccation and windrowing, wiper technology, grazing, silage and haymaking, manuring, and mulching have been observed to prevent weed seed set. Following techniques have been reported to stop weed seed setting in cropping systems:

- Spraying weeds at the reproductive stage with post-emergent selective herbicides, a technique is known *as* “selective spray-topping”, prevent seed set of certain weed, thus reducing additions to the weed seedbank with minimal impact on the crop (Cook et al. 2014). This strategy can also be used to control "escapes" as a late post-emergent salvage treatment or for managing herbicide resistance (see Beckie 2006).

- Crop topping using nonselective herbicide like paraquat or glyphosate at flowering or early grain fill stage of weed, minimizing the production of viable weed seed and also reduced the crop yield losses (see Steadman et al. 2006). Efficacy of this technique in reducing weed seed set can be increased by using nonselective herbicide in conjunction with selective herbicides.
- Control of upright weeds by using herbicide wiper technology for the application of translocated herbicides on their foliage and stems above the height of surrounding vegetation. This technique ensures herbicide application with minimal damage to desired crops as well as saves herbicide up to 80% as compared to broadcast spraying (see Moyo et al. 2016).
- Strategic termination of crop growth using knockdown herbicides prevents seed set in weeds. This technique broadens the weed management tool in pulses and strengthens their role in crop sequences of southern farming systems (see Armstrong et al. 2015).
- Collection and/or destruction of weed seeds at harvest weed seed control (HWSC) system to prevent the spread of weed seeds across the fields and reduces seedbank inputs. This system includes narrow windrow burning, chaff lining, chaff tramlining, chaff carts, and Harrington Seed Destructor (HSD) to target weed species with a potential weakness of retaining a large portion of their seed at maturity (Walsh et al. 2013). This new method has been used to reduce the impact of HR weeds on Australian grain production.
- Incorporation of leguminous green manure suppresses weed growth through high biomass production, which ultimately results in preventing weed seed setting and dispersal (Koehler-Cole et al. 2017). Incorporation of brown manure crop into the rotation and employing the double-knock herbicide technique prior to weed seed set have bolstered in the battle against HR weeds through reducing seed viability.

13.3.4 Depleting Weed Seed Bank Reserves

Changes in crop rotations and weed management greatly influence the weed population in cropping systems; limited studies have characterized the effect of these crop management practices on weed seedbank dynamics (Kleemann et al. 2016). Use of diverse crop rotations, competitive crops, higher crop seed rates, specific timing and placement of fertilizer, crop mulches, and cover crops can effectively manage weed seedbank dynamics, especially when used in conjunction with limited but targeted use of herbicides (Ball 1992). Weed populations resulting from the seedbank comprised of many species with few dominant species. Therefore, effective management of these dominant weed species depends complete on the preventing weed seed production and exhaustion of the seedbank, influenced by the

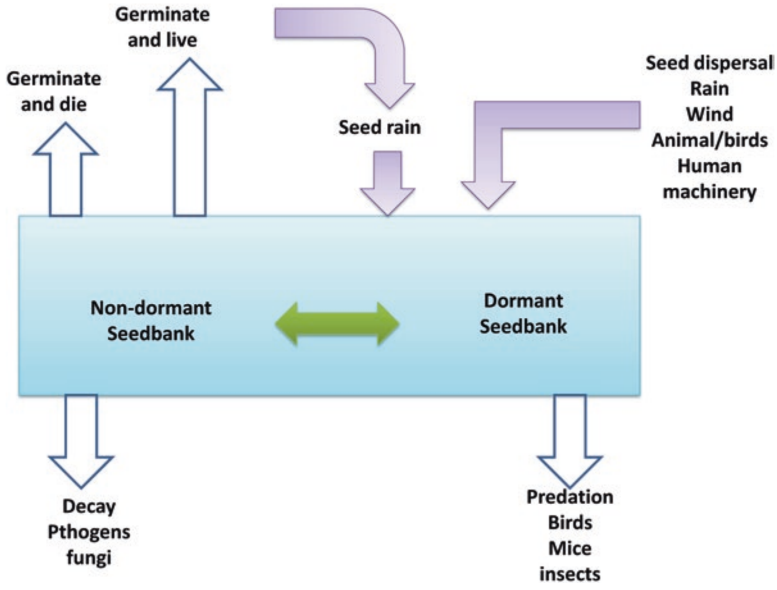

Fig. 13.6 The fate of weed seeds, showing inputs of seedbank (purple arrows) and losses (white arrows). (Adapted from Menalled and Schonbeck 2010 with permission)

persistence of weed seeds in the soil (Fig. 13.6). Techniques to deplete weed seedbank in soil involve:

- Stimulating weed germination and then destroying weeds deplete weed seedbank of certain species for a number of years. Shallow cultivation and delayed sowing are some techniques which change the moisture, temperature, or the amount of light to maximize weed emergence.
- Preventing new weed incursions between the fields by using clean seed and farm equipment.
- Inversion ploughing helps in placing weed seeds on or just below the soil surface deep into the depth from which seeds cannot germinate.
- Seed predation through pathogens increases the mortality rates of weed seeds, particularly in no-till systems in which weed seeds are left on the soil surface (see Li and Kremer 2006).
- Preventing harvest losses, particularly in the case of HT crops, will prevent volunteer crops to emerge as weed problems in future crops in subsequent years.
- Chaff collection will potentially reduce the weed seed return and possible will reduce the need for weed control.
- Clipping tall weed above crop canopy or terminating crop early, as green manure, will prevent weeds from seed production and returning it to weed seedbank.
- Manipulation of crop management practices such as narrow row spacing, competitive crop cultivars, and increased plant density could lower the weed seed production and ultimately soil seedbank (see Dyer 1995).

- Techniques like herbicide application, in-crop tillage, and the use of perennial or annual forages which are harvested prior to seed maturation will be effective strategies to stop weed seed set.
- Incorporation of succulent legumes or other cover crops stimulates weed seed germination by increasing soil nitrate (N) levels or promotes weed seed or seedling decay as a result of soil microbial organisms on the green manure residues (Kumari et al. 2018).

Depending upon the weed species, seedbank could be exhausted within a few years of effective weed control achieved consistently in the crop sequence (Chauhan et al. 2006). Despite the importance of numerous economically important weed species, limited information is available on their long-term seedbank dynamics in cropping systems. This information is more likely to contribute towards the development of cropping systems and weed management to achieve high productivity as well as to maintain weed populations at low levels (Kleemann et al. 2016).

13.3.5 Limiting Weed Seed Dispersal

Depending upon the dispersal mechanism, spatial distribution resulting from seed dispersal varies greatly within the weed species, ranging from a few centimetres to hundreds of kilometres (Benvenuti 2007). Reducing weed seed dispersal is extremely difficult as most of the weed species possess specific characteristics that allow their seeds and other reproductive parts to be easily transported over long distances (GRDC 2018). Techniques mentioned in 3.1 also helps in minimizing the weed seed dispersal within the fields and across the regions.

- Improved knowledge of weed biology to acquire an in-depth awareness of the factor involved in an agroecosystem population dynamics to achieve a trade-off between agricultural productivity and environmental protection (Benvenuti 2007).
- Investigation of the biotic, abiotic, or anthropic weed seed dispersal mechanism in integration with weed prevention strategies will help in developing a valid agronomic tool for long-term management of weed species in the agroecosystems (Benvenuti 2007).
- Refraining from driving vehicles and machinery through weed-infested areas during the seed production period.
- Reducing tillage practices, as in conservation systems, can restrict the weed seed spread both within and across the field.
- Washing the undercarriage of vehicles after driving through the weed-infested area.
- Using certified weed-free feed.
- Grinding and pelleting forage or grains.

13.3.6 Maximizing Crop Competitiveness

Over the time period, development of herbicide-resistant weed species and weed populations shifts; researchers have been highlighting the significance of cultural strategies for the management of weed species in different cropping systems (Peerzada et al. 2017). In the recent years, manipulation of cultural practices, such as altered row spacing, competitive crop cultivars, etc., is gaining rapid attention in many countries once again as a possible strategy to suppress weed competitiveness. The use of crop management practices has been reported to have the capability to suppress weed and their integration aid in the development of sustainable weed management strategy (Mishra et al. 2015). Crop competitiveness can be maximized through:

- Selection of crop cultivars with specific growth characteristics, such as rapid emergence, fast biomass accumulation, leaf characteristics, height, canopy structure, as well as allelopathic potential, can significantly affect the growth and population densities of weeds in cropping systems (Buhler 2002; Bhadoria 2011).
- Reduced row spacing and altered row orientation parallel to the sun direction minimizes the photosynthetic active radiation (PAR) availability to the weed species, thus reducing the weed germination, establishment, growth, and ultimately the seed production due to faster canopy closure (Scott et al. 2013).
- High seed rate or increased planting densities have proven to be an effective approach to increase crop competitiveness against weed and also facilitate rapid canopy closure, which helps in suppressing the weed emergence and growth effectively (Gibson et al. 2002).
- The use of different crop sequences creates varying patterns of resources competition, allelopathic interactions, soil disturbance, and mechanical damages that create an inhospitable and unstable environment, preventing the proliferation of particular weed species (Liebman and Dyck 1993). These temporal and spatial diversification strategies have been marked to reduce the weed population densities and biomass production in the published literature. Thus, proper understanding related to these dynamics is required for the manipulation of cropping systems to improve weed management.
- Better crop nutrient and irrigation management by manipulating fertilizer placement and irrigation timing can increase the nutrient and water availability to the crops instead of the weeds (Blackshaw et al. 2003).

Under the aforesaid circumstances, adoption of potential alternative ecological approaches like manipulated crop management practices could be more viable and sustainable strategies for suppressing weeds on large scale. With the increasing incidences of herbicide-resistant weeds, suppressing weed growth through improving crop competition will more likely impact the weed seed biology and thus can help in reducing the seed viability and might influence the seed dormancy as well in the next generations. Therefore, farmers need to adopt these strategies to increase crop competitiveness as a component of integrated weed management systems (Peerzada et al. 2017). Further researches on quantifying competitive effect and providing rules of thumb will facilitate farmers' decision for weed management, particularly in herbicide resistance scenario (Lemerle et al. 2016).

13.3.7 Optimizing Herbicide Use and Performance

Herbicide efficacy can greatly depend upon a number of factors, including plant physiology, environmental conditions, chemical properties of herbicides, and edaphic conditions (Cieslik et al. 2013; Matzenbacher et al. 2014). For optimization of herbicide, three-step-based improved decision-making is prerequisite: prevention, the timing of weed control and herbicide choice, and rate (Kudsk 2007). Under field condition, successful use of herbicide depends on the herbicide selection for the weed spectrum, correct application timing, rate, and method. Reliability of chemical weed control can be improved by:

- Understanding herbicide classification helps farmers, advisors, and researchers to choose herbicides best suited to combat specific weed problems in specific crops (Shaner and Leonard 2001). Herbicide classification will increase farmer's awareness of herbicide mode of action and provide more accurate recommendations for resistance management and will make it easier to keep records on which herbicide mode of actions are being used on a particular field from year to year.
- Identifying weed species correctly to prevent wastage of herbicide applied for controlling weed species and to prevent unnecessary chemical entering into the environment, a cash outlay for no return and a crop full of competitive weeds. In case of highly competent, persistent, and difficult-to-control weed species, possessing greater threat to compete with crop and reduce yield, correct identification ensures herbicides to be able to effectively control and to decide on an appropriate response.
- Maximizing crop competition through using cultural practices, such as competitive crops and cultivar, high seed rates, and optimum agronomic practices, and disease or insect control measures to effectively improve chemical weed management programmes in cropping systems (Christensen 1994).
- Diversifying crops to reduce the weed populations, directly or indirectly, through entailing the weed-competitive crop species and/or species with varied growth cycles and phonologies, enables herbicide diversity and enforces different sowing and harvesting dates which exert different selection pressures on weed communities (Beckie and Harker 2017).
- Rotating herbicide and/or using herbicide mixtures with different MOAs to avoid the selection of weeds with the ability to detoxify herbicide or to mitigate the oxidative stress (Waggoner et al. 2011; Camargo et al. 2012). This strategy safeguards the evolution of herbicide resistance (Anwar et al. 2012) and reduces the chances of ecological shifts in weed populations (Murphy and Lemerle 2006).

- Understanding the effect of weather conditions before and after herbicide application on the herbicide performance is essential to realize the influence of climate change on the herbicide efficacy (Bailey 2004).
- Considering temperature, humidity, and high irradiance during the herbicide application and their influence on the effectiveness of numerous herbicide groups. Consideration related to choosing the best application timing would be helpful in optimizing the herbicide efficacy, particularly for post-emergent herbicides (Cieslik et al. 2013; de Queiroz et al. 2013).
- Preventing spray drift by maintaining due care and attention at all times when spraying herbicide and also by knowing how to apply the product carefully. Violation of a specific user instruction on the label and incorrectly assessing the prevailing conditions at the time of spraying (wind direction and speed, etc.) is a common example of herbicide misuse, causing herbicide drift.

13.3.8 Strengthening Farmer's Knowledge

To get benefits from the technological innovation in weed management, institutes and research organizations need to create a capacity building of the farming community to mitigate the menace caused by ever-adapting dynamic weeds under the enormous challenges to crop production, including climate change, soil degradation, and resources scarcity. Thus, updating farmers' knowledge with timely, relevant, accurate technical information is an urgent need (see Adusumilli et al. 2014). In developing countries, the following ways need to be followed to strengthen farmer's knowledge and ability in managing weed effectively as:

- Farmer's need-based extension efforts, counselling assistance, high-calibre extension agents, proper information dissemination, and technical farming experts are the essential ingredients for effective extension (Adusumilli, et al. 2014). Effective extension activities ensure farmers are equipped with the knowledge of improved weed management technologies for optimized long-term agricultural productivity.
- Better linkage between farmers and agricultural researcher in order to couple the scientist subject expertise with farmers' location-specific experience. Farmer's participatory process in the technology development process will strengthen their knowledge and will increase the adoption rate of existing and new technologies.
- Farmers should be involved in the development of technologies, which will increase the chances of a farmer's adoption; this will strengthen their knowledge.
- Training approaches, like farmer field schools (FFS), involving active farmers' participation to share knowledge with other farmers and learning new concepts through the experiential learning cycle (i.e. learning from practical experience).
- Developing partnership between the public, private, and global scientific research organizations to achieve dissemination of new technologies to the end-users.

Partnerships with global institute led towards faster progress as well as changes behavioural/attitude among bureaucrats and policymakers.
- Due to women actively involved in both Asia and Africa, focus on gender during technology development and extension will greatly enhance the efficiency and research impact; also it reduces gender inequalities in access to technologies.
- Involvement of private sectors will ensure high production through effective weed control by ensuring the timely availability of different components of weed management, such as herbicide, competitive cultivars, mechanical implements, and other inputs.
- Advance information dissemination systems and existing communication systems have been effectively used for transferring technological information. Weed management technologies can be passed effectively to the farming communities, facilitated by the Internet, mobile phones, and other communication networks (Adusumilli et al. 2014).

13.3.9 Promoting IWM Practices

Redesigning crop systems in order to reduce the weed population's densities and interference capacity would be one step forward in proactively reducing the need for herbicides (Peerzada et al. 2017). Cropping systems employing IWM approaches produce competitive yields and realize profit margins on a long-term basis, which are comparable to that system that relies chiefly on herbicides (Liebman et al. 2008; Anderson 2015). For promoting IWM knowledge, the following researchers highlighted some important keys to be followed (Nord et al. 2011; Mortensen et al. 2012), such as:

- Integration of IWM complexities into user-friendly decision support systems to satisfy farmers' demands for simple, effective, and flexible methods of weed management with respect to increasing farm sizes.
- Estimation of risk of weed management methods used alone or in combination through statistical approaches, such as collective risk theory (see Cummins 1991) and/or examining crop yield variability over time, for the adoption and long-term viability of IWM strategies.
- Region-specific information on crop and weed ecology for the selection of planting date to optimize the trade-off between weed control and the shorter growing season.
- Locally adapted and ongoing public research, combined with effective extension education programmes to address current and future weed management challenges.
- Concrete policy steps to ensure that the new HT crops will be adopted as only one component of fully IWM systems to ensure negative consequences for food production and the environment.
- Improved farmers education programmes implemented through industry-university-government collaborations and environmental support payments, con-

necting IWM to broader environmental goals, such as on-farm efficiency, soil quality management, and agro-diversity conservation.
- Implementation of spatially explicit, area-wide management plants to reduce selection pressure at the landscape or regional scale, mandating carefully the defined herbicide rotation patterns or setting upper limits on the sale of specific herbicide active ingredient or seeds of HT variety within an agricultural country.

13.3.10 Best Management Practices (BMP) for HT Crops

The adoption of HT crops and their associated agronomic practices facilitate the achievement of effective weed management and overcome increasing HR weed problems and other environmental concerns associated with agricultural intensification (Lamichhane et al. 2017). Sustainable practices and measures should be integrated with diversified herbicide as a key tactic for weed control as weed control without herbicide use are presently not conceivable in intensive farming systems. Such practices might be costly for farmers on a short-term basis; they will be beneficial in the longer term, especially if appropriate policies and incentives are put in place. For the transition towards IWM with HT crops, five action plans have been recommended (see Lamichhane et al. 2017);

- Education programmes to maintain and improve knowledge of weed and their management.
- Revision of current stewardship programmes.
- Integration of socio-economic studies to understand and change farmers' attitude and behaviour.
- Development of adequate public policy.
- Regulatory revisions.

13.3.11 Reducing the Evolution of Herbicide-Resistant Weeds and Their Management

Herbicide resistance is threatening the crop production, and farmer's response varies across different countries, which are largely reactive rather than proactive (Llewellyn and Allen 2006; Wilson et al. 2008; Norsworthy et al. 2012). In developed countries, farmers are more focused on managing resistance through non-chemical methods and/or looking for alternative herbicide options due to the loss of many sites of action. To some extent, a similar situation exists in developing countries or countries with less number of herbicide resistance reports. Under such circumstances, diversification of weed control methods seems to be the only practical solution for managing herbicide resistance in weeds. Norsworthy et al. (2012) suggested 12 best management practices (BMPs) to be employed in herbicide-resistant management programmes, which consider all cultural, mechanical, and herbicide options available for effective weed control:

(i) Understanding weed biology to devise a strategy, targeting the life stage most sensitive to management.
(ii) Diversified weed management approaches focusing on reduced weed seed production and minimized seedbank reserve, which adds to short-term management costs as compared to long-term costs associated with future herbicide resistance management.
(iii) Keeping field weed-free as possible sing residual herbicide before or at planting, especially in conservation tillage systems.
(iv) Plant weed-free crop seeds prevent the spread of herbicide resistance into new areas.
(v) Routine weed scouting of the fields.
(vi) Use of multiple herbicide modes of actions (MOAs).
(vii) Herbicide application on the labelled rate at the recommended weed size.
(viii) Suppress weed growth through increased crop competitiveness.
(ix) Use of appropriate mechanical and biological management practices.
(x) Prevent field-to-field and within-field dispersal of weed seeds and vegetative propagules.
(xi) Management weed seed at harvest and after harvest to deplete weed seedbank.
(xii) Prevent an influx of weeds into the field by management field borders.

Minimizing the continuous use of herbicide with the same mode of action through rotations and combination of products could be the key step in herbicide resistance management. In addition, integration of chemical weed control with effective cultural, mechanical, and physical options could possibly delay the onset of resistance. Furthermore, selection of nozzle size, carrier volume, and spray angle or orientation will do the right job the first time and will avoid unnecessary repeat applications. Dissemination of information related to herbicide group classification to the farmers and farm advisors to understand will make it easier for them to understand which herbicide shares the same mode of action. Most of the herbicide labels now indicate the group number and active ingredients; thus alternation or sequencing products with different MOAs or limiting the total number of application per season could be included in resistance management programmes.

13.4 Recommendations

Despite the development of broad-spectrum post-emergent herbicides, weeds continued their journey as a big constraint towards the adaptation of conversation agriculture, requiring more effective and economically viable integrated technologies in diverse cropping systems. Therefore, the development of more resilient weed management is prerequisite under the highly diverse emerging agricultural scenarios for an economically sustainable future agricultural management system.

- Responses of most of the economically damaging weed species towards changing climate have been rarely investigated and, consequently, are not well understood. It necessitates the proper understanding of the weeds, their biology, and population shifts under changing crop management practices and the predicted climate change.
- Early detection, combined with an understanding of the ecology of the weed, would play a vital role in the prevention and successful elimination of the invasive weed species from the agroecosystems.
- Prevention of seed production during the fallow period is potentially a low cost and valuable approach in preventing the buildup of the seedbank or perennial vegetative structure.
- Farmer’s knowledge of herbicide mode of action will deliver a practical approach for preventing, delaying, and managing herbicide resistance.
- Broad understanding related to these factors helps farmers in minimizing the negative impact of herbicide on agroecosystem and will increase herbicide performance.
- Collaborative approaches among farmers to optimize the extension of improved weed technologies give them an opportunity to modify agricultural technologies and add value to them.
- Creating awareness regarding modern technologies, balanced herbicide doses, and land preparation through farmer training and workshops are needed to benefit agriculture in developing countries.
- Studies on integrated approaches including site-specific weed management using precise herbicide delivery techniques, controlled release formulation of herbicides, and weed-competitive crop cultivars with allopathic potentials would be acceptable in future.
- Information on herbicide-environmental risk assessment, particularly related to IWM strategies and BMP in HT crops, will help in better understanding and adoption of these strategies.

13.5 Conclusion

The significance of integrated weed management as an integral component of crop production cannot be neglected if the sustainable and economic development of agricultural systems in changing agroclimatic scenarios is to be achieved. Under such changing trends, increased concerns of herbicide failure and weed population shift in arable lands pressurized weed scientists to develop environmentally sustainable and economically viable options for controlling weeds in crop production systems. Strategies for minimizing weed spread, reducing weed seed production, maximizing crop resources use, improving herbicide efficacy, and depleting weed seedbank reserves could potentially be helpful approaches for better weed management under these systems. Farmer's awareness regarding maximizing crop competitiveness through suppressing weed growth will reduce herbicide rates for controlling difficult to control weed species. Furthermore, their understanding related to biology and ecology has largely been ignored, which need encouragement as such studies contribute significantly to developing integrated weed management programmes. Therefore, development of best management practices manuals and dissemination of information regarding weed identification, herbicide selection, and possible control options using the latest information technologies would be helpful in developing sustainable weed management programmes.

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Integrated Weed Management for Agronomic Crops

14

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Abstract

Weeds are one of the significant constraints for crop production worldwide. Actually weeds compete with crops for input resources like; nutrients, water, light and space leading to drastic reduction in yields. Furthermore, weeds act as inhabitants for insect pests and disease causing organisms. Weed managemnt is an integral part part crop production to reduce losses. Integrated weed management (IWM) is a useful and successful strategy for controlling weeds and improving efficiency of weed control techniques.

Keywords

Weed · Crop · Competition · Management · Cultural · Chemical

14.1 Introduction

Feeding the world population in the future will need more food, and there are two options for getting more food, i.e., horizontal increase in the area under crops or vertical increase by increasing the yield of the crops. In addition, the agricultural intensification is also gaining popularity among the masses, but this concept of intensification causes concern about essential resources like water, land, soil, the overall biodiversity, and the ecosystem services (Friedrich et al. 2009).

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Agriculture contributes significantly to the economic growth of Pakistan by providing food, supplying raw material to industries, earning foreign exchange, and employing a large portion of the population (Afzal and Ahmad 2009). Cereals such as wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and maize (*Zea mays* L.) are the main food crops and major foundations for earning foreign exchange (Afzal and Ahmad 2009). Pakistan is known for its "basmati rice" as a primary source of aromatic fine rice, the country's major agricultural export product (Akram 2009). Moreover, Pakistan is the fifth largest producer and the third largest exporter of raw cotton (*Gossypium hirsutum* L.) in the world, providing a livelihood to more than 50 million people (Morris 1989). Sugarcane (*Saccharum officinarum* L.) is widely cultivated in Sindh, Punjab, and Khyber Pakhtunkhwa provinces and is thought to be the largest source of government revenue in the form of taxes and duties (Nazir et al. 2013). These major agronomic crops, including legumes, account for 5.3% of GDP. Therefore, realizing maximum yield potential of these crops is important for the uninterrupted growth and development of the agriculture sector, as well as for the capacity utilization and growth of industries dependent on agriculture for raw materials (Nosheen and Iqbal 2008). Therefore being an agricultural country, the sustainability of agriculture and growth will ultimately affect the economic status of the country.

Agronomic crops are considered as the most widely cultivated crops all over the world. These crops contribute to the world's economy and serve as major food for human and livestock. In addition, the industrials uses are innumerable. The agronomic crops face insects, diseases, and weeds. All these constraints decrease the yield of agronomic crops in a variety of ways, depending on the environment and the cultural practices used in a region. Scientists are involved in finding the solutions for all these constraints. Among these constraints the weed infestation is common in the world as weeds cause great yield losses. Thus not only the quantitative reduction but the qualitative reduction is common in many crops. Therefore, management of weeds is important so that high yield and better quality agronomic crops can be secured. In the absence of these management strategies, several negative effects such as crop failure and increasing cost of production and negative effects on the environment can be faced. Similarly, single type of management practice cannot meet to cope with the problem, because all available methods have their demerits and thus may not be acceptable to the farmers. Therefore, it is necessary to combine different weed management practices to reduce the harmful effects on the ecosystems. This chapter provides an overview regarding different weed management practices.

Weeds are one of the most important biological constraints in agricultural production systems. They negatively affect crop growth and yield by competing with crops for nutrient, sunlight, space, and water (Chauhan 2012). Those plants which grow where it is not desirable are called weeds. Thus any unwanted plants are considered as weeds that divert human efforts. For example, a maize plant grown in the wheat field is considered as weed because it effects the growth and development of the main crop (wheat). Similarly, any flowering plant grown in the landscape, lawns, pastures, ranges, and gardens is also considered as weed if it interferes with human intentions. So, weeds are unwanted and undesirable plants which grow in a place where it is not required. A plant may be weed in place, but it may be a valuable plant at other places. Such *Brassica* plant growing in the field of wheat crop is considered as weed while the same plant grown as a crop. Many types of the weed that infest annual crops are those which are suit to settle in frequently disturbed habitats. The distribution and composition of weed species are strongly influenced by biological and environmental factors, which play a role in the determination of the habitat type (Radosevich et al. 1997). Biological factors include insects, plant pathogens, crop type, crop-weed interaction, and other biotas of that specific area. Similarly, temperature, precipitation pattern, quality and quantity of light, soil type, pH, and moisture content are the important environmental factors. As species change, weed composition and distribution are further affected by human efforts to control weeds in a crop (Vencill et al. 2012). That is why it is stated that changing the habitat will change the vegetation.

14.2 Importance of Crop-Weed Competition Studies

Weeds are undesirable plants which interfere in the field with crop plants. It competes for nutrients, water, and other resources with the crops. Usually weeds compete with the crop plants for belowground and aboveground resources. It is considered that weeds are more aggressive than the field crop due to its natural evaluation. Usually the nutrient- and moisture-absorbing capacities and capabilities of the weeds are greater than the crop plants. Due to poor competitive ability of the crop plants, weeds grow more strongly than the crop plants and hence cause yield losses. Annual economic losses of more than $100 billion US dollars occurred due to weeds worldwide (Appleby et al. 2000). Similarly, it is also reported that about $25 billion has been spend on the sale of herbicides for the control of these weeds (Agrow 2003). Keeping in view these losses, it is essential to understand the interaction between weeds and crops. In developing countries like Pakistan, 100% losses have been recorded due to presence of weeds (Fig. 14.1). In addition to direct yield losses, the presence of weeds makes the harvesting complicated. Therefore the comprehensive understanding of biology and ecology of weeds can greatly help to avoid the yield losses (Fig. 14.2). Such understanding can help to develop sustainable weed management practices in cost-effective manners. It provides information about different components of the cropping pattern. It includes seed rate of the crops, intercropping, crop rotation, fertilizer application, dose and row spacing, etc. These components can influence the competitive ability of the crops against weeds. Some of the related attributes which reduce weed competition and cost related to weed control are rate of leaf appearance, crop establishment, and canopy spread. All of these are related to sustainable and competitive cropping system (Swanton et al. 2015).

Fig. 14.1 100% yield losses due to the presence of weeds

Fig. 14.2 Weed infestation

14.3 Factors Affecting Crop-Weed Competition

There are three major components of the weed competition on the basis of which crop yield is affected. The most important one is the weed emergence time in relation to the crop (Kropff and Spitters 1991). Those weeds which emerge before the emergence of crop are considered the most competitive weeds, and as a result, maximum yield losses occurred in crop plant. On the other hand, those weeds which emerge after crop emergence are considered less competitive in relation to yield losses in crops but still considered challenging if they affect harvesting of the crop and reduce its quality (Swanton et al. 2015). Second important variable that effect crop yield is the seedling density of the weed. Duration of interference and weed density are interrelated, and weed control depends upon weed emergence relative to the crop (Dunan et al. 1995). The third important variable is the species of weed. It may be different in competitive ability which is based on various traits such as plant height, rapid leaf area development, and high-density rooting systems. For the determination of competitive ability of a weed species, its morphological features, life cycles, and reproductive strategies must be considered (Swanton et al. 2015).

14.4 A Summary of Weed Science Practices and Concepts

Weed population have been evolved with the passage of time in response to control practices that are imposed on them. In the last five decades, one of the most widespread methods for the control of weeds on commercial basis is the use of synthetic herbicides. In response to these herbicides' application on a large scale, weeds develop resistance against these herbicides which is the main issue in weed management since 1970 (Timmons 1970). This resistance is due to the selection pressure which is caused by the repeated use of the herbicide having same mode of action in the conventional crop cultivars. However, it does not mean that it suddenly change the plant genetically by causing mutation. But herbicides that select for a plant have some level of genetic resistance against the mechanism of action. Therefore, cultivars have been developed to resist against the treatment of a herbicide that otherwise not tolerated by the conventional cultivars. However, all the herbicide resistance crops are not transgenic. But the induction of transgenic plants that are herbicide resistance significantly changed the weed management strategies. These transgenic plants are now using worldwide (Price et al. 2011). Examples of these crops are canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.), and corn (*Zea mays* L.) which are dominant in the production than local cultivars. On the other hand, such development of herbicide-resistant varieties can cause the creation of super weeds. These super weeds will become a major threat to agroecosystem and sustainability. Therefore judicious use of the weed control methods are more environment friendly and sustainable as compared to reliance on a single method of weed control.

14.5 Common Categories and Specific Methods of Weed Control

Weeds are unwanted and undesirable plants that grow out of place and interfere with human activities. It strongly affects crop yield. So, there are different strategies which are used to control its population so as to reduce the losses that are caused by the associated weeds. Some of these strategies include preventive weed control, mechanical method of weed control, cultural control, biological control, and chemical control.

14.6 Management Strategies

14.6.1 Preventive Measures

Preventive method of weed control is one of the basic practices. It is the safest method for weed control in all the countries of the world. Different approaches are used to prevent the introduction of weed in the area where it is not present before, and if a weed is introduced to a new area, its spreading has to be restricted. Different laws regulating purity of seed and prohibiting the spreading of noxious weeds are the main contributors to the preventive method of weed control (Buhler 2002). The level of crop seed contamination by weed seeds is greatest when weed seeds resemble the shape and size of crop seeds (Chauhan et al. 2012). Even in cleaned seeds, a similarity between certain weed and crop seeds in shape and size makes it very difficult to distinguish between species during the seed-cleaning process (Christoffoleti et al. 2007). In addition the similarity of weight of crop and weed seed can also be easily disseminated (Figs. 14.3 and 14.4). To control the spread and introduction of new weeds, the weed laws and seeds laws are in practice in many countries of the world. Other practices that are important in preventive weed control include planting of crop which is not contaminated with seeds of weeds. Before using the field machinery, it must be cleaned to avoid the transportation of weed seeds from one field to the other. Another practice which is helpful in prevention of weed spread is to avoid the transport of weed propagules with the movement of livestock, compost, and manures and through irrigation and drainage water (Walker 1995). Timely field inspection is another method of preventive weed control. It permits early detection of uncontrolled and possibly resistant weeds which can be managed in its earliest stage. Currently we have Kissan councilor in our local bodies at union council level. Therefore such farmer's representatives can play a vital role in stopping the introduction and spread of new weeds in an area. Such practice can be implemented for already introduced major invasive weeds. However, long-term efforts will be needed at regional level.

Fig. 14.3 Wheat crop seed contamination by weed seeds

Fig. 14.4 Crop seed contamination by weed seeds

Cultural Control

Cultural practices are the best tools that are used to exploit the competitiveness of the crop, so as to decrease the emergence and growth of the weed. These cultural practices include selection of the cultivar, adjustment in the row spacing, use of high seed rate than recommended, crop rotation, irrigation management, and use of fertilizers. All of these practices hamper the emergence and growth of the weed. It also reduces fertility of the weed seed which is helpful in the reduction of soil seed bank. It also reduces the risk of herbicide resistance and improved crop yield (Norsworthy et al. 2012).

Mechanical Weed Management

It is one of the weed control methods which come under cultural weed management strategy. It is the safest method of weed control without using any chemical. It includes type of tillage employed before crop emergence by the farmers. It has very profound effect on weed and crop interaction. It also improves crop competitive ability (Malhi et al. 1988). Due to deep tillage, weed seeds are buried under the soil and reduce its germination chances (Fig. 14.5), because most of the seeds required sunlight for its germination. In this way, weed seed bank reduce to some extent (Beckie and Gill 2006). Hand weeding is also practiced under this method, but it is time-consuming and effective for small areas (Fig. 14.6). Sometimes zero tillage techniques are also used for specific agronomic crops to avoid or restrict

Fig. 14.5 Weed management by tillage implements

Fig. 14.6 Hand weeding

weed seed germination that is buried into the soil. However, wind-blown weed seeds create problems in this type of weed management. Using various tillage operations for weed control may cause injury to potential crops. It can also increase the incidence of disease. Tillage is also a major cause of moisture losses and favors soil erosion (Derksen et al. 1993).

14.6.2 Cultivar Selection

Different genotypes of the crop are different in their competitive ability in relation to weed suppression. Suppression of the growth of weed species is desirable that reduce weed seed production. In case of soya bean improvement in early season, growth rate is very important trait for competitive genotypes. Similarly, other common traits are plant height, tillering, leaf angle, and canopy formation which are important during selection of cultivars for improved weed suppression. In rice, hybrid line has greater tillering ability and higher growth which is more competitive than the non-hybrid with weedy rice (Shivrain et al. 2009). Recent reports have indicated that weed-suppressive rice cultivars may lessen reliance on herbicides and facilitate effective weed control at reduced herbicide rates (Mahajan and Chauhan 2013). Barley cultivars also can vary in their competitiveness with weeds (Paynter

Fig. 14.7 Crop cover suppresses weeds

and Hills 2009). Selection of a full-season cultivar to exploit the period with crop cover will suppress weed emergence for long period of time (Fig. 14.7a, b), while planting an early maturing cultivar may expand the window of postharvest seed production of escaped weeds that possibly contribute to seedbank perseverance and herbicide-resistance development (Reddy and Norsworthy 2010). It is indicated that extensive leaf display and shading ability were characteristic of competitive cultivars (Lemerle et al. 1996).

14.6.3 Seed Rate and Row Spacing

It is one of the tools of cultural weed control. In this technique seed rate is increased to increase the crop population in the field. It improves the competitive ability of the crop against weeds due to speedy development of the canopy. This technique is successfully used in the dry lands of Australia for the production of wheat (Walsh and Powles 2007). It is also reported that an increase in wheat seed rate from 50 to 300 kg ha^{-1} reduced redstem filaree (*Erodium cicutarium* [L.] L'Her. ex Ait.) biomass and seed production by 53–95% over the years (Blackshaw et al. 2000). Increase in seed rate of winter wheat reduces total biomass of sterile oat and also decreases the number of flower heads of black grass (Fig. 14.8). Similarly, increase in crop density of spring barley reduces competitive ability of wild oat. Dense populations of the safflower speed up dense canopy formation and thus improve competitive ability of the crop against weeds (Llewellyn et al. 2004). For instance, biomass and yield of wild oat were reduced by 20% when the sowing rate of winter wheat was increased from 175 to 280 plants m^{-2} (Xue and Stougaard 2002). Due to increase in benefits, it is standard practice in the dry land of Australia for crop

Fig. 14.8 Increase seed rate reduces weed growth

production (Walsh and Powles 2007). Row spacing also effects weed density in the field crops. Decrease in row spacing can improve the competitiveness of the crop against weed. It is due to the canopy development which intercepts more light that is associated with weed (Arce et al. 2009). In soybean crop, reduction in row spacing increases its production due to improvement in its competitive ability (Harder et al. 2007). Similarly, in cotton field, reduced row spacing increases its production than normal row plantation (Vories et al. 2001).

14.7 Nutrient Management

Nutrient management in the field crop can be used as a vital tool, keeping in view the perspective of weed management. Factors including time of application, quantity, and placement of the fertilizer can be customized to encourage crop growth and reduce the establishment of weeds in the field (Fig. 14.9). On the other hand, use of inappropriate fertilizers can help the growth and development of weeds; it leads to increase weed establishment which results in high weed crop competition. In case of rice, weedy rice utilized 60% of the total N applied to it (Burgos et al. 2006). Nitrogen fertilizer is known to break the dormancy of certain weed species and thus may directly affect weed infestation densities (DiTomaso 1995). Similarly, banding N fertilizer with barley seed at planting reduced green foxtail density and interference compared with N-applied broadcast (O'Donovan et al. 1997). In this situation, it has great advantage of competition over the crop. It leads to produce high amount

Fig. 14.9 Fertilizer application reduces the establishment of weeds

of seeds, and in this situation the risk of herbicide resistance evolution also increases (Norsworthy et al. 2012). It is also reported that redroot pigweed seed germination was stimulated by 10–100 ppmv of ammonium nitrate or urea (Sardi and Beres 1996).

14.8 Irrigation Management

Irrigation management is one of the tools used to reduce the weed competition in the field. Irrigation done before planting of crop in the field allows the weed seed to germinate. After germination, through tillage or use of broad-spectrum herbicides, these weeds are killed. It allows to reduce germination fraction of the soil seed bank that will germinate along with field crop. Flooding was also used for weed control in the rice field (Norsworthy et al. 2012). Early flooding in the rice field is very helpful in weed control (Fig. 14.10). After the application of preflood herbicide, immediate flooding reduces the emergence of weeds. Similarly, another technique that is used for the control of weeds is planting of pre-germinated rice plants in the flooded field. It is very helpful in weed management especially in the control of red rice in conventional rice (Baldwin and Slaton 2001).

14.9 Intercropping

Intercropping, growing of two or more crops together at the same time in the same field, can be used as an effective weed management strategy (Liebman and Dyck 1993). In this method due to increased crop population, weeds have very less chance to establish. It enables the plant to exploit more available resources than the

Fig. 14.10 Early flooding in the rice field is very helpful in weed control

single crop. It may allow suppressing of weed due to competition for resources (Melander et al. 2005). In addition to weed suppression (Fig. 14.11), intercropping may provide several other benefits, including increase in net returns and biological diversity, less chance of complete failure of crop, better use of resources, and suppressive effects on diseases and insect pests (Ali et al. 2000). Intercropping of cowpea in the field of *Sorghum* reduces weed density and its dry matter (Fig. 14.12). Density of weed seed also decreases due to intercropping which is also use as a tool for ecological diversity maintenance (Barberi 2002). Intercropping may also be accepted by the farmer due to increase in income by growing two cash crops (Melander et al. 2005). In general, crop yield increases with simultaneous decrease in weed growth if the intercrops are more effective than sole crops in usurping resources from weeds (Olorunmaiye 2010).

Fig. 14.11 Weed suppression by intercropping

Fig. 14.12 Intercropping weed control

14.10 Crop Rotation

Rotation of crops on the same piece of land also helps in the management of weed. It also dictates tillage intensity, variation in sowing dates, and application of herbicides. Sometimes tillage influenced seed bank of the soil more than crop rotation. However, crop rotation also strongly affects soil seed bank (Cardina et al. 2002). Crop rotation, growing of different crops in sequence in a particular field over a definite time period, can be helpful in overcoming the autotoxicity and decreasing the pressure of plant pests, including weeds, pathogens, and insects (Cheema et al. 2012). In crop rotation, the allelochemicals released in the rhizosphere by plant roots and decomposition of previous crop residues help in weed suppression (Voll et al. 2004). For example, in sunflower-wheat rotation, density and dry biomass of wild oat (*Avena fatua* L.) and Canada thistle (*Cirsium arvense* [L.] Scop.) were decreased significantly in the succeeding wheat crop after sunflower (Cernusko and Boreky 1992). In those areas where crop rotation is not practiced on a piece of land, weeds have less diversity in their community, and as a result choice of herbicide reduces which control those weeds. Those cultivation systems where crop rotation is rarely practiced have greater risk of developing resistance in the weeds (Neve et al. 2011).

14.11 Mulching

It is another physical approach that is used to control weed. In this method physical barriers are established between the rows of the crop. So, it helps to reduce availability of light and reduce weed growth between rows. This method of weed control gets attention especially in organic crop production system (Bangarwa et al. 2011). Mulching inhibits the germination and seedling growth of weeds through the release of certain allelochemicals (Bilalis et al. 2003). Sorghum is the most-studied crop in this regard. For example, surface-applied sorghum mulch (10–15 t ha^{-1}) in maize at sowing provided weed control of about 26–37% (Cheema et al. 2004). Other than sorghum, several other allelopathic mulches also provide a good weed control. For example, sunflower mulching suppressed the germination and seedling growth of several weeds (Wilson and Rice 1968). It not only controls weed population but also is helpful in improving soil nutrient status by the use of materials that are compostable such as stubbles, straw, and hay (Fig. 14.14). In case of using leguminous crop as cover crop, it benefit the field by providing nitrogen, reduction of soil nitrogen in the soil that is unused in the root zone, improve the structure and texture of the soil and helpful in the control of soil erosion (Salmeroń et al. 2010). It also increases the soil's water-holding capacity (Younis et al. 2012). Soil incorporation of wheat straw suppressed the horse purslane (*Trianthema portulacastrum* L.) growth (Aslam 2010). Use of black polyethylene sheet as mulch is

Fig. 14.13 Control of weed population by straw mulching

found very effective in agronomic crops (Fig. 14.13). It gives good results in the control of weeds such as yellow nutsedge. It may be used in combination of additional layers of barriers for the effective suppression of more aggressive weeds (Daugovish and Mochizuki 2010). Transparent plastic is less effective in weed control as compared to the black one. But it is more effective when use for soil solarization. It raises the temperature of the soil and induces mortality in seed (Newton et al. 2008). It is use to reduce the soil seed bank by germinating the weed seeds and then exposing them to lethal soil temperature (Cohen et al. 2008). Polyethylene sheet is also used as mulch in combination with various herbicides for the control of weeds (Bangarwa et al. 2011).

14.12 Allelopathic Control

The role of allelopathy in weed management has been exploited over the time (Jabran et al. 2015). The implications of allelopathy as a weed management phenomenon are established at laboratory scale, but the practical demonstration in the field is rare (Farooq et al. 2013). The expression of allelochemicals through cover crops, allelopathic extracts' applications, intercropping, and residue management may offer successful weed control in different cropping systems. These water-soluble allelochemicals are extracted in water and then are utilized for managing weeds (Bonanomi et al. 2006). Application of sorghum water extract (Sorgaab) has been very effective in suppressing weeds (Cheema et al. 2012) (Fig. 14.15). For example,

Fig. 14.14 Control of weed growth by Balck polyethylene sheet

Sorgaab application suppressed wild oat, field bindweed, and little seed canary grass in wheat (Cheema et al. 2002).

Bajwa et al. (2015) proposed that allelopathy could be a useful nonconventional weed management strategy in modern-day agriculture. In wheat crop, mixed application of Sorgaab and sunflower water extract was more effective in suppressing the little seed canary grass and wild oat than the individual extracts (Jamil et al. 2009). In sunflower, Sorgaab application 20 DAS decreased the density of purple nutsedge and horse purslane by 10–21% and dry weight of weeds by 18–29%, respectively, with yield increase of 25% (Nawaz et al. 2001). Likewise, in soybean, Sorgaab application at 25 and 50 days after sowing (DAS) reduced the total weed dry weight by 20–42% (Khaliq et al. 1999).

Fig. 14.15 Suppression of weeds by allelopathic of sorghum

14.13 Biological Weed Control

Weed suppression are done by using biological agents or biological process. It is an economically affordable method of weed control having no hazardous effect on the environment. However this method of weed control is feasible for the control of perennial weeds (WSSA 2007). A conventional biological control method is the control of invasive weeds that are non-native, with natural enemies originating from native weed species. It is very effective in the area having less intensity management including forests, preserved natural areas, rangeland, and waterways. Another method of biological control is the use of bioherbicides, which also show success in weed control to some extent. In the future specific genes may also be introduced to control growth, development, and competitive ability of weeds (Vencill et al. 2012). It is the safest method of weed control. In this method natural enemies of the weed are introduce in the infested areas. In this method first natural enemies are identified (Fig. 14.16). These natural enemies are allowed to feed on the specific plant. After increasing its population to a certain level, these animals are introduced in the infested areas to establish itself. They feed on the host plant and dramatically reduce its population (Fig. 14.17), which is helpful in the reduction of reproduction and development of the host plant (Pitcairn 2011). This decline in the population of a specific plant in an area is the perfect example of invertebrate consumers controlling a plant’s abundance (Pitcairn 2017). In Thailand pigs were used to control weed in

Fig. 14.16 Weeds control by natural enemies

Fig. 14.17 Biological weed control

rice, while in Australia *Cactoblastis cactorum* was used as biological agents for the control of weed population. In the USA and Canada, farmers are using different biological agents for the control of various weeds. Prickly pear cactus (*Opuntia* spp.) was controlled by using cactus moth (*Cactoblastis cactorum* Berg) as its biological agent which feed on it. Similarly, St. Johnswort (*Hypericum perforatum* L.) was controlled by using Klamath weed beetle (*Chrysolina quadrigemina* Suffrian) (Appleby 2005). Sometimes goats and sheep are also used to control weed population in local areas (DeBruin and Bork 2006).

14.14 Chemical Weed Control

Use of chemicals for the weed control is the fast method. It is easy to apply, less time-consuming, and most effective method of weed control. Herbicides are chemicals that inhibit plant growth and also kill it. Herbicides are classified in various categories which include time of application such as preplanting herbicides. It applies to the field before plantation of crop. The other one is postemergence herbicides applied after seed germination. The other classification is based on chemical family such as dinitroanilines and sulfonylureas. Similarly, on the basis of path of mobility inside the plant, i.e., translocation through xylem, phloem, or both. Another classification is based on mode of action of herbicide such as inhibitors of photosystem II and ALS inhibitors (Vencill et al. 2012). The importance of herbicides in modern weed management is underscored by estimates that losses in the agricultural sector would increase about 500% without the use of herbicides (Pacanoski 2007). Mode of action of herbicide is very important in case of resistance in weeds due to its best description on how herbicide imposes pressure on the weed. So, in herbicide-resistant weed management, its manipulation may be used. Nowadays, above 200 active ingredients are registered for herbicides all over the world. However, plant growth regulators and growth retardant are not included in it. According to the mechanism of action of herbicides, there are only 29 groups, 1 of these groups' mode of action is still unknown (WSSA 2010). Application of contact herbicides might not always be an effective tool for weed killing before planting, and glyphosate application might be a better solution. Glyphosate, a nonselective, broad-spectrum herbicide, controls most grass, sedge, and broadleaf weeds (Reddy 2004). Herbicide resistance is the natural capacity of the plant to cope with the particular chemical. For this purpose they improve its capacity. It is develop in some progenies instead of the whole population. So, it becomes an issue for herbicide; therefore advancement occurs in the chemicals for specific species of weed. Increase in resistance against specific herbicide in the weed population allows increasing its population and no more that particular herbicide able to control that weed.

14.15 Integrated Weed Management

Different practices are carried out to restrict weed population under economic threshold level that cannot significantly affect crop growth and yield. Those management strategies are recommended for weed control that is economically feasible and environment-friendly. In weed management strategies, none of the single practices is able to control weed population to an acceptable level. Therefore, for best management of weed population, some of the management practices are used together to reduce weed population below economic threshold level and increase yield. Integrated weed management offers a great opportunity to reduce weed biomass, density, and population. This allows the farmer to combine and use all the required practices which are helpful for weed reduction and sustainable environment (Sanyal 2008). For example, corn yield loss due to foxtail millet (*Setaria italica*) interference was 43% when corn was planted at 37,000 plants ha^{-1} in rows 76 cm wide with N fertilizer applied broadcast (Anderson 2000). The most effective method of weed control is the use of mechanical, preventive, cultural, biological, and chemical combination. It also depends upon the agroecological and climatic conditions of an area. Sometimes all of these methods of weed control are not feasible to apply. So, for this purpose, we just use the most effective method for weed management. It enables the farmers to carry out its management practices that suit his economic status and interests.

14.16 Current Status of Weed Management Practices

Nowadays most of the farmers are fully aware of the losses that cause in the production due to weed infestation. So, most of the farmers around the world are using various management practices to reduce these losses caused by weed competition. With the passage of time, improvement in these management practices and awareness about the biology of weed species enable the growers to take decision on critical time for control (Blackshaw et al. 2006). Farmers try to control weed population by cultural tools such as tillage, hand weeding, time management of germination, and growth stages. Similarly, biological control through grazing of goat and sheep for small areas. But the most widespread method for weed control nowadays is the use of chemicals. It is the most effective method for weed control which is easy to apply and fast for weed management. But it is reported that weed develop resistance against these herbicides. Herbicide dose that is applied one time cannot able to control the same weed next time. So, it is a major issue related to chemical weed control (Brookes and Barfoot 2011). On the other hand, these herbicides are dangerous for the environment and have negative impact on the lifestyle of the people and animals as well. While the other management practices are sometimes not feasible that effectively controls weeds in the crop so that yield not affected due to weed infestation.

Future Perspective

Weed management is a major issue in field crops. Due to its diverse ecological adaptation, they are fast growing and have high seed production rate. These plants have very high competitive ability and mostly short duration plant species, due to which they are very hard to control. Use of the abovementioned practices alone or in combination is helpful to reduce yield losses. But with the passage of time due to development of new progenies which are very much resistant to the chemicals, there is a need to find an alternative way that can be best suited for weed management in agronomic crops. For this purpose, adaptation of new technologies is necessary that will help to prevent weed seed dispersal during the movement. Similarly, breeding of new cultivars are very much important which is more competitive as compared to weed species. Adoption of organic farming which allows minimum use of chemicals will help to reduce the development of resistance in weed species against herbicide.

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15 Optimizing Herbicide Use in Herbicide-Tolerant Crops: Challenges, Opportunities, and Recommendations

Arslan Masood Peerzada, Chris O'Donnell, and Steve Adkins

Abstract

Rapid, large-scale adoption of herbicide-tolerant (HT) cropping systems is attributed to recent shifts in herbicide use patterns globally. With the dramatic increase in herbicide use, particularly glyphosate, herbicides' diversity for weed management has consequently declined, resulting in increased herbicide-resistant (HR) weed species, weed population shifts, and serious environmental threats. Despite its increasing importance, no new herbicide has been commercialized, particularly in no-till cropping systems. Globally, government regulatory bodies have taken strict stances to minimize the use of agrochemicals due to increasing environmental and human health concerns. Nowadays, the research and industrial sectors are more focused on the development of new approaches for delivering herbicides into the field through an optimized way. Focusing on this, old and new technologies have been adopted for weed management due to the paradigm shift from heavy dependence on herbicide to the more integrated system, involving a wide range of technologies and cultural practices. Focusing on the above-mentioned circumstances, this chapter highlights the possible socio-economic and environmental constraints affecting herbicide performance in the HT crop production system in Sect. 15.2. In Sect. 15.3, possible opportunities regarding better use of herbicide through employing better management practices and integrated weed management (IWM) approaches have been discussed briefly.

Keywords

Weed · Herbicide resistance · Weed management · Genetical modification

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Abbreviations

DR	Disease resistance
GM	Genetically modified
GT	Glyphosate tolerant
HR	Herbicide resistance
HT	Herbicide tolerance
IR	Insect resistance
PC	Pollen control
PQ	Modified product quality

15.1 Introduction

Herbicide-tolerant (HT) crops are the current modification in genetically modified (GM) crops, withstanding spraying of certain non-selective herbicide aimed to control all weeds (Bonny 2016); the devastating majority of HT crops are glyphosate-tolerant (GT) with a tiny percentage of glufosinate-tolerant (Livingston et al. 2015). Depending upon the regulatory aspects and agro-economic success, the adoption rate of HT crops may vary within different countries and among crops (Fig. 15.1; ISAAA 2017). For example, GT soybean represents 50% of all HT crops in 2014, which covers around 80% of the total cultivated soybeans worldwide (Bonny 2016). Between 1996 and 2005, with the growing acceptance of GT crop cultivars, several

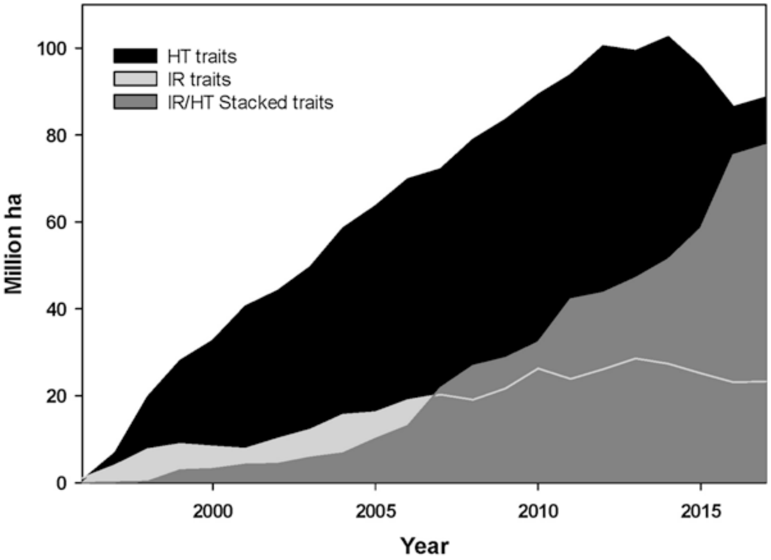

Fig. 15.1 The global area under approved crop traits from 1996 to 2017 [ISAAA 2017]

herbicide types diminished as it supported the concomitant development of conservation tillage to which GT crops are well-matched (Osteen and Fernandez-Cornejo 2013).

The rapid HT crops' adoption in general and of GM HT crops especially with their linked crop managing practices, particularly tillage and herbicide regimes, become important tools for managing weeds (Lamichhane et al. 2016). These changes in weed management practices due to HR crops contributed significantly to the production of economically important agronomic crops worldwide, which resulted in low farm costs and more feasible and flexible weed management options (i.e. use of non-selective herbicide-like glyphosate and glufosinate), reduced risks of crop injury, and their compatibility with conservation tillage systems. Despite controlling diverse weed populations congeneric to the crops, HT crops and their related crop management practices, particularly simplified weed control, improve the resource's utilization efficiency and contribute towards increased farm size (Owen et al. 2015).

This rapid increase in farm size with the development of GM HT, particularly GT crops, increased crop acreage, reaching 86.5 million hectares or 47% of the total 185.1 ha of the biotech crop planted by up to 17 to 18 million farmers globally (Bonny 2016). Minimal increase in the area planted with HT crops was observed in the USA, Canada, South Africa, Bolivia, the Philippines, and Australia; however, the area planted with HT crops decreased in Uruguay, Mexico, Chile, and Honduras (ISAAA 2017). In the USA, large-scale adoption of GT crops favoured the decrease of glyphosate process when its patent expired in 2000. This huge increase in glyphosate use worldwide, linked to GT crops, forced the production of large quantities of generic glyphosate in some countries like China (Bonny 2016). In the first year of adoption, HT crops lead towards some decrease in herbicide, which was generally predicted, through repeated use of GT crops and a decline in glyphosate rate, increased average rate and number of applications, which resulted in no sufficient alternations and reduced herbicide diversity (Green and Owen 2010).

The overreliance on herbicide use and lack of crop diversity raised several ecological and socio-economic challenges, including the development of herbicide resistance (HR) in weeds, their population shifts, and groundwater/surface water contamination (Green and Owen 2010; Busi et al. 2013; Bonny 2016). Use of single herbicide or mode of actions (MOA) over the site for a prolonged time frame increased the selection of HR weed biotypes (Lamichhane et al. 2016). For example, 38 weed species have developed glyphosate resistance in 34 different crops across 37 countries and 6 in non-crop situations (Heap and Duke 2018). Furthermore, this enhanced selection pressure due to repeated single MOA usage manipulated the weed species abundance and diversity (Davis et al. 2012; Lamichhane et al. 2016). Factors like natural tolerance herbicide or other weed control options and rapid spread of HR biotypes fasten the shift in weed species communities (Owen 2008). In addition, increased herbicide use resulted in run-off from farm fields and polluted surface water/groundwater and degraded soil (Myers et al. 2016).

In recent times, the worldwide adoption of GM HT crops has not fallen, suggesting farmers must be continuing to derive important economic benefits from using this technology (Brookes 2014). Therefore, changes in weed management, emphasizing the broader agenda of developing strategies across all forms of cropping systems like the overall profile of applied herbicides, might minimize and/or slow down the potential threats of this existing technology solution (Brookes and Barfoot 2016). From the last decade, farmers are facing an increasing pressure to optimize herbicide use in many countries due to increasing concerns of herbicide resistance, weed population shifts, public health, and environmental degradation (Kudsk 2008). Under the prevailing situation, environmental and economic issues of herbicide use may well find at least partial solutions in the intelligent use of GM HT crops.

No doubt, weed management has dramatically transformed with the extensive adoption of HT crops, i.e. GR crops. Repeated use of herbicide influenced their initial efficacy and jeopardized the current herbicide-based weed management system as demonstrated by the rate at which weed is evolving resistance as discussed in Sect. 15.2 (Green and Owen 2010). The utility of glyphosate is still not lost yet as it is still effective in controlling more weeds than other herbicide, though it can no longer be applied along anytime on any weed in the near future (Green 2018). Even other herbicide traits like glufosinate, auxins, and HPPD-inhibitors in combination with GR are the incremental and transitory solution. No new herbicide or trait technology is more likely to match the glyphosate importance in agriculture. Therefore farmers need to diversify the herbicide tactics, crops, cultural practices, as well as field hygiene measures (discussed in Sect. 15.3). The utility of herbicide resistance (HR) traits and herbicide technology will be preserved by using diverse weed management practices, which will help in sustaining profitability and environmental safety of HT cropping systems.

15.2 Challenges Associated with Herbicide Use in HT Crops

In the last couple of decades, the adoption of transgenic HT crops increased intensely, which is mostly attributed to GT crops, i.e. soybean, cotton, maize, and canola (Green 2018). The increasing trend of adoption resulted in unprecedented changes in agricultural practices; the most dramatic is weed control tactics, such as the use of single MOA at elevated rates and repeated application during the growing season. Numerous agriculturists and economists predicted that the adoption of GM HT technology might reduce herbicide use dramatically, while others believed it will actually increase (Bonny 2016). Though the herbicide numbers have been reduced, it has increased the ecological implications, such as reduced biodiversity in cultivated lands, shifted weed population communities, and evolved HR biotypes.

15.2.1 Increased Herbicide Use

Impact of herbicide use, particularly in HT crops, is an important matter of discussion in the last two decades. Some scientists claimed that HT crops might decrease the total herbicide use, while others claimed the opposite (Bonny 2016). In the very first years of adoptions in 1996, these HT crops often lead to some decrease in herbicide use (Bonny 2016). However, rapid cultivation of HT crops promoted and significantly increased herbicide use, thus forcing farmers to put their faith into chemical treadmill with ever-increasing herbicide quantities needed to sustain crop productivity (Bonny 2016; Schütte et al. 2017). For example, the amount of active ingredients in HR soybean has been increased to 64% as compared to 19% in conventional soybean from 1998 to 2013 (Brookes and Barfoot 2016). This intensive herbicide use lead towards the evolution of more and more HR weed biotypes, causing substantial crop yield losses, and increased managerial costs, thus possess a significant menace to farm productivity (Keith et al. 2017).

About 56% of the total glyphosate used globally (8.6 billion kg) is used on GR crops, accounted for more than 50% of the total 180 million ha under GM crops planted in 2015 (Green 2018). Since the release of GT GMO seeds by Monsanto in the 1990s, the use of Roundup Ready® technology (i.e. glyphosate and GR crops) spread rapidly in Australia, Argentina, Brazil, and the USA, where this technology currently dominates. For example, four crops including cotton, maize, soybean, and wheat account for 95% herbicide used in the USA (Osteen and Fernandez-Cornejo 2016). Based on environmental concerns and political economy reasons, herbicide use will continue to rise in countries like the USA with consecutive waves of herbicide technology packages, while herbicide use in Europe and Australia began or will begin to drop in the near future, respectively (Bonanno et al. 2017; Swinton and Van Deynze 2017).

In developing countries, herbicide use is increasing rapidly in the last few years, and since 2005 a sharp flow in herbicide adoption in these countries has been observed which is diverse as in developed countries (Haggblade et al. 2017). On-farm adoption of herbicide-based technologies depends predominantly on herbicide prices which have been reduced by 50% over the past few decades. In most developing countries, the herbicide adoption rate is 80–100% in farming zones near urban cities to below 25% in remote zones, where labour cost is lower as compared to herbicide prices (Haggblade et al. 2017). Therefore, changes in international prices, local wages, and herbicide products' availability and regulations directly alter the adoption trajectories over time in developing countries.

15.2.2 Shifts in Weed Populations

Historically, significant changes in agricultural systems, particularly crop management practices, caused a substantial impact on weed communities (Owen and Zelaya 2005). The introduction of herbicide-tolerant (HT) crops, particularly the GR, lead towards changes in cultural practices such as simplified rotations and conservation tillage (Frisvold et al. 2009; Fausti et al. 2013). With these innovations, it was assumed that these GMHT crops might be so efficient that some of the weed species will disappear permanently from agroecosystems. The adoption of conservation tillage and weed management plans focused on single-MOA herbicide-accelerated shifts in several economically damaging weed species (Owen 2008). Evolution of HR weed biotypes exerted intensive selection pressure from herbicide use, which shifted the relative prominence of weed species in the weed communities. As a result, some of the common populations and other relatively new weed problems shifted in HT, for example, increasing dominance of sowthistle (*Sonchus oleraceus* L.), horseweed (*Conyza bonariensis* L.), giant ragweed (*Ambrosia trifida* L.), etc in GT-based cropping systems in Australia.

Due to the use of GM HT for a prolonged time period, populations of many weed species experienced widespread decline; generally, broadleaved weeds decreased and grassy weeds increased, but the varieties and abundance of both declined overall (Heard et al. 2003). In the Eastern Indo-Gangetic Plains, adoption of zero-till increased the population of purple nutsedge (*Cyperus rotundus* L.) and Bermuda grass [*Cynodon dactylon* (L.) Pers.] (Kumar et al. 2013). In Georgia, many glyphosate-susceptible weed species in cotton has been replaced by GT weed species, including Asiatic dayflower (*Commelina communis* L.), Benghal dayflower (*Commelina benghalensis* L.), Florida pusley (*Richardia scabra* L.), Palmer amaranth (*Amaranthus palmeri* L.) (Webster and Sosnoskie 2010). Most of these genetically diverse weed species are at risk for developing or have developed resistance in GR cropping systems due to repeated use of this glyphosate over time and space (Powles 2008).

Despite damaging to crop yield and quality, weeds offer considerable benefits to agroecosystem as a part of biodiversity to support a wide range of organisms like decomposers, predators, pollinators, and parasitoids. In the absence of weeds, the fulfilment of these certain functions becomes obvious within the agroecosystem (i.e. reduced crop yield and quality due to less insect-dependent pollination). Shifts in the diversity of the associated agricultural flora and the soil seedbank in cultivable lands might reduce the abundance and diversity of associated weeds and arthropods, which might affect the food chain components including small mammals and farmland birds (Guerrero et al. 2012). In comparison to the conventional farming system, organic farming has large positive effects on biodiversity and the effect size varies with the organisms and crops (Tuck et al. 2014).

Generally, strategies adopted by farmers to mitigate weed population shifts due to overreliance of glyphosate in GR crops have a minimal impact. In many cases, the flexibility and overall effectiveness of glyphosate have allowed farmers to overcome weed problems more effectively in these crops (Kruger et al. 2009). In addition, farmer's hesitancy to use other herbicide options in addition to or in rotation with glyphosate is due to additional seed cost for the GR traits. In many countries, most farmers are concerned and often focused on the short-term economics of weed control and occasionally implement proactive strategies to develop a long-term and sustainable weed management program (Powles 2008). This attitude leads farmers towards implementing practices necessary to control weed within each cropping system without taking weed population dynamics or future economic implications in consideration (Wilson et al. 2011).

15.2.3 Single Selection Pressure and Herbicide Resistance in Weeds

The simplicity of HT crops, particularly GR crops, attracted farmers followed by their widespread adoption, combined with use on the same field year-after-year without herbicide diversity, and contributed to the selection pressure in weeds and evolving resistance against most widely used herbicides (i.e. glyphosate; Bonny 2016). Primarily, glyphosate was remarkably operational in GT crops, and countless farmers trusted on glyphosate extensively for weed control (Green and Owen 2010). Some of the researchers and scientists were in doubt about the sustainability of HR technology (HT crops and herbicide use to weed control) and predicted the evolution of resistance (Green and Owen 2010). However, no cases of GR weeds were recorded after more than two decades of broad use in non-crop situations, and most of them began to think that GR weeds will not be a problem. Then the scene changes when first GR rigid ryegrass (*Lolium rigidum* Gaud.) was first reported during 1996 in Australia.

A total of 255 species has evolved resistance against 23 of the 26 mode of actions (MOAs) in many agroecosystems; most of them evolved with the selection pressure resulting from the adoption of HT crops (Fig. 15.2; Bonny 2016; Heap and Duke 2018). It is believed that herbicide resistance evolutions have been highly favoured by GT crop, inducing repeated use of glyphosate without sufficient alternation in weeding practices and/or without concern for crop injury (Owen and Zelaya 2005; Bonny 2016). More than 38 weed species globally has been known to be resistant against glyphosate (Table 15.1 and Fig. 15.3; Heap and Duke 2018). Currently, 18 of GR weeds species have been reported for their resistance against other herbicides as well, so no good herbicide alternative is left behind (Heap 2018). Today, all

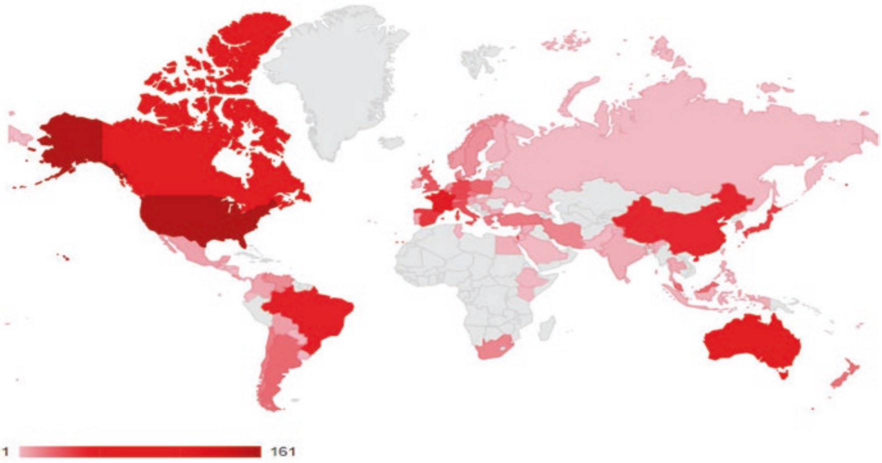

Fig. 15.2 Herbicide resistance cases reported globally. (Adapted from Heap 2018 with permission)

Table 15.1 Glyphosate resistance cases reported in weed species, globally (Heap 2018)

Weed species	Reported cases	Weed species	Reported cases
Conyza canadensis	42	*Parthenium hysterophorus*	2
Amaranthus palmeri	41	*Salsola tragus*	2
Amaranthus tuberculatus (=A. rudis)	29	*Biden spilosa*	1
Lolium perenne ssp. multiflorum	26	*Brachiaria eruciformis*	1
Ambrosia artemisiifolia	20	*Bromus catharticus*	1
Ambrosia trifida	17	*Bromus diandrus*	1
Kochia scoparia	17	*Bromus rubens*	1
Lolium rigidum	17	*Chloris elata*	1
Conyza bonariensis	13	*Cynodon hirsutus*	1
Eleusine indica	13	*Hedyotis verticillata*	1
Conyza sumatrensis	8	*Helianthus annuus*	1
Poa annua	7	*Hordeum murinum* ssp. glaucum	1
Echinochloa colona	6	*Leptochloa virgata*	1
Sorghum halepense	5	*Paspalum paniculatum*	1
Lolium perenne	4	*Plantag olanceolata*	1
Amaranthus hybridus	3	*Raphanus raphanistrum*	1
Chloris virgata	3	*Sonchus oleraceus*	1
Digitaria insularis	3	*Tridax procumbens*	1
Brassica rapa	2	*Urochloa panicoides*	1
Chloris truncata	2		

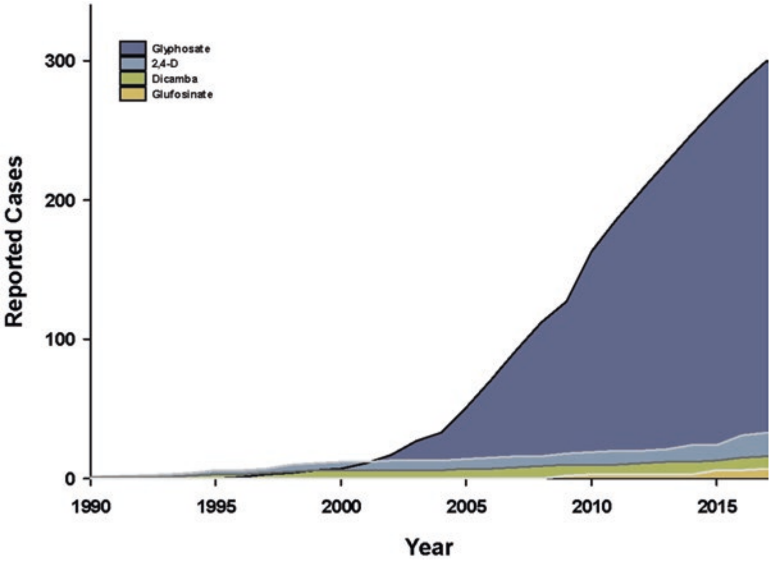

Fig. 15.3 Herbicide resistance cases reported for commonly used herbicide (Heap 2018)

except the evolution of GR weeds are threatening the continued success of GR crops and the sustainability of glyphosate.

In the next few years, transgenic crops with resistance to the herbicide that inhibits auxin, acetolactate synthases, acetyl-CoA, carboxylase, and hydroxyphenylpyruvate dioxygenase stacked with glyphosate and/or glufosinate resistance will be available (Duke 2014). These technologies are expected to provide additional weed management options for farmers, but would not have positive features like reduced cost, simplified weed control, lowered ecological impact, and reduced tillage that GR crops initiated. Other HR crops, including non-transgenic crops, herbicides with new MOAs and HR technologies are in the juvenile stage, which might outcompete transgenic crops in weed management (Duke 2014). These genetically engineered crops will be or are commercialized, which will be genetically engineered to withstand the additional herbicide application, including herbicide with a greater threat to environments, crops, and human health such as dicamba and 2,4-D (Mortensen et al. 2012).

Herbicide mixtures at high doses have been recommended for their effectiveness in managing herbicide-resistant weed species (Diggle et al. 2003). It is expected that commercially available mixtures of glyphosate and glyphosate traits combination will be the mainstays of weed management, while glufosinate, auxins, HPPD-inhibiting, and other herbicide traits are incremental and temporary solutions (Green 2018). Herbicide industries are not going to be able to support what critics call the chemical and transgenic treadmill for much longer. In addition, the long-time without the discovery of a new herbicide MOA and the expanding herbicide resistance in weeds forces farmers to spend more time in managing weeds and creating a worst of time, threatening the future of crop production and seed industry.

15.2.4 Herbicide-Tolerant (HT) Volunteer

Transgenic HT crops, predominantly tolerant to glyphosate and glufosinate, represent one-tenth of the global areas planted to major crops (Beckie and Owen 2007). Inappropriate handling resulting in high seed loss before or during crop harvest combined with the potential of seeds to establish a soil seedbank enforces HT crops to emerge as HT volunteer weeds in following crops (Huang et al. 2016). HT volunteers create a significant weed problem by reducing crop yield and quality, as well as interfere with harvesting efficiency. For instance, early-season competition from volunteer GR corn reduced 55–68% yield and 19–45% sucrose yield in GR soybean and GR sugar beet, respectively (Kniss et al. 2012; Chahal and Jhala 2015). In addition, these volunteers may harbour pathogens, insects, and nematodes thereby diminishing the positive effect of crop rotations. A study reported volunteer HT corn in soybean to attract adult rootworms if the maize survives to the reproductive stages (Meinke et al. 2009). Furthermore, the HT volunteers can facilitate intra- and interspecific HR gene flow in space or time (discussed in the next section). Uncontrolled HR volunteers can act as pollen sources and contaminate non-HR crops or transfer resistance to weedy relatives (Rainbolt et al. 2004).

HT volunteers cannot be controlled by herbicides with the same MOA, thus complicating the problem due to the limited choice of effective herbicides (Kumar and Jha 2015). For example, imidazolinone-tolerant oilseed rape (Clearfield® CL OSR) introduction in Europe triggered new challenges for chemical weed control as CL OSR volunteers are tolerant to common ALS-inhibitors (Huang et al. 2016). Given the large-scale use of HR crops, the presence of HT volunteers is becoming a significant agroecological concern in many countries (Simard et al. 2002). Seed spillage during harvesting, seed shattering, seed escape during post-harvest handling, and seeding with contaminated seed lots are the major causes of seed migration (Mallory-Smith and Zapiola 2008). The threat posed by the migrated seeds can vary with their dormancy and seed persistence (Gruber et al. 2009).

HT crops that produce abundant seeds pose greater threats as an adverse environment, or a delay in harvest may result in substantial seeds escaping to the environment (Dong et al. 2016). In addition, HT crops with characteristics like seed shattering and persistence are particularly more likely to emerge as volunteers, e.g. oilseed rape (OSR). Due to its high seed production, high seed losses during harvesting and transport, HT OSR readily produces volunteers with secondary dormancy. Despite the regular control of the fields for volunteers, HR OSR has been found up to 15 years after experimental release (Geddes 2017; Schütte et al. 2017). Knispel and McLachlan (2010) reported seed spillage outside the fields and along the transport routes potentially leading to HR feral plants which may persist over the large spatial and temporal scale (Fig. 15.4).

15.2.5 Gene Escape from Crop to their Wild Relatives

More than 15 years after the introduction of transgenic crops, movement of HR transgenes via pollen to compatible wild relatives from commercial field production was documented with no reports of negative environmental impacts (Mallory-Smith and Olguin 2010). Gene escapes via pollen movement from crops to weedy relatives, particularly from HT crops to closely related wild species is a major concern with GM HT crops. These escaped transgenes might persist and disseminate within

Fig. 15.4 HT volunteer corn in soybean. (Photo courtesy Anke Belter and Amit J. Jhala)

the wild populations through sexual or asexual reproduction, which might increase the ecological fitness of the weedy populations, causing serious environmental threats, such as the evolution of aggressive or difficult-to-control weeds (Chen et al. 2004). These weeds might infest arable lands and get out of human control, resulting in unpredicted damage to agroecosystems (Ellstrand 2003). As a consequence, transgene escape might contaminate the wild populations, leading towards the extinction of endangered and biologically important wild species in the local agroecosystems (Chen et al. 2004).

If the plant species are closely related, the probability of gene flow further increases as shown in Table 15.1 (Knezevic and Cassman 2003). In HT crops, oilseed rape (*Brassica napus* L.) is one of the most problematic crops, prone to gene flow to weedy relatives. Being a self-pollinated crop, it is known to possibly hybridize with wild radish (*Raphanus raphanistrum* L.), wild turnip (*Brassica rapa* L.) and shortpod mustard [*Hirschfeldia incana* (L.) Lagr.-Foss] under field conditions (Senior and Dale 2002). Katsuta et al. (2015) reported the natural hybridization extremely remote between canola and other relative species in the wild. Studies reported high fertility rate, prolonged seed dormancy and longevity, and inherited herbicide resistance compared to its parent in an outcrossed hybrid between *B. napus* and Indian mustard (*Brassica juncea* L.) (Song et al. 2010). Therefore, transfer of glyphosate or glufosinate tolerance to wild relatives could render their control more difficult in both Brassica and subsequent rotational crops, thereby shifting reliance back on the use of less effective herbicides (Fig. 15.5).

For future crop production, the importance of crop-weed hybrids produced due to gene flow from HT crops to wild population depends upon the traits introduced into the progenies (Chen et al. 2004). Whitton et al. (1997) reported that gene originated from cultivated sunflower persist in wild populations over the 5-year period following the hybridization. However, proper understanding about what happened to the gene which has been introduced into the wild population from HT crops after a long period is limited as most studies conclude with the first hybrid generation. Therefore, evaluation of the relative fitness of hybrids would be helpful in assessing gene flow occurrence, besides estimating the degree of gene flow (Chen et al. 2004; Lu et al. 2016).

15.2.6 Volatilization and Spray Drift

The impending approvals and use of crop cultivars with tolerance to 2,4-D and dicamba have generated some conflicts and debate. Over the last 20 years, scientists are seriously concerned about the risks associated with the drift and volatilization of 2,4-D and dicamba which have triggered thousands of non-targeted crop damage (Fig. 15.6; Benbrook 2012). For herbicides with low vapour pressure like glyphosate, metazachlor, etc., volatilization can be considered negligible. However, an increasing number of cases have been reported for trifluralin due to high volatilization flux and high ecotoxicity (Mamy et al. 2010). Most of the weed scientists, agronomists, and farmers are concerned about these cultivars. It is believed that

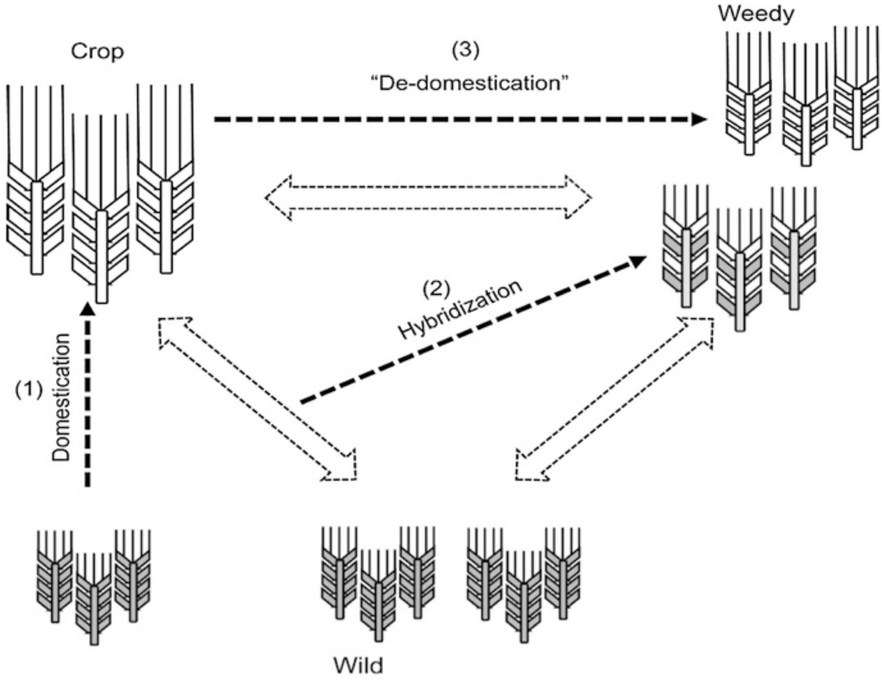

Fig. 15.5 A schematic illustration demonstrating the evolutionary relationship among the populations of a domesticated species, its wild progenitors, and a weedy taxon conspecific with the crop. (Adapted from Lu et al. (2016))

Fig. 15.6 Dicamba injury on squash plant, maple tree, and non-HT soybean. (Photo courtesy of John Seward, Little Shire Farm, Aurora South Dakota, and Aaron Hanger, University of Illinois, USA)

2,4-D- and dicamba-tolerant cultivars will make farmers dependent on the intellectual property held by large corporations, and as a result, it will increase threats of non-targeted crop injury and will also accelerate the evolution of HR weed species. Other claims that wide use of this herbicide on millions of hectares has not caused any widespread damage yet, therefore the use of these HT crops would not be a major concern for farmers growing high-value horticultural crops.

In the state of Missouri, 257 suspected cases of dicamba damage have been reported, of which more than 100 has been reported soon after the issuance of an additional restriction on the pesticide use by the state's agriculture department (Bradley 2017). The unknown volatilization problems of these herbicides are well documented and are being addressed by developing newer herbicide formulations with low volatility. In addition, changed label instructions and improved application techniques were suggested, seeking to reduce the amount of damage the herbicides can effect on speciality crops. However, the new formulations of dicamba endure enough volatility to cause some of the damage to sensitive crops. Herbicide companies claim that the users do not follow the labelled instructions, which results in herbicide misuse and damage to non-targeted crops as well as non-HT soybean. Edaphic and climatic factors, like soil moisture, and non-incorporation probably contribute to enhanced volatilization.

In modern agriculture, spray drift and non-target movement of herbicide droplets are major concerns related to herbicide use, which increased greatly with the use of non-selective herbicide, like glyphosate and glufosinate (Bonny 2016). Inappropriate information regarding the crops growing in the neighbouring areas of HT crops can cause serious damage to conventional crops due to inappropriate herbicide application. The possibilities of potential herbicide drift onto susceptible crops increase with the rapid adoption of HT crops over the last 20 years. Several studies on simulated herbicide drift have reported serious injuries to conventional cultivars of corn, sorghum, wheat, rice, and cotton (Ellis and Griffin 2002; Al-Khatib et al. 2003; Ellis et al. 2003; Roider et al. 2007). Despite the visual crop damage, some of the aforementioned scientists reported reduced plant heights and increased yield losses due to herbicide drift in HT crops. For example, simulated glyphosate drift followed by in-crop application of nicosulfuron/rimsulfuron + dicamba/diflufenzopyr significantly reduced the plant heights by 19–45%, shoot dry weight by 46%, and yield by 49–59% in maize (Brown et al. 2009).

15.2.7 Impact on Farmland Biodiversity

In general, agriculture relies on the ecosystem functions, its services, and on biodiversity including biological pest control, insect-mediated pollination, nutrient cycling, and hydrological services. The cultivation of GM HT crops followed by increased herbicide use adversely affects these ecological services in the farmland regions by reducing the biodiversity (Hartzler 2010). Increased adoption of HR crops decreases crop diversity, reduces crop rotation, restricts the farmer's seed exchange, minimizes drainage, controls landscape consolidation, and promotes herbicide use (Schütte and Mertens 2010). As the results, the shift in the weed populations reduces the weed species diversity and ecosystem complexity in the HT field and on neighbouring farms. A recent study reported the influence of HT crops on the species' abundance and diversity of wild plants and serious impact on flora, arthropods fauna, and other farmland animals (Schütte et al. 2017).

Exposure of honeybees (*Apis mellifera*) to the sublethal levels of glyphosate present in agricultural settings impairs cognitive capacities which recover and incorporate spatial information for a successful return to the hive (Balbuena et al. 2015). Therefore, ingesting traces of the most widely used herbicides can affect honeybee navigation, exerting potential negative effects on colony foraging success on a long-term basis (Balbuena et al. 2015). Increased glyphosate use has reduced the surface casting activity and reproductive success (by 56%) in vertically burrowing earthworms (*Lumbricus terrestris*) and soil-dwelling earthworms (*Aporrectodea caliginosa*) inhabiting in agroecosystems (Gaupp-Berghausen et al. 2015). Glyphosate-based herbicides at ultralow doses have also reported exerting a negative impact on the embryonic development in African clawed frog (*Xenopus laevis*) and chicken (*Gallus gallus domesticus*) embryos through interfering with retinoic acid signalling which is involved in gene regulation during early vertebrate development (Paganelli et al. 2010). Depending upon the weed management, weed populations might be reduced to low levels or practically eradicated, which consequently affect on the local use of fields by birds due to a major loss of food resource (Watkinson et al. 2000).

Compared to glyphosate, ecotoxicity of glufosinate and other herbicides has been reported less, presumably due to lower use. Glufosinate has been reported to influence the activity of soil microorganisms and is slightly toxic to fish and aquatic invertebrates. However, the activity of most fungal pathogens seems to be reduced by these herbicides potentially due to the inhibition of glutamine synthetase. Glufosinate-ammonium has been reported to have excellent acaricidal activity against larval, nymphal, and adult stages of two-spotted spider mite (*Tetranychus urticae* Koch) and its natural enemies (Ahn et al. 2001). In addition, increasing use of the old Hebrides, such as 2,4-D and dicamba, in herbicide-resistant crops has raised serious concerns. Due to high volatility, both herbicides have been reported to cause potential damages to non-target organisms (sensitive crops, vegetables, ornamentals, and plants in home gardens) due to spray drift. Both plant and arthropod communities in the field edges and seminatural habitats have been affected with dicamba and 2,4-D (Bohnenblust et al. 2016). Stimulated particle drift (=1% of the field rate) delayed the onset of flowering and reduced the number of flowers and affected the pollen quality in terms of protein concentration, thus was less frequently visited by pollinators (Bohnenblust et al. 2016).

15.2.8 Human and Animal Toxicity

Due to overuse in HT crops, most of the herbicides, particularly glyphosate, contaminate the soils and waters, and their residues have been found in our food

(Tarazona et al. 2017; Zhao et al. 2018). In the recent years, independent scientific studies are emphasizing to have an urgent reassessment of herbicides and their related products due to their negative effects on human and animal health, such as birth defects, suspected endocrine hormones, non-Hodgkin's lymphoma, and nervous disorder (Gupta 2017). Direct use of herbicides by herbicide applicators or bystanders' exposure are directly linked with these chronic effects of glyphosate and its derivative products (Ward 2017). Therefore, these scientific proofs have stressed that these health issues must be addressed very seriously (Riley et al. 2011).

In Paraguay, women exposed to glyphosate-based herbicide during pregnancy delivered offspring with congenital malformations with repeated spontaneous abortions in the village of Ituzaingo, Cordoba, which was surrounded by GMHT cropping system (Paganelli et al. 2010). A year ago, researchers observed that low rate of a commercial formulation caused disruption to the development of the craniofacial skeleton of tadpole embryos, followed by shortening trunk, reduced head size, and eye defects (Paganelli et al. 2010). Benachour and Séralini (2008) reported that reduced glyphosate far below the recommended rate rigorously affected embryonic and placental cells of human, causing mitochondrial damage and cell death within 24 h. The cell death that occurred at the concentration corresponding to the glyphosate residues in food from glyphosate-treated GM crops would result in a severe impact on fertility, carbohydrate metabolism, immune system failure, and water imbalance.

In the recent years, epidemiological and laboratory studies have indicated glyphosate along with other pesticides to be responsible for the significant increase in cancer, particularly child cancer including leukaemia, lymphoma, and brain tumours (Riley et al. 2011). These studies have shown glyphosate and other metabolites to be genotoxic or mutagenic in human cells, including live and lymphocytes (Gasnier et al. 2010). In addition, numerous studies have demonstrated genotoxicity and mutagenicity of glyphosate in mouse, bovine, fish, caiman, tadpole, fruit fly, sea urchin, and bacterial cells (see Riley et al. (2011) for references). Furthermore, glyphosate has been reported to affect the nervous system and even be implicated in neurodegenerative diseases such as Parkinson's disease (Barbosa et al. 2001). This herbicide at low concentrations inhibits the growth of neurite-like structures (Axelrad et al. 2003) as well as depletes serotonin and dopamine (Anadón et al. 2008) and causes loss of mitochondrial transmembrane potential in rat brain cells (Astiz et al. 2009). In addition, acute exposure symptoms include a wide range of effects on the skin and eyes and on respiratory, gastrointestinal, and cardiac systems.

15.3 How to Optimize Herbicide Use in HT Cropping Systems?

Changes in thoughtful weed management systems are prerequisite to stabilize HR technology and then reduce herbicide use, the cost of weed management, and herbicide-related impacts on human and environment in HT crops (Benbrook 2012).

Most of the weed experts agreed to reduce the per cent of cropland area planted with HT crop dramatically as a realistic approach to prevent resistance evolution in weeds. However, limited interest appears in seed industries in increasing the production of non-HT or non-GE crops. Farmers shift towards more sustainable conservation tillage practices, adopting HT crop cultivars, has increased the global herbicide use over the last two decades (Rose et al. 2016). Furthermore, future changes in herbicide use patterns will likely be driven by a reduction in the effectiveness of glyphosate due to weed shifts and herbicide resistance (Young 2006). Consequently, the economic and biological success of HT crops suppressed the development of innovative non-chemical weed control methods that may be critical to the long-term success of HT crops.

15.3.1 Understanding Weed Eco-Biology

Integration of weed biology-based knowledge with herbicide and non-chemical weed management programs can help in developing sustainable weed management for HT crops. This development of integrated weed management programs requires proper understanding about emergence patterns, seed fecundity, and persistence of soil seedbank dynamics, as well as dispersal mechanism of weed species. However, to address weed species with a diversity of life-history traits, investigation on both ecological and biological aspects of weed seeds could help in devising IWM strategies and tactics to achieve a difficult, but a manageable, goal (Lamichhane et al. 2017). To date, the knowledge on weed eco-biology is confined, which are merely descriptive with poor information on the mechanisms of weed responses to production systems, which needs to be filled (Lamichhane et al. 2017).

Within the ecological contexts, research on weed resistance will be of crucial importance to understand and manage the impact of herbicide selection within a systems' perspective (Thrall et al. 2011). Studies at a genetic and cellular level to develop deep and sophisticated understanding related to molecular, biochemical, and physiological bases of herbicide resistance will help in interpreting the evolutional and ecological aspects of herbicide resistance in weed species (Neve 2007). Information on these adaptive values of selected herbicide resistance alleles will develop a detailed understanding of the causes, dynamics, and processes of resistance evolution. In addition, information related to the effect of climatic changes on the fitness level of the resistant gene will help in determining the persistence, reproduction, and invasion mechanism of resistant weed species and could help in identifying conditions to decrease the heritability and frequencies of these resistant alleles in HT cropping systems (Vila-Aiub et al. 2013). In this regard, studies have not systematically addressed the effects of climate change on herbicide resistance evolution, which could be helpful to make a robust prediction that how genetics, seed biology, spatial population structure, prevailing climatic conditions, and management option will interact (Busi et al. 2013).

HT crops causes shift in weed populations to more persistent weed species via a change in type of resistance mechanisms selected for increasing the amount of exerted selection pressure, change in competitive abilities of crops relative to weeds, and by impacts associated with introducing multiple-resistant crops in long-term rotations of crop and herbicides (Dekker and Comstock 1992). It is not surprising that many of our common weeds share characteristics with the crop they thrive in best, i.e. little seed canary grass (*Phalaris minor* Retz.) and wheat crop. In addition, most species share the same taxonomic tribe, such as grain sorghum and milo, rapeseed and wild mustards, etc. These plant species become weeds either by adapting and change to mimic crops to survive weed control strategies or have been crop plants that have been selected in agroecosystems for weedy adaptation, allowing them to survive. Furthermore, unpredicted seed germination, seed dormancy, and prolonged seed dispersal are key adaptations that allow a weed to survive and build-up huge reserve of weed seeds in the soil. Combining these seed characteristics with herbicide resistance will not be a desirable situation for HT crop farmers.

Recent concerns of herbicide resistance and agronomic sustainability of herbicide-dominant weed control have directed scientist's interest in integrated weed management that is underpinned by knowledge of weed biology and ecology (Van Acker 2009). Understanding the genetic diversity and population genetic structure might guide our decisions regarding the optimum rate and timing of herbicide application. In addition, it will help in the introduction of new technological developments is promoting the use of reduced herbicide doses, variation in herbicide doses within a field in HT crops (Hall et al. 2000). Optimized use of these technologies requires farmers to make major assumptions about weeds based on scientific knowledge. Therefore, to completely get benefits from these technologies, mechanistic research on weed ecology, genetics, and physiology must be conducted to understand the weed-crop interactions, weed population dynamics under various management practices, and other aspects of weed invasion, adaptation, and persistence (Hall et al. 2000). Furthermore, predicted climatic changes, such as elevated CO_2 concentration, increased temperature, and unpredicted rainfalls, are reported to influence herbicide efficacy in C3 and C4 weed species. Therefore, studies on the morpho-physiological changes, particularly under changing climatic conditions, will help in predicting the future of chemical weed management in HT crops (Ziska 2016).

15.3.2 Maximizing Crop Competitiveness/Diversity

Since the mid-1990s, the introduction of GM HT cultivars with the continuing availability of relatively inexpensive herbicides (i.e. glyphosate) largely replaced conventional crop production systems due to successful weed management (Davis et al. 2012). However, expanding concern of environmental toxicity and increasing prevalence of HR weed species forced farmers to develop weed management strategies with less reliance on herbicides (Mortensen et al. 2012). In the development of such strategies, diversification of cropping system may play an important role (Davis et al. 2012).

The challenges of managing HR weed populations have renewed interest in cultural weed control options (Andrew et al. 2015), including maximizing crop competitiveness. Increased crop competitiveness with weed through diversification is a double-edged sword, which will allow crops to suffer less yield loss at the hands of the weeds and will also reduce weed fecundity (Holloway et al. 2008; Mathews et al. 2002). Use of crop plant manipulations, such as row spacing, planting density, row orientation, crop rotation, competitive crop cultivars, and intercropping and/or their combinations for weed management can reduce the need for and use of herbicides as well as their associated impacts on the environment (Davis et al. 2012; Harker et al. 2016).

Use of competitive varieties/cultivars reduces post-emergent herbicide usage, decreases the selection pressure for herbicide resistance, minimizes the risk of herbicide contaminating food, and improves herbicide performance (Lemerle et al. 2001; Stanton et al. 2010). Crop management practices, like increased seed rate and/or planting densities, provide supplemental weed control when herbicide inputs are reduced, which remains an apropos research issue (Kirkland et al. 2000). In addition, modifying row arrangement as a technological alternative to obtain increased grain yield through better resources use allows reduced herbicide use (Buhler 2002). Similarly, rotation of HT crops encourages diversity in cropping patterns, through changing the tillage operations, and herbicide use patterns, which can dramatically reduce the selection pressure and/or make it difficult for weeds and volunteers to adapt (Stanton et al. 2010). Use of soil-conserving cropping practices (i.e. intercrops and covers) with less synthetic herbicide inputs for weed control would be a compatible component for better weed control (Nagabhushana et al. 2001).

Over time, the development of ecosystem services in more diverse cropping rotation increasingly displaces the need for external synthetic inputs to main crop productivity (Davis et al. 2012). Integration of multiple complementary tactics in an ecological weed management framework in rotations improved the efficiency and environmental sustainability of weed management (Davis et al. 2012). In this study, diversifying crop systems (3-year and 4-year rotations) reduced the herbicide input by 6 to 10 times and freshwater toxicity by 200 times when compared to the 2-year rotation (as shown in the figure). Therefore, cropping systems with weed-suppressive characteristics reduce herbicide inputs and contribute to a diverse suite of tactics for the development of more effective, reliable, and durable weed management (Fig. 15.7).

15.3.3 Diversifying Herbicide Options

In HT cropping systems, herbicides are often the strongest selection agents for weed species; repeated use of single MOA across vast areas with genetically diverse weed population is the greatest risk associated with herbicide resistance evolution (Beckie 2006). To target the most troublesome and resistance-prone weed within the field, use of different MOAs minimizes the selection pressure imposed on weed

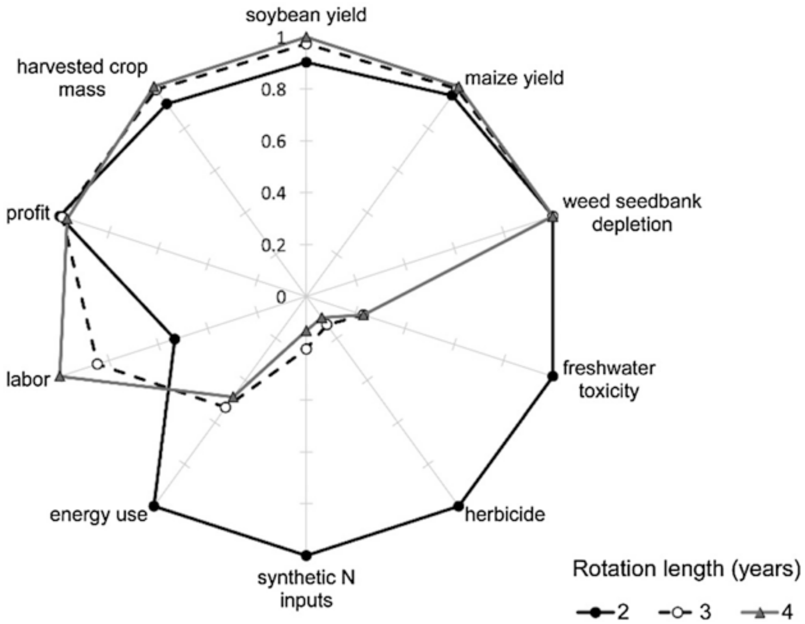

Fig. 15.7 Performance of maize-soybean (1-year), maize-soybean-small grain/red clover (3-year), and maize-soybean-small grain/alfalfa-alfalfa (4-year) cropping systems (Davis et al. 2012)

populations by a particular herbicide MOA; thus the evolution of herbicide resistance can be delayed (Norsworthy et al. 2012). These herbicide management strategies have often been recommended by weed scientists to prevent weed species shifts and to delay the evolution of herbicide-resistant weeds (Vencill et al. 2012).

Combination of two different rates of MOAs, simultaneously, sequentially, or annually, reduces the survival and reproduction of the resistant individuals (Norsworthy et al. 2012). Both herbicide MOA sequence and mixing within a growing season and rotation across growing seasons effectively delayed herbicide resistance because of a single resistance mechanism in weeds (Beckie 2011). Herbicide rotation and mixing have been predicted to be the most effective strategies in preventing evolution in species with limited pollen movement, limited resistance allele transfer via pollen, and limited seed dispersal (Diggle et al. 2003). Through keeping the resistance frequency at a low level, single-gene target-site resistance evolves more slowly in weed populations with the continuing establishment of susceptible individuals from persistent seedbanks. The epidemiological information from farmers' questionnaire surveys, modelling simulations, and field researches supported the greater effectiveness of herbicide mixtures compared with rotations in delaying resistance through herbicide selection (Neve 2008; Beckie and Reboud 2009).

Over the past decades, the level of adoption of herbicide rotations has increased markedly for weed resistance management; even though awareness was high, few farmers practised herbicide rotation (Beckie and Reboud 2009). However, this is the most commonly used practice for herbicide resistance management in Canada and Australia. However, limited availability of suitable herbicide option in accordance to crop rotation could be a substantial deterrent to herbicide rotation HT cropping systems. In developed countries, most of the herbicide products include group identification symbols and guidelines for resistance management practices in the use direction (Beckie and Reboud 2009). Implementation of labelling regulation in Canada probably facilitated the adoption of herbicide rotation in 1999 (Beckie and Reboud 2009). The inclusion of herbicide group labelling and guidelines for preventing resistance practices will minimize the risks of herbicide resistance in most developing countries (Fig. 15.7).

Herbicide mixtures could be effective against HR weed biotypes as mixing MOAs deplete the resistance alleles by decreasing the survival probabilities of all HR individuals (Evans et al. 2016; Evans et al. 2018). Nowadays, it is more challenging to find possible MOA mix against a particular weed which has already evolved resistance against multiple effective herbicide options (Evans et al. 2016). It seems to be only possible if new HT crops are introduced into the market with multiple HT traits. However, herbicide mixtures, if applied at low or marginal rates, might confer the broad cross-resistance and non-target-site resistance (Evans et al. 2016). Furthermore, the increase in the number of herbicide compounds might increase herbicide costs and farmer's exposure as well as elevate environmental risks. Therefore, truly diverse management practices are required for long-term, cost-effective, and environmentally sound weed management with minimized selection for herbicide-resistant traits (Norsworthy et al. 2012). Therefore, integration of chemical weed management with cultural, physical, and biological approaches will provide such weed management programs with reduced reliance on herbicides (Davis et al. 2012).

15.3.4 Integrating Weed Management Strategies

To preserve the utility of HR crops/technology, greater diversity in weed management technologies is badly needed (Duke and Powles 2009). It includes alternative herbicides, mechanical tools, and biological factors, which restrict the evolution of herbicide resistance in weed species or may slow the process if there is sufficient diversity in weed control. For example, with the adoption of HR soybean since 1996, herbicide diversity was minimized, resulting in the disappearance of many widely used herbicides from most fields. Thus, lack of diversity in weed control options followed by repeated application of herbicide on the same field every year in HT crops increased selection pressure over weed species. Thus, minimal diversity in weed control accompanied by frequent herbicide use and no mandated herbicide resistance programs to delay resistance evolution resulted in fastest evolutions of herbicide resistance and their rapid spread (Evans et al. 2016). In addition, HT crops enable farmers to adopt minimum or zero-tillage systems and remove mechanical tools for weed management and therefore reduced weed control diversity (Duke and Powles 2009).

Diversification of weed management tactics might reduce the risks of herbicide resistance(s) evolution in weeds species and will promote biodiversity (Nazarko et al. 2005). Therefore, use of HT crops as part of an integrated weed management(IWM) strategy will help ensure the long-term benefits of a profitable and environmentally sound weed management program (Knezevic and Cassman 2003; Lamichhane et al. 2017). Proper use of HT crops as part of an IWM program might preserve the long-term benefits of this technology while avoiding many of the concerns. Practically, the potential benefits of HT crops are rarely appreciated due to a wide range of technical and socio-economic limitations that obstructs the farmers' shift of IWM. Based on the experience gained in countries where conventional and GM HT are widely grown, Lamichhane et al. (2017) proposed five action points to facilitate the rapid shift towards IWM with HT crops:

(i) Education programs to maintain and improve knowledge of weeds and their management to help farmers in identifying factors promoting or hampering the successful uptake of diverse weed management practices and how implementation by other growers could be facilitated.
(ii) Revision of current stewardship programs to include both mandatory and recommended practices to develop an important and rational understanding for IWM programs and the need to adopt best management practices.
(iii) Integration of socio-economic studies to understand and change farmers' attitude and behaviour, which might impact the proactive adoption of IWM and BMP for HR weed management.
(iv) Development of adequate public policy to formulate and implement strategies associated with alternative programs, promoting mutual interactions between farmers, crop consultants and extension personnel, and the herbicide industries to manage HR weeds.
(v) Regulatory revisions to encourage risk assessors and managers to consider perspectives on the sustainable deployment of HT crops within the IWM crop system.

In the USA, farmers were recommended to adopt more diversified weed control practices to proactively minimize and manage increasing onset of weed populations showing herbicide resistance (Norsworthy et al. 2012; Vencill et al. 2012). In response to this, farmers of GM HT responded proactively and diversified their weed management strategies involving other herbicides in combination with glyphosate, even where the incidence of herbicide resistance has not been found. This willingness to proactively diverse weed management systems in these cropping systems was also influenced by a desire to maintain effective weed control and hence continue to enjoy the benefits of conservation tillage (Brookes 2014). It, therefore, showed that the maintenance of a diversity of weed management tactics is critical for sustaining the use of herbicide options. Therefore, herbicide programs must be integrated with preventive, cultural, biological, and mechanical weed control practices to develop diversified weed management strategies.

15.3.5 Improved Herbicide Technologies

15.3.5.1 Future HT Crop Technologies

HT crops revolutionized crop production in the developing countries, and the benefits have been spilling gradually over to the developing world (Reddy and Nandula 2012). The recent developments in this technology warrant the sustainability and stewardship of previously commercialized HT crops. Among these technologies, the development of transgenic crops that are tolerant to two or more herbicides remains a major challenge and a priority area of agricultural programs (Fartyal et al. 2018). To counter the problem of glyphosate resistance in weeds, agrochemical and agribiotech companies have proposed and are working to introduce multiple HT traits in crops, in addition to glyphosate tolerance (GT) traits.

Recently, Fartyal et al. (2018) developed dual-herbicide-tolerant transgenic rice plants, exhibiting tolerance to bensulfuron-methyl (ALS inhibitors) and glufosinate (GS inhibitors) herbicides. In addition, the development of Clearfield∗ crops is the best example of commercially available non-transgenic crops, which is tolerant to various imidazolinone herbicides (Tan et al. 2005). Last year, a novel imidazolinone-tolerant mutant is developed and characterized in Indica rice that is able to tolerate increased application of imazethapyr herbicide (Shoba et al. 2017). In addition, most of the new HT technologies are currently under development, and all the new traits will be stacked with glyphosate (Reddy and Nandula 2012). Some of these technologies will include dicamba, and 2,4-D resistance has also associated formulations specifically developed for application with these new technologies.

Use of herbicide rotation and mixtures are always suggested to over the problems of HR weeds; this technique reduces the possibilities for a weed species to acquire herbicide resistance (Green and Castle 2010). Thus, the development of transgenic plants with tolerance against more than one herbicide group will be a great solution to overcome this problem (Fartyal et al. 2018). In modern agricultural systems, the development of multiple-tolerant transgenic plants will add further information to the knowledge of crop herbicide tolerance for sustainable weed management. This technology will be extremely important in maintaining the diversity of herbicide use in HT crops for efficiently exploiting the properties of importantly available herbicides and to manage weeds proficiently in the long term. However, high cost, lengthy development time, and high economic risk have been the primary reasons for the slow development and introduction of new HT crops.

15.3.5.2 Nanotechnology

Improvement in the efficacy of herbicides through the use of nanotechnology resulted in greater production of crops. Nano-formulations of pesticides, the development of nanosensors, and nanoparticle-mediated resistant crop varieties are part of agricultural nano-application spectrum (Ojha et al. 2017). These nano-herbicides contain many trillions of active ingredient particles per litre and create an extra surface area by the reduction on particle size which boosts potency, accelerates plant uptake, increases tank-mix solubility, and reduces settling and separation risks. In addition, this technology is spawning breakthrough products such as herbicide sensors, which can dramatically reduce the number of products used and toxicity of herbicide treatment. The potential to create these products with revolutionary properties prompted the world's leading agrochemical and agribiotech companies to speed up their commercial developments. In 2012, DuPont initiated a 10-year $12 billion research program for the US National Nanotechnology Initiative (NNI) to review groups and workshops and design teams that contributed to the identification of research priorities (Alharby et al. 2019).

In the recent years, BrasÍlia and Sao Pãulo Brazil (BASP) and Embrapa's Cultivance® soybeans receive approval for commercial cultivation in Brazil, combining HT soybean varieties and broad-spectrum imidazolinone herbicides, tailored to regional conditions and made possible in part by nanotechnology (Homrich et al. 2012). This technology will be convenient and flexible for farmers, offering an opportunity to control a broad spectrum of weeds with several imidazolinone herbicides during the first few weeks of crop growth. This technology allows farmers to attain season-long control of broad-leaved and grassy weeds with a single application, thus reducing the use of farm machinery; energy consumption thus reduces farmer's production costs and decreased CO_2 release into the environment (Ali et al. 2014).

Despite developing HT crops, agro-based industries are focused on developing nanotechnologies targeting weed seeds in the soil seedbanks. These nanoformulations, including nano-dispersants or nano-emulsions of herbicides, will sterilize weed seeds by damaging seed coating (Dhillon and Mukhopadhyay 2015). These suitably functionalized nanoparticles would be an intelligent solution for exhausting the weed seedbank through degrading phenolic compounds responsible for the dormancy of seeds. Researchers believe that this nano-formulated herbicide will destroy the weed seed buried in the soil and will limit their germinability even under favourable weather or edaphic conditions. This technology will be equally effective for controlling weeds that reproduce asexually and disperse through vegetative propagules (Prasad et al. 2014). In very small proportions, these herbicides will blend with soil and easily reach the targeted weed seeds buried below the reach of tillers and have developed resistance to conventional herbicides.

In addition, nano-adjuvants are a critical component of making effective herbicide application to control most problematic weeds (Prasad et al. 2014). These adjuvants are specifically engineered from the ground up to safely improve the performances and efficiency of post-emergent herbicides and might prove beneficial with stubborn burn-down issues and off-label weed control. In other words, nano-adjuvants help in optimizing the overall herbicide performance by translocating existing microparticles into a synergistic relationship throughout the plant and will remain for as long as there is circulation of liquid amino acids, enzymes, and nutrients. If these nano-adjuvants are combined with smart delivery systems, herbicide application may be achieved in a controlled and targeted manner with a minimum impact on the environment and human health (Manjunatha et al. 2016). It is also believed that this adjuvant will overcome resistance mechanisms by promoting a higher level of herbicide penetration into the plants. However, no scientific evidence has supported the fact that weed resistance to glyphosate is simply a lack of foliar absorption. Recently, one of the nano-surfactants based on soybean micelles has been reported to make GR crops susceptible to glyphosate (Yata et al. 2017).

Nanotechnology has revolutionized the agricultural industry through innovative enhancements on lowering herbicide doses (Omanović-Mikličanina and Maksimović 2016). These sensors make appropriate and on-time decisions through monitoring and measuring environmental variables and perform targeted actions to maximize outputs with optimal use of herbicide (Rai and Ingle 2012). Networks of connected nanosensors for monitoring soil and plant conditions possess the potential to alert automatically about the prevailing conditions and influence more efficient use of herbicide (Omanović-Mikličanina and Maksimović 2016). These nanosensors use nanoscale devices to identify and sense conditions, either physically, chemically, and biologically suitable for weed control, and translate that response into signals and outputs in a useful form and then transmit it to users (Dhillon and Mukhopadhyay 2015). These nanosensors can also be used to reduce pollen contamination from GM HT crops to conventional field crops (Agrawal and Rathore 2014).

If carefully introduced, nanotechnology could be promising in the field of agrochemicals, farming, and food production with new product being trailed around the world. Development of new HR technologies integrated with nanotechnologies might reduce or eliminate the risks of herbicide resistance and weed population shifts. Development of nano-herbicides or nano-formulated adjuvants will address the problems in perennial weed management and will help in exhausting weed seedbank. This technology will decrease or eliminate the effect of excess toxins on the environment and allow HT crop farmers to increase their yields at lower use and costs of herbicides. Though new tools are underway, challenges related to nanotechnologies, such as high processing costs, scalability of research and development, industrial production, and concerns related to public perception of environment and health and safety issues require more research and understanding.

15.3.5.3 Drift Reduction Technology (DRT)

Due to the introduction of HT crops, concerns of volatility, spray drift, and non-target movement of herbicides, such as 2,4-D, dicamba, glyphosate, and glufosinate, become major threats for conventional field crops (Knezevic and Cassman 2003). DRT program has been proposed to encourage the manufacturer, distributors, and farmers to use spray technologies that are scientifically verified to reduce herbicide drift. As compared to technologies with minimum DRT standard, the use of DRTs results in a significant reduction in herbicide from spray drifting and being deposited to non-targeted areas. The successful adoption of these technologies will shift crop production towards the widespread use of low-drift technologies. This initiative will provide a standardized, verified system for reducing herbicide drift by the cooperation of manufacturers, distributors, and farmers.

For air-assisted sprayers, in particular, it is necessary to evaluate the spray drift-reducing potential. DRTs have been tested and categorized in some countries for their capabilities to reduce the spray drift (Balsari et al. 2011). This technology is mainly focused on measures to reduce the number of fine droplets through the modification of hydraulic nozzles used in field crops, which has been largely accepted in some European Union countries. Drift-reducing nozzles, adjusting boom height, and driving speed are some examples of mitigation measures for field crops. Depending on these mitigation options, the drift risks will either increase or decrease. Some countries have started to classify sprayers on the basis of their spray drift-reducing potential. This technology also includes devices, adjuvants, and sprayer components useful in mining spray drift through increasing average droplet size (air induction nozzles, anti-drift adjuvants, etc.) or through preventing spray dispersion out of the applied fields (air curtain sprayers, shield, tunnels etc.).

An analysis of the hazards and risks to neighbouring crops and sensitive areas showed that for most situations vapour drift following herbicide application is a minor risk compared to particle drift during herbicide application. Vapour drift is highly dependent on the herbicide's vapour pressure and climatic conditions, particularly temperature and low humidity during and 24 hours following herbicide application. Increased use of auxin-resistant crops promoted the use of dicamba and other auxin herbicides, which possess the potential to injure other dicotyledonous crops and reduce biodiversity around field boundaries and nearby crops via spray and/or vapour drift (Green and Owen 2010). Literature report dicamba in acidic form as more volatile as compared to amine salt formulations and some of these formulations are more volatile than others. However, scientists are developing ways to abate volatilization with new salts and formulations with an objective to reduce potential off-target movement with application restrictions (Green and Owen 2010). For example, new 2,4-D choline formulation has been reported with much lower volatility potential.

15.3.5.4 New Use of Existing Herbicide Technologies

Researchers are proposing reuse of most of these herbicides, such as phenoxy-based herbicides, after 10–15 years in the form of new products or formulations with low volatility. In the short term, the improvement of existing herbicide technologies will provide further opportunities to counter the appearance of resistant weeds and to reduce the use of herbicides in HT crops (Lombardo et al. 2016). Most of the previously used herbicides with known MOAs are available in new formulations containing new salts and esters or new active with minor chemical modification, claiming increased weed control efficiency, crop safety, and reduced rates and soil residual activity (Kraehmer 2012). Examples of such herbicides are aminocylopyrachlor and halauxifen-methyl (synthetic auxins), pinoxaden (ACCase inhibitor), saflufenacil (PPO inhibitor), bicyclopyrone, tembitrione, and pyrasulfotole (HPPD inhibitors), trifamone (ALS inhibitor), indaziflam (cellulose biosynthesis inhibitors), and pyroasulfone and fenoxasulfone (very-long-chain fatty acid inhibitors).

A new generation of crops with resistance to glyphosate, glufosinate, and other existing herbicide MOAs is underway. Though most companies are involved in discovering new MOAs, these industries are developing new HT traits in combination with GR, including glufosinate, 2,4-D, dicamba, and other herbicide types (Service 2013). Some of these HT traits are widely available, and most of them should be available to farmers as seed companies are getting access to these new HT traits after government approvals. Crop with multiple HT traits will allow farmers to control HR weeds via new options with existing herbicide. These new chemical analogues can control HR weeds but are not a permanent solution because of cross-resistance in weeds (Green 2014).

With the launch of HR technology (i.e. GR crops and glyphosate, a simple non-volatile herbicide), most of the high-volatile herbicides, including dicamba, were replaced. In addition, this technologies reduced the amount of high-volatile herbicide in crop production systems as most of the chemical companies gave up their agrochemical business due to a high standard of existing products in the market and high registration costs (Kraehmer et al. 2014). Some scientists are wondering to sort out the problem with the introduction of new-generation GM crops with phenoxy-based herbicide resistance. As an example, the introduction of broadleaf crops resistant to synthetic auxins (i.e. dicamba and 2,4-D) are more likely to have a significant impact because HT trait in soybean and cotton will enable the new use of these existing herbicides with broader utility (Wright et al. 2010). In addition, few weeds have evolved resistance against these herbicides in the last 60 years (Heap 2018). New formulations with less volatile salts and drift control adjuvants will help in reducing the non-target movement of herbicides and will reinvent this technology (Green 2014).

15.3.5.5 Discovery of New MOA

Over the last three decades, the lack of success discovering a MOA is a major concern in HT crops (Green 2018). New MOA is needed to counter the rapidly increasing evolution of herbicide resistance. The success of HR technology removed a major portion of profit margins from the global herbicide market, and investment in new herbicide discovery waned considerably (Duke and Dayan 2015). Agrochemical companies' consolidations and the availability of more generic herbicides are major obstacles in the new herbicide discovery research (Duke 2012). Possibilities might also be that the best target sites have already been revealed. Still, many of the target sites have not been exploited as suggested by the molecular biology studies and natural product research (Duke and Dayan 2015).

Use of microorganisms' by-product and plant extracts could be a promising direction in the discovery and development of novel herbicide based on natural products (Westwood et al. 2018), though a limited number of plant and microbial organisms have been screened for their herbicidal potential. Other prospective new tools will be the use of RNA to target key weed genes through RNA interference (RNAi) process which enhancing weed susceptibility to herbicides or outright death of the weed (Westwood et al. 2018). This technology is assumed to control the cross-resistance of traditional herbicides through inhibiting targets of current herbicide chemistries because RNAi works through different mechanisms.

Research takes around 11 years with a cost of 236 million US dollars to commercialize a herbicide, involving screening of more than 20,000 chemicals to find one new herbicide, one which is certainly without a new MOA (Green 2018). Development of new herbicide technologies is prerequisite to sustain the chemical herbicide systems, especially since the evolution of non-targeted site resistance, which can result in cross-resistance to newly developed herbicides before their commercial use (Han et al. 2016). These are the main reasons for the slow and expensive process behind the development of weed management solutions with new herbicides paired with GM crops (Green 2018). Therefore, weed scientists need to understand primary drivers in herbicide discovery, such as in vivo testing, scientific observations, and hypothesis-based research as these factors remain the same as they were 50 years ago in the discovery of new MOA (Epp et al. 2018).

15.3.6 Farmer's Training and Improved Herbicide Knowledge

Non-judicious pesticide use in agriculture contributes is highly vulnerable to the environment and human health (Jallow et al. 2017). Comprehensive intervention measures to reduce these hazards include farmers' herbicide safety training programs, rigorous implementation of pesticide laws, and the promotion of cohesive weed-managing strategies. Despite endangering the environment, farmworkers' exposed to herbicide use has been associated with an adverse health issue, e.g. birth defects and cancer, in the developing countries. In developing countries, farmers face great risks of exposure due to the use of toxic chemicals that are banned or restricted in other countries, incorrect application techniques, poorly maintained or totally inappropriate spraying equipment, inadequate storage practices, and often the reuse of old pesticide containers for food and water storage (Matthews 2008).

Deficiency of pesticide hazardous information, rigid farmers' perspective about herbicide risks, and unawareness to safety practices regarding storage, handling, and disposal have exacerbated the risks associated with herbicide use. No doubt, high level of education gives herbicide users access to improved knowledge about herbicide-associated risks, though illiteracy in the developing countries hampered farmer's abilities to understand these hazards and restrict them to follow recommended safety and application guidelines to avoid unwanted exposure.

Government and stakeholders in agriculture should organize training programs to enhance farmer's attitude in the use of herbicide, with the main focus on herbicide-related health hazards, proper use of protective equipment, practising hygiene measures, and become familiar with and adopt proper work practices. In addition, policymakers, extension agents, NGOs, and related organizations should educate the farmer group regarding the dissemination and implication of information on herbicide use. Farmers need to minimize dependence on herbicide through integrated weed management including continuous monitoring of adversities, such as escape weeds and test their resistance level.

15.4 Recommendation

In the past 50 years, weed scientists have not improved the potential of farmers to use herbicide in conjunction with alternative weed management strategies, which resulted in increased cases of herbicide resistance and weed population shifts.

Farmers can achieve optimized herbicide use by following below-mentioned recommendations:

(i) Modification in HT cropping systems and weed control strategies reduces the risks of HR evolution and promotes diversity in an economically and environmentally sound manner (Lamichhane et al. 2017).
(ii) Farmers need to be educated about MOAs and should be informed about the rarity of new herbicide discovery, exhaustibility of existing herbicide resources, and impacts of indiscriminate herbicide use (Norsworthy et al. 2012).
(iii) Breeding approaches to prevent outcrossing of HR genes should further be developed (Schutte 2000). In addition, isolation distance for large sources and sinks of genes should be established on the basis of seed production experiences and knowledge of gene flow.
(iv) Herbicide-tolerant crops, relatively new weed control technology, should be considered as one component of an IWM program, utilizing other management tools to ensure long-term profitability and environmentally sound weed management approach (Knezevic and Cassman 2003).
(v) Fostering awareness-training programs and coordinating responses related to HR weeds and associating costs, thereby promoting the implementation of an integrated solution for the alleviation of practical and socio-economic issues, hampering the shift towards IWM (Lamichhane et al. 2017).
(vi) Environmental harms associated with the changes in agricultural practices and management of HT crops needs to be monitored and fully assessed.
(vii) Development of Technology Use Guide for HT crops will provide detailed weed control recommendations related to herbicide doses, mixtures, and rotation with an objective that farmers stick to good agricultural practices.
(viii) Development of local advisory centres and boards where independent experts recommend farming measures and develop obligatory guidelines (Schutte 2000).

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Non-chemical Weed Management for Field Crops

16

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Abstract

Weeds are unwanted plants that enhance the production cost of crops, which causes economic loss to growers. Historically, hand-weeding is one of the oldest methods to control weed, and all other weed control methods during earlier times were chemical-free. Use of inorganic chemicals started during the late nineteenth century. Non-chemical means to control weed include preventive, cultural, physical, or mechanical measures, exploiting allelopathic means, and bio-measures. While among other approaches, preventive methods and cultural means of controlling weeds, like cover cropping, intercropping, and crop rotation, are usually less frequent but implemented. Similarly, thermal weeding, utilizing the electromagnetic fields and electric systems, is an another tool for conquering weeds. Integrated weed management offers usage of all available tools to effectively minimize weeds in a short- and long-term approach because farming community always preferred to choice an inexpensive, informal, and eco-friendly measure to manage weeds.

Keywords

Weeds · Weed control · Cultural methods · Allelopathy

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16.1 Introduction

Weeds are the unwanted plants that increase the production cost of the crops, which can cause economic loss to the farmer. Historically, hand weeding is considered to be the most ancient practice followed by the growers to remove unwanted plants (Timmons 2005). So, weed control is relatively an oldest art, but because of the modern techniques and approaches, it is one of the youngest of sciences. All the weed control techniques of the earlier time were chemical-free. However, farmers started using inorganic chemicals to manage weeds during the late nineteenth century. Later on, in the middle of twentieth century, a new era of weed control was started with the discovery of 2,4-D. But even then non-chemical ways of controlling weeds are used in combination with herbicides due to their safe usage. There are several ways of weed control by non-chemical means including preventive, cultural, physical, or mechanical measures, exploiting allelopathic means, and bio-measures. Table 16.1 gives a brief overview of the currently available non-chemical weed control measures. In weed management approaches, exploiting tillage practices is a reliable component for the farmers. While among other approaches, preventive methods and cultural means of controlling weeds, like cover cropping, intercropping, and crop rotation, are usually less frequent but implemented. Selection of appropriate sowing techniques can also offer a good alternative for weed control (Farooq and Cheema 2013) as in the case of bed plantation of different crops (wheat, cotton, maize, sunflower, etc.) and flooding in rice. Other options like agronomic management (e.g., narrow row spacing and high seed rates) and selection of cultivars with good competitive ability are important choices for the farmers that do not require extra costs but prove effective in controlling weeds in all crops. Exploiting

Table 16.1 Different choices of non-chemical weed control methods

Choices of non-chemical weed control	References
Prevention measures	Jabran et al. (2017)
Use of mulches	Crutchfield et al. (1986) and Jabran and Chauhan (2015)
Soil solarization and stale seedbed	Jabran and Chauhan (2015)
Planting geometry	Farooq and Cheema (2013, 2014)
Flame weeding	Ascard (1995)
Allelopathic/competitive cultivars	Sardana et al. (2017), Jabran et al. (2015) and Jabran (2017)
Row spacing, seed rate, row direction	Sardana et al. (2017)
Exploiting allelopathy	Farooq et al. (2011a, b, c), Jabran et al. (2015), and Jabran (2017)
Intercropping, cover crops	Jabran and Chauhan (2015)
Crop rotation pattern	Shahzad et al. (2016)
Mechanical measures (tillage)	Shaner and Beckie (2014)
Biological measures	Winston et al. (2014)

allelopathy to suppress weeds is also gaining good attention of the researchers to devise non-chemical weed control programs. Similarly, thermal weeding and utilizing the electromagnetic fields and electric systems are other tools for conquering the weeds. In a nutshell, each method has its own practical advantages, but we always should adopt an integrated approach to tackle this uninvited guest (weeds). Integrated weed management offers usage of all available tools to effectively minimize the weeds in a short- and long-term approach because farming community always preferred to choose an inexpensive, informal, and eco-friendly measure to manage weeds.

16.2 Why Non-chemical?

Up to now, herbicides are contributing enormously not only in monitoring weeds but also for improving crop productivity. Herbicides are significant but not a single option for killing weeds. Moreover, there are several concerns related to herbicide usage (Table 16.2). Although there are some observations in using non-chemical weed management like these may be complex, retain a lower efficacy (in comparison to herbicides), and these require high costs, but even than these are required for the sake of health and environmental security (Moss 2010).

Resistant development in weeds to certain weedicides is one of the supreme challenges met by the weed scientists (Heap 2014). It has been reported that more than 250 weeds have developed resistance against 161 weedicides; among these, nearly 100 are narrow-leaved, while 150 are broad-leaved. So far, there are 26 known weedicide modes of actions, while against 23 modes of actions, weeds have developed resistance (http://www.weedscience.org/). In 68 countries, 91 crops have been reported where herbicide-resistant weeds have developed. There are several reasons that why weeds have attained resistance against herbicides, among these repeated use of same herbicide, growing of same crop again and again, are dominant problems. While development of new herbicides with model site of action is very slow or limited. Misuse of chemical herbicides leads to the risk of environmental safety, and quality is badly deteriorated. Herbicide residues can contaminate the houses in close vicinity (<750 m) of the farming fields (Ward et al. 2006). While during

Table 16.2 A summary of negative impact of herbicides

Herbicide negative impact	References
Resistant development in weeds against herbicides	Heap (2014)
Contaminated with herbicide residues	Ward et al. (2006)
Killing of non-target plants	Gaba et al. (2016)
Adverse effects on beneficial insects like honeybees	Jumarie et al. (2017)
Negative impacts on environment	Hayes et al. (2002)
Several diseases and health issues in human beings	Camacho and Mejia (2015)
	Sterling and Arundel (1986)
	Lebov et al. (2015)

application of herbicides, non-targeted plant species can also be killed (Gaba et al. 2016) that causes severe economic loss to the farmer. Negative impact of herbicides on human beings (causing severe illness, chronic diseases, cancer, etc.) and other living organisms has been reported in several studies (Sterling and Arundel 1986; Rohr and Palmer 2005; Potts et al. 2016).

So, because of the aforementioned concern regarding the use of chemical herbicides and to provide safe food (free of chemical residues) and clean environment (free of contamination) to the increasing population of the world, we should highly encourage the usage of chemical-free weed control strategies in our farming systems. It is the prime and moral duty of weed scientists to promote this tool among the farmers.

16.3 Preventive Measures: A First Choice

Prevention is always a keystone in the weed control programs all over the history, so that's why it was considered as a first choice. It is no doubt the cheapest choice that a farmer can assume. However, preventive strategy is diverse that involved combination of practices and policies that avoid weed introduction and spread or dispersal of certain species to areas which were free of those weed species (Rizzardi et al. 2004). Preventive management is an efficient technique for any area, from a small vegetable cropped area to a large major field crop area. In many countries, there are specific organizations (that have laws and regulations) that control the movement and spread of weed seeds. These organizations also have seed laws that are intended to safeguard the purity of crop seeds but also prevent the spread of weed seeds.

Prevention strategy is considered as an important pillar of integrated pest management (IPM) (Norris et al. 2003), but this management option sometimes requires great attention because in many cases certain farmers are unwilling to practice this specifically if the land is leased or rented. There are several factors that are responsible for the spread of weed seeds in cropped areas (Table 16.3), so a keen effort is required to stop them at all these levels. Farmers should be made aware about these entry points also. There are some key considerations that should be strictly followed to avoid weeds or to deal with the problem of weeds.

Table 16.3 Various elements of weed seed dispersal

Sources of weed seed in crop lands	References
Dissemination by wind	Shields et al. (2006)
Transport by animals	Harper (1977) and Couvreur et al. (2005)
Transport by water	Dastgheib 1989 and Lorenzi (2000)
Dispersal by human activities	Upadhyaya and Blackshaw (2007a, b)
Dispersion by machineries	Blanco-Moreno et al. (2004)
Transportation by plant parts	Baker (1974)
Transportation by soil	Upadhyaya and Blackshaw (2007a, b)
Composting materials	Larney and Blackshaw (2003) and Cudney et al. (1992)

- A careful monitoring should be done for the sources/vectors of new weed introductions to the farm and ecosystem.
- Weeds must be controlled at their vegetative stage (before the start of reproductive phase).
- If matured weed plants are uprooted, these must be buried in un-infested plots.
- Whenever you deal with farm machinery, it must be properly cleaned prior to use in the field.
- Weeding should also be done in nearby areas, like water channels supplying irrigation water to the field and surrounding fallow areas to stop the possibility of weed seed entry.
- Farmyard manure must be obtained from a reliable livestock farm to check the entry of weed seeds.
- In case of perennial weeds, vegetative propagules should be carefully eradicated.
- Everyone should follow the government laws and regulations regarding the entry and movement of plant, seeds, and plant materials.

16.4 Cultural Measures

Cultural controls are mainly aimed at manipulating the agroecosystems that ultimately lead to the cropping system less favorable to the established and propagating weeds. Historically, cultural control was primarily used to manage weeds and other pests, but later on these were often restricted due intensive labor demand in favor of herbicides. Research indicates that various cultural ways can be efficiently utilized for the effective weed control in several ecosystems. These cultural practices include management of crop density, crop cultivar selection, sowing time, line spacing, intercropping, cover crops, crop rotations, and selective fertilization.

16.4.1 Crop Density

Among the non-chemical weed control methods, enhancing crop density is an important tactic to suppress the dominating weeds (Eslami 2015). In enhancing crop density, generally row spacing is reduced that ultimately improves the competition for light, soil moisture, and soil available nutrients, and it has been further mathematically suggested by Fischer and Miles (1973). There have been several studies in all major crops that indicated the benefit of weed control by increasing the plant density like in maize (Williams and Boydston 2013), wheat (Olsen et al. 2005), cotton (Gwathmey et al. 2008), rice (Chauhan 2012), soybean (Korres and Norsworthy 2015), and even in vegetables like lettuce and spinach (Simko et al. 2014).

16.4.2 Crop Cultivar Selection

Selecting an appropriate cultivar within crop species is an important decision in integrated weed management choices for farmers because cultivars differ in their ability to compete against weeds. In this regard, old taller crop cultivars have more competitive ability than the modern semidwarf cultivars (Gibson and Fischer 2004). Selection of the better cultivar can be based on two parameters: first is the ability of a cultivar to tolerate weed competition while maintaining its high yield targets under prevailing weedy conditions, while 2nd is the capability of the cultivar to overwhelm the growth of competing weed plants (Korres and Froud-Williams 2004; Andrews et al. 2015). There are several factors to be considered while selecting a cultivar, like rapid seedling development; biomass accumulation and leaf area development; ability to efficiently utilize the available resources (water, nutrients); better growth characteristics (tallness, shading ability); tillering capacity; growth period; and most importantly allelopathic ability (Korres 2018).

16.4.3 Sowing Time

Time of sowing is one of the examples of the many crop management operations that can be deployed to suppress weed populations, and it also influences the type and the degree of weed infestation during a growing season. For example, Farooq and Cheema (2013), during 2-year experiments, observed that weed dynamic in wheat is significantly influenced by sowing time. They recorded very low weed pressure in late planted wheat in comparison to early plantation. Similarly, in various field observations, planting time was practiced for managing weed problem (Vidotto et al. 2016; Korres 2005; Gibson et al. 2002).

16.4.4 Line Spacing

For the purpose of controlling weeds in a non-chemical weed management system, line spacing plays a vital role. Many crops are grown in wide distant rows to allow better crop growth and facilitate a good weed control between rows, but on other hand this provides enough space for the weeds to grow and flourish, and ultimately yield of the crop can be reduced in some situations, whereas reducing row space with increased crop density enhances the competitive capability of crops with weeds (Mohler 2001; Lemerle et al. 2001).

16.4.5 Intercropping

Growing of two crops simultaneously on a same piece of land in alternative rows or more than two crops in alternative rows is termed as intercropping. In intercropping, annual crops can intercropped with annuals, annual crops with perennials, or perennial crops with perennials. One of the main objectives of intercropping is to control the weeds (Chikoye et al. 2001) with a parallel benefit of reducing the risk of failure of crop (Liebman and Dyck 1993). In this regard the choice of 2nd crop is very much important. Intercrops may inhibit the germination and growth of weeds (Baumann et al. 2000) by limiting the resources for weeds (Liebman and Dyck 1993), by shading the weeds (Itulya and Aguyoh 1998), or by allelopathic interactions (Farooq et al. 2011a, b, c).

16.4.6 Cover Crops

A cover crop is primarily planted to give a cover to the soil. Besides other several advantages of cover crops like managing soil erosion, improving soil fertility/soil quality, and enhancing biodiversity and wildlife, these crops are also helpful in controlling weeds in any agroecosystem (Lu et al. 2000). It is not a very common practice for weed management in several countries but an important component of sustainable agriculture. Dense cover crop stand during its growth period competes with the germinating weeds and not allowing them to complete their life cycle. Moreover, sometimes cover crop forms a thick impenetrable mat-like stand that drastically checks the light penetration to the soil, which in turn reduces the weed seeds to germination (Teasdale 1993); hence those cover crops that establish rapidly and have huge biomass production are most suitable for weed management (Teasdale 1996; Ekeleme et al. 2003). During the growing period of cover crops, these strongly compete with weeds for space, nutrients, and light (resources), while after death they form a thick mulch layer and exert a smother effect on the new emerging weeds. So, these cover crops inhibit the weeds both during their growth and even after death (Blackshaw et al. 2001).

16.4.7 Crop Rotations

Crop rotation is the sequence of growing crops one after the other on a specified area and time with the objective of obtaining the highest economic returns and lowest production cost by maintaining the soil fertility status. Diverse crop rotation patterns are required for improved weed management program. So, crops with different life cycles should be rotated that can interrupt the development of weed-crop associations. Variables that are responsible for better control of problematic weeds in a rotation pattern are competition for resources, disturbance of soil, mechanical injury, and allelopathic interference. However, despite of all these positives, it is difficult to design long-term crop rotation patterns only for weed management, due to economic concerns and market forces associated with the farming community. So, the principles upon which crop rotation practices should be based are the following (Korres 2005):

- Deep root and shallow root crops should follow each other for right and uniform consumption of nutrients.
- Legume crops should be sown after non-legume; legume crops can supplement the nitrogen status of soil and prove beneficial for the upcoming crop.

- Crops requiring high nutrients (exhaustive crops) must be followed by crops requiring fewer nutrients.
- Crops in rotation should have high market value (as possible).
- In crop rotation, the same family should not be grown in one after the other.

16.4.8 Selective Fertilization

Selective fertilization can provide a selective control over specific weed species only. Nitrogen application before sowing can enhance the competitive capability of crops (especially those have speedy early growth) against weeds, but this is influenced by the type of weeds present in the field. Like in sunflower field under Mediterranean conditions, if we apply the whole nitrogenous fertilizer before sowing, it will enhance the suppression of late germinating weeds like *Chenopodium album*, *Xanthium strumarium*, and *Solanum nigrum* in comparison to the split application of the said fertilizer, i.e., half before sowing and half as topdressing (Paolini et al. 1998). Whereas, under same situation, early emerging weeds like *Sinapis arvensis* took a competitive advantage. Likewise, if we delay the topdressing of nitrogen in sugar beet, it will increase crop competitive capability with domination of late or early germinating weeds, respectively (Paolini et al. 1999). Weeds can consume available nitrogen and phosphorus more efficiently in comparison to crops (Blackshaw et al. 2004a), and even nitrogen can break the dormancy of certain weeds and, hence, enhance their density (Agenbag and Villiers 1989). So, the only solution is to manipulate the fertilizer application timing, quantity, and placement method to minimize its interference in crops, like *Lolium rigidum* which was found to be less competitive when application of N was done before the 3-leaf stage of wheat (Forcella 1984). Similarly, topdressing in comparison to broadcasting was also observed to minimize the competitiveness of several weed species (Blackshaw et al. 2004b).

16.5 Manual Means

Manual weeding by hands is an efficient method for weed control. Manual method of controlling weeds like pulling, cutting, and damaging plants may be used for the control of some specific weeds (invasive plants) or if the area concerned is relatively small. Generally, this method is considered as labor and time intensive also and, so, accordingly becomes uneconomical (Jaya Suria 2011). Due to this reason, manual weeding by exploiting several hand-operated tools is the choice of poor, lowland-holding growers round the world. Weed management by manual methods often needs to be repeated several times to check the weed from re-establishing because such methods provide prime conditions for regrowth of the same or other weed species. This method is generally preferred if there are small infestations and where a big pool of volunteer labor is accessible. Manual weeding is usually done with the help of implements like hoes and sickles. Various types of hoes have different forms and objectives and are prehistoric. Multipurpose hand-operated implements are

Table 16.4 Advantages and disadvantages of manual weeding

Advantages	Disadvantages
Provides thorough cleaning	Time-consuming
Effective weed control	Labor-intensive
Ecologically sound, no residual effect	Costly method
Best in small-scale farming	Challenging, if soil is dry, not moist or loose
Good for a poor farmer where cheap labor is available	Difficult to identify and remove certain weeds at early stage due to resemblance with crops

Fig. 16.1 Typical sickle (close) (**a**), working with sickle in grassy lawn (**b**) *photo, Omer Farooq*; typical hand hoe and weed eradication in standing crop (**c**) *photo, Shakeel Ahmad*

utilized to form soil and weed control and also to harvest root crops. Hoes target the weeds by disturbing the soil or cutting the leaf of weeds, both causing the mortality of weeds. Some hoes are versatile, while others are devised for some specific functions. Collected weeds can be either piled up on bunds nearby or, in case of certain weeds, taken home to feed the domestic animals. Comparative advantages and disadvantages are shown in Table 16.4. Various hand-operated implements used for weeding purpose (hand hues, root talon, weed wrench) are shown in Figs. 16.1, 16.2 and 16.3. Manual weeding performs better in field experiments (Hasanuzzaman et al. 2008; Hassan et al. 2017) but always not recommended due to high cost and labor intensive (Khaliq et al. 2012).

16.6 Mechanical Means

Mechanical means for controlling weeds are effective methods particularly adopted in crops sown in rows, organic farms, and in fruit and vegetable garden or crops sown for seed purpose. Such means can offer efficient weed management even if other measures are failed to perform, indeed, can overtake them under certain conditions. Mechanical measures kill the weed plants in three ways: cut them, uproot them, and finally bury them. Weed tissues, especially young seedlings, can be cut that leads to the collapse of weed reserves and finally drying and withering of weed

Fig. 16.2 Root talon used to pull up the shallow-rooted weeds. (Source: https://europeantoolsaustralia.com/junior-double-hoe/)

Fig. 16.3 Weed wrenches used to eradicate deep-rooted weeds. (Source: https://www.diy.com/departments/fiskars-xact-weed-puller)

plants. Mechanical weed control has been closely associated with agri-farming. As the first weeding action was done by hand pulling, followed by utilizing a rod which developed into a hand hoe. As the agri-farming became more and more mechanized, fields were productively kept weed-free with mechanical weed controlling techniques and tools pulled earlier by animals and eventually by tractors.

The development of herbicides during the mid-twentieth century has lessened the reliance on mechanical weeders at farms. Nonetheless, these equipments have continued to advance and are very effective and handy in controlling weeds under a variety of cropping systems. Various techniques of mechanical weeding are ranging from hand tools to the modern instruments like vision-guided hoes. Hand weeding can be done on small scale only, like home gardening, as it is not safe to utilize chemicals/herbicides there due to the lack of training and possible threats of residual effects. Moreover there is very short time between weedicide application and harvesting. Burying is another method to kill the weed plants. Like, puddling can bury mostly weeds in rice crop before sowing. Mechanical weeding can supplement other weed controlling techniques. Likewise, to achieve integrated weed control strategies, it can also be included with other weed controlling practices. Secondary tillage operations or seedbed preparation also plays a very important role in controlling weeds by burying these deep into the soil. Similarly, stale seedbed preparation is a very much effective approach in this regard. Weeds are invited to germinate and then controlled by secondary tillage operations. Mechanical weed controls have several negative effects as well with many positive aspects (Hussain et al. 2018). These include:

- Time constraint can influence other farming operations.
- High cost required for purchasing implements.
- Highly dependent on soil and weather conditions for its effectiveness and further correct time of action.
- Generally not efficient for intra-row weed.
- Skilled labor is required.
- Sometimes can damage plant roots also.

It is generally assumed that intra-row weeds remained uncontrolled through mechanical means of controlling weeds, but recent advances in agri-engineering have developed many instruments (computer-vision-guided hoes, brush weeders, finger weeders, torsion weeders, and mini-ridgers) that provide satisfactory intra-row weed control (Figs. 16.4, 16.5, 16.6, 16.7 and 16.8). To deal with the problem of intra-row weeds, there are two main strategies:

1. Discriminatory weeding approach.
2. Non-discriminatory weeding approach.

Fig. 16.4 Finger weeder. (Source: http://solan.lublin.pl, interrow-cultivator-mechanical-weeder/)

Fig. 16.5 RabeWerk tine weeder. (Source: https://weedecology.css.cornell.edu/RabeWerkback.jpg)

Fig. 16.6 Vertical spring tine weeder. (Source: http://solan.lublin.pl)

Discriminatory weeders are operated as an intelligent system that can discriminate between crops and weeds, while the non-discriminatory weeders have no such intelligent or high-tech approach, but their mechanisms mainly rely on the greater resistance of the crops to the weeding techniques in comparison to the weeds (Merfield 2013). Discriminatory weeders are more costly but easier to operate; they cannot control the most critical weeds close to the crop, but they can easily kill the big weeds. Whereas non-discriminatory weeders are very cheap or less expensive

Fig. 16.7 Non-discriminatory intra-row thermal weeder. (Source: Pinterest)

and require a skillful operator, they normally can damage young weeds only but additionally can also control weeds that are close to the crop.

16.7 Thermal Means

An alternative to other non-chemical weed control strategies, thermal weed control is a good choice to control many problematic weeds. Weed plants are heated for about 1 s at up to 70 °C. The mechanism of thermal weed control is a bit complex and includes cuticle breakdown, loss of membrane semi-permeability, and protein coagulation or denaturing. This method of thermal weed control is comparatively weak against weeds with established root system, and killing efficiency is also affected with some morphological or external features of weed plants (leaf shape and orientation, presence of hair, growth stage, location of growing points, and nature of storage organs), whereas, it is much better against young weeds having weak root establishment (Collins 1999).

Among the thermal means, flaming is a widely recognized technique which utilizes heat wave to break the cells of weed plant. In comparison to manual and mechanical means of controlling weeds, this method is best suited as it required least labor that reduced its expenses and also minimum disturbance of soil (reduce soil erosion, least chances of transferring of weed seed to the upper soil layer). Moreover with advances in thermal weeding techniques, many tractor-mounted flame weeders have been developed for easy weeding on a large area (Fig. 16.7),

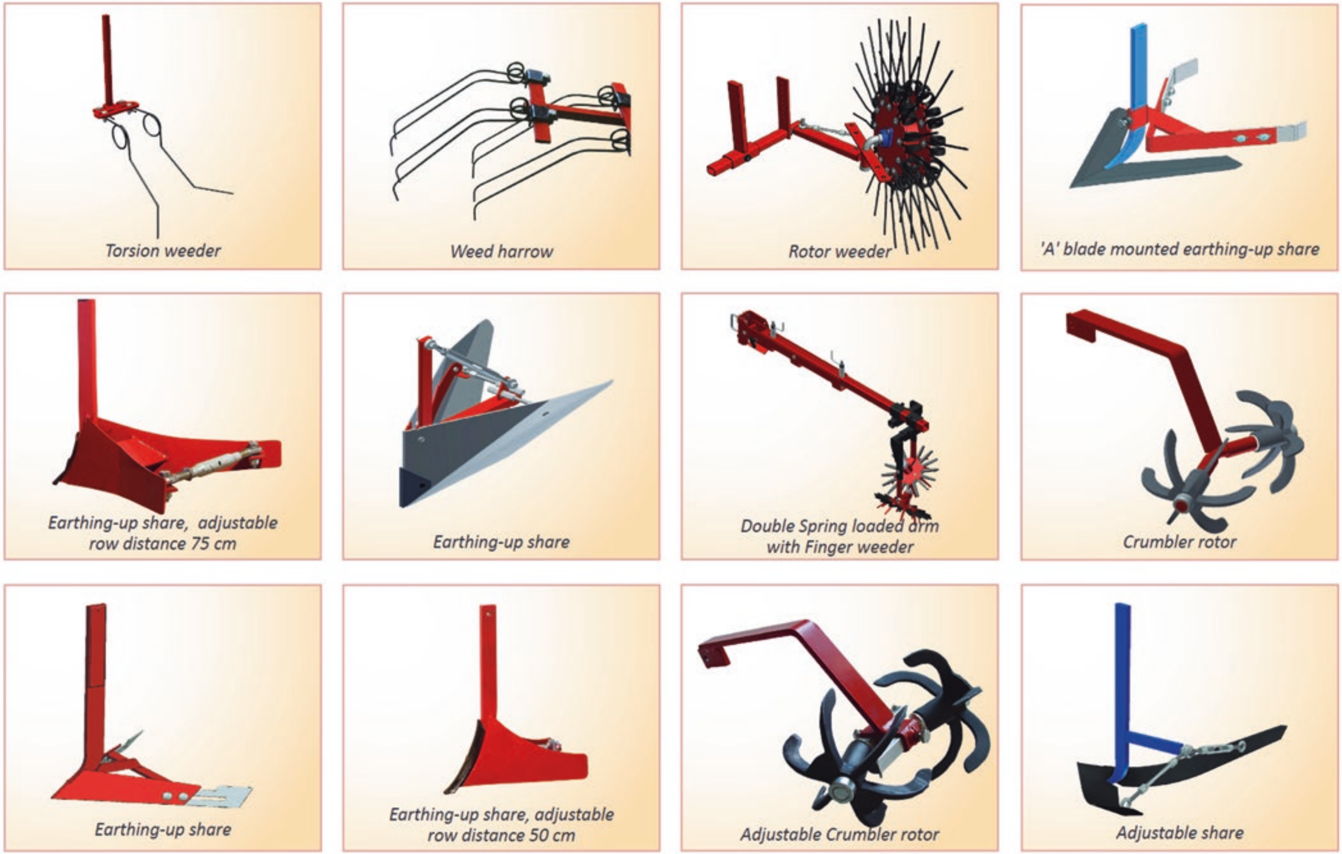

Fig. 16.8 Various options for weed mechanical control. (Source: https://steketee.com)

while for small areas, hand-operated flamers were utilized (Ascard 1995). Flame weeding can control common rye by 72% and volunteer alfalfa by 80%, while weeds like *Chenopodium berlandieri* and *Kochia scoparia* L. Roth were also controlled by 65%. Flame weeding also has some demerits despite all these benefits, and flaming is sometimes expensive because of higher labor, fuel, and equipment cost in comparison to herbicide application. Additionally, speed of application is slow; deficiency of selectivity of the plants; established weeds may not be controlled; deficient in residual weed management; and sometimes required repeated applications (Ascard 1995).

Sometimes we use heat by applying hot water, to kill the weeds, a preferred performance todestroy weeds present in cracks and along roads. It is one of the safe, efficient, and preferably economical practices without any damaging effects, likewise some problems in microwave radiations and also in flaming. Moreover it is assumed as the best strategy to deal with many annual weeds, but it also limits the development of perennial weed plants. The performance of this method is higher in dense weed pressure due to better penetration ability.

So, that's why, this hot water treatment has been thought as a precision weed control plan because of its greater success rate in European countries.

Hot foam weed management technique is thought to be a very harmless practice and can be applied against many weed species. With the expanding values of organic farming and sustainable agriculture growth, this practice has gained marketable demands for the future. In addition to weed control in cropped areas, this practice has more success in public as well as in urban areas to control different weeds, as in the case of compact surfaces where weeds can pose several problems. Additionally, this thermal foam technique can be applied to control the fungal diseases, bacteria, and other harmful pests in the soil.

Stubble burning practice has been mostly applied for reducing the number of weed seeds that are returning into the soil after the harvest of crop, which is considered as a conventional approach for thermal weed control. This practice has been discouraged due to production of smoke and other hazards related to fire. Weed management by burning contains direct and indirect practices to destroy weeds and the production of their seeds. Nowadays, many weed management practices through burning are utilizing various sources of energy for the killing of weeds and their seeds. Soil solarization practice contains various sources including infrared and microwave radiation, electrostatic fields and flame, lasers, irradiation, ultraviolet beams, and steam and hot water techniques (Heisel et al. 2002; Mathiassen et al. 2006; Sivesind et al. 2009).

Black plastic mulch highly suppressed the weed germination through physical pressure and to stop the radiations of sun to approach toward the emerged weeds and their seeds, heats up the soil and creating the effect of solarization on the surface of soil. All of these causes destroy the germination of weed seeds and inhibit emerged weed.

So, keeping in view all these options of thermal weed control, it can be suggested that it is a better option in non-chemical weed management systems.

16.8 Exploiting Allelopathic Measures

Depending upon the environmental conditions (edaphic and climatic), plants released certain chemical compounds that may influence (positively/negatively) the growth of adjacent plants, and this phenomenon is also observed in other organisms as well and referred as allelopathy (Inderjit and Weiner 2001). This phenomenon can be successfully utilized for the non-chemical weed management; approaches may include as (i) exploiting allelopathic crops in rotation pattern; (ii) allelopathic cover crops; (iii) mulching of allelopathic crops; and (iv) using extracts of allelopathic crops (Jabran 2017; Jabran et al. 2015. Although this phenomenon is not widely utilized for its herbicidal potential, it is considered as a safe and environment-friendly approach to deal with the problem of weed management in all the agroecosystems. Plants released these chemicals (allelochemicals), either if these are alive or dead via root exudates or decomposition of plant residues, respectively (Bhowmik and Inderjit 2003). Weed management can be executed by sowing potential allelopathic plants that released chemicals (allelochemicals) to suppress the weeds (Tesio and Ferrero 2010), or by insertion of allelopathic ingredients (that is attained from harvested plants) near to weeds. Different approaches of allelopathy are discussed here in detail.

16.8.1 Crop Rotation

Crop rotation is the special sequence of sowing different crops one after the other over a definite time period in a specific field. In rotation pattern specified for weed management, allelopathic crops are included, and such crops released allelochemicals exuded by crop roots or by decomposition of preceding allelopathic crop residues to suppress the weeds (Narwal 2000). Alone crop rotation can lower weed problem in field crops, but if combined with other methods, it enhances the effectiveness of weed control. In New York, USA, crop rotation was the major strategy to suppress weeds adopted by organic growers. Similarly crops sown after sorghum (*Sorghum bicolor* L.) suffer less weed competition because of the destruction of weeds by allelochemicals released into soil by the sorghum crop (Sauerborn et al. 2000). In many Asian countries, rice-wheat rotation is a dominating crop rotation pattern, and due to heavy infestation of weeds, this system is highly dependent upon herbicides for weed control. Adding of smothering allelopathic crops like maize, pearl millet, and sorghum in aforementioned rotation, after harvesting of wheat and before the transplanting of rice nursery, gives better weed control for about 45 days. Another option is the inclusion of fodder crops, like Egyptian clover or oats, which can be replaced with wheat crop field, heavily infested with weeds for natural weed control of at least one season (Peter et al. 2003). More recently, it's been proven allelopathic plants add allelochemicals in the soil that suppress different weeds in the following next crop (Dmitrovic et al. 2014).

16.8.2 Cover Crops

Cover crops are planted with the primary objective of agroecosystem's sustainability, while other purposes of growing such crops consist of protection from erosion of soil and improving soil health, fertility, and quality status of soil and conquering pests (mainly weeds). Some cover crops have allelopathic potential that is utilized for the control of weeds (Jabran et al. 2015). Several crops like rape seed, velvet bean, canola, cereal rye, red clover, wheat, oats, crimson clover, brown mustard, fodder radish, cowpea, mustards, annual ryegrass, and black mustard can be used as cover crops. Organic agriculture chiefly depends on cover crops for weed management (Mirsky et al. 2013). Different observations have witnessed that these allelochemicals released from the cover crops are responsible for weed destruction at organic farms (Altieri et al. 2011). The role of white mustard and rape seed as cover crops was explored in agroecosystems, and it was observed that these crops released allelochemicals (e.g., glucosinolates that can be further decomposed into numerous other compounds like isothiocyanates) that suppress the emergence and growth of weeds (Haramoto and Gallandt 2004; Halkier and Gershenzon 2006). Similarly, mission grass, the most problematic weed in the plantation of rubber, can be effectively controlled due to the smothering effects of velvet bean, jack bean, and hyacinth bean (Kobayashi et al. 2003).

16.8.3 Intercropping

Sowing of two or more crops simultaneously sharing the same area of land is termed as intercropping, and it has been described as another viable strategy for weed control (Leibman and Davis 2000; Baumann et al. 2002). In an ideal intercropping system, crops that have the same resource-use characteristics are mixed, so that these are prevented from competing with each another. Furthermore, this approach provides an opportunity to destroy the weeds in an eco-friendly environment by better utilization of available resources by the crops (Vandermeer 1992; Makoi and Ndakidemi 2012). More specifically, when allelopathic crops are intercropped with other crops, it helps to control the weed population by releasing allelochemicals. Alternative rows of cowpea and maize intercropping were helpful in reducing weed dynamics by 50% with improved land use efficiency (Saudy 2015). In another field trial, relay intercropping of legumes and wheat was examined with the sole wheat crop for weed dynamics (Amosse et al. 2013).

Legumes included in the trial were red clover, white clover, alfalfa, and black medic. Weed density was significantly reduced where intercrops were included in comparison to the lone wheat crop, while the most effective intercrop was red clover for suppressing weeds.

Following is a list of some other examples of intercropping for successful weed reduction in field experiments (Table 16.5).

Table 16.5 Practical examples of choices of crops for intercropping

Intercrops	References
Cotton + black gram	Jayakumar et al. (2008)
Field beans in maize	Jurgensen and Muller (2000)
Maize with fodder legumes	Khan et al. (2012)
Pea grown as intercrop with barley	Hauggaard-Nielsen et al. (2001)
Groundnut, mung bean, and sweet potato in maize	Steiner (1984)
Berseem with legumes (broad bean and pea)	Fernandez-Aparicio et al. (2010)
Sorghum and sunflower in cotton	Kandhro et al. (2014)
Barley with peas	Corre-Hellou et al. (2011)

16.8.4 Living Mulches

Cover crops with allelopathic potential may act as living mulch and, besides normalizing the soil temperature, strongly retard the weed's growth also. Inhibition of weed dynamics with living mulches was studied in different experiments (Fujii 1999; De Gregorio and Ashley 1986), while allelochemicals are responsible in such inhibition. Allelopathic substances exuded from roots of plant into the rhizosphere, through diffusion, move into the soil and interact with adjoining plants. This ultimately leads to a radius effect, where closeness to the allelopathic organisms results in larger concentrations of the allelochemical, which in turns result in reduction of growth of adjacent plants (Westra 2010). Mulches impede weed seed germination and by releasing allelochemicals obstruct seedling growth of such plants (Teasdale and Mohler 2000; Bilalis et al. 2003). However, weed plants that have developed their root system are not properly controlled with mulching.

Living mulch can be effectively used for suppressing weeds. However, success of this approach is very conditional (Grossman 1993; Williams 1989).

Therefore, specified knowledge regarding the use and combination of crop plants should be developed for desirable results in obtaining ideal weed management. A single living mulch species will not work at all sites or under every type of conditions. Different factors defining the feat of living mulch as a weed suppressing agent must also be taken into account in this context.

16.8.5 Allelopathic Plant Extracts

Allelochemicals or secondary metabolites in plants can be utilized for the pest management (Bonanomi et al. 2006). These are extracted in water, and water extracts of allelopathic crops are used to suppress the growth of other organisms (Macías et al. 2007; Bonanomi et al. 2006). Exploitation of allelochemicals, extracted in water for the control of weed dynamics, has been studied by many scientists under laboratory as well as under field conditions (Jabran et al. 2010; Chung et al. 2006; Cheema and Khaliq 2000). Application of sorghum water extract (WE) (at different doses and frequencies) reduced the weed density and biomass by 44% and 49%, respectively (Cheema et al. 1997). Similarly, in another investigation, sorghum WE spray significantly controlled the lambsquarters, little seed canary grass, wild oat, field bindweed, and toothed dock weeds in wheat (Cheema et al. 2002). Allelochemicals from different plant extracts (if combined) have synergistic action (Duke and Lydon 1993). Accordingly this idea was tested by mixing sorghum WE with sunflower and eucalyptus WEs, and remarkably, in comparison to sole application of sorghum WE, mixture of WEs gave more better results in controlling weeds of wheat (Cheema et al. 2003). Furthermore, this was again proved by Jamil et al. (2009) where they combined WE of sorghum with sesame, tobacco, eucalyptus, sunflower, and brassica WEs and recorded more better results for controlling wild oat and little seed canary grass. In a bioassay, different portions of allelopathic rice (leaves, stem, and roots) were separated for preparing extracts, and it was observed that all these parts of rice showed allelopathic activity in inhibiting the germination as well as growth of different plants used for investigation (berseem, wheat, barley, and oat), while the stem extract showed maximum inhibition, while leaves showed least inhibition of the target species (Farooq et al. 2008).

16.8.6 Non-living Mulches

Mulching, besides suppressing weeds (Abul-Soud et al. 2010), improves water availability to the crops (Sarkar et al. 2007), irrigation efficiency, and crop yield increase (Mukherjee et al. 2010). The darker mulches cause soil temperature to rise and hence promote root development (Lamont 2005; Moreno and Moreno 2008). Mulches may either be living or non-living on the base of their origin. Living mulch is applied in the form of cover crops usually, whereas non-living mulch is an artificial material or recycled product and used on the soil surface for physically suppressing germination of weed seeds. These may be either flat sheets laid by hand or machine or loose particles spread on soil in the form of a continuous cover. Some of such mulches may be restricted to be used in landscapes because of cost and availability issues. Somewhere else, use of mulch in which form and where is decided by its physical characteristics. Mulches can also be used in integration. For example, film mulch is spread on the planted area, and particle mulch is put along the paths in some crops. On the other hand, use of particle mulch improves the look and durability in landscape. However time duration for which mulch remains on the soil surface is variable. Depending upon the nature of crop, mulch may remain intact for just one growing season or may last for years. In case of year's long use, woven polypropylene mulch having higher durability is a good option. Nonetheless, if intention is to suppress weed seedling emergence for just few weeks, black polyethylene mulch can be put over the recently prepared seedbeds.

Polyethylene mulch needs to be removed when the crop growing season ends due to its non- biodegradability (Anzalone et al. 2010). However use of plastic mulch that is biodegradable (starch made) resulted in higher yield of tomato and degraded into a non-hazardous compounds (Miles et al. 2012). However, higher

Table 16.6 Advantages and disadvantages of non-living mulches (Upadhyaya and Blackshaw, 2007)

Advantages	Disadvantages
Retention of soil moisture Prevention of leaching Improved soil structure Disease and pest control Improved crop quality Extended growing season in many crops which reaps financial rewards Weed suppression by both particle and sheet mulches can achieve significant long-term savings in labor and the need for herbicide spray	Pressure from being walked on or punctures caused at or after laying reduces seed longevity Paper is more easily damaged when it is wet, while heavy cellulose sheets deteriorate when they become brittle Sheets of plastic, paper, and other mulch materials are also susceptible to storm or physical damage

cost of such plastic mulch is a major limitation in its wide adaptability, when we compare it with other materials like straw mulch (Anzalone et al. 2010; Fontanelli et al. 2013).

16.8.6.1 Advantages and Disadvantages of Non-living Mulches

The weed populations and the environment will determine the mulch efficacy. For instance, particle mulches may show initial suppression but generally are not effective against established perennial weeds. Emergence of annual weeds can be prevented by use of a 3 cm layer of composted waste (Ligneau and Watt 1995). However, 10 cm layer of bark cannot stop the growing of perennial grass, common couch (*Elytrigia repens*). Fine materials facilitate conducive environment for weed seed germination when compared with coarse materials like bark (Pickering 2003). However, depth of coarse particles should be more than depth of fine particles. Non-living mulches provide a number of benefits along with some disadvantages (Table 16.6).

Weeds are difficult to manage at the sides of mulch strips with sheeted mulches, and covering large areas for a long time is also difficult to manage. Creeping weeds may appear around the sides of the mulch or may penetrate through thin or damaged parts of the mulch. Furthermore weeds are established in the hole cut made for crop seed planting, and weeds also emerge on top of non-living mulch where decayed leaf litter has been accumulated (Benoit et al. 2006). One of the greatest challenges in the use of non-living mulches probably is damage from weathering. Similarly, plastic sheet stretched too much during covering may split on a warmer day or contract at night when the temperature goes down.

16.9 Weed-Crop Interaction for Managing Weeds

Weeds are one of the severe pests of field crops and are invading crops from the beginning of agriculture. Crop growth and development merely rely upon nutrients, water, space, and photosynthetically active radiation. There is constant competition between weeds and crops for nutrients, water, space, and light. Although billion dollars are consumed on weed control, weeds still create substantial losses in terms of decreasing yield potential of the crop. Weed management in successful crop production includes greater expenses in comparison to insect and disease management, since weeds are comparatively persistent delinquent and insect and disease begin occasionally. Nowadays, scientists have been concentrating on non-chemical approaches for managing weeds.

In chemical-free weed controlling, growers have opportunities to select the competitive crop species to tackle the weeds, so to raise the burden on weeds through agronomic practices (e.g., increasing seed rate and narrowing the row space). Moreover, this system offers environmental safety with healthy and pure food production. Such weed management approaches are also unavoidable for the effective employment of organic farming methods (Jabran et al. 2015). Although chemical-free weed control practices could be difficult, keep a lesser effectiveness over chemical, and need great costs sometimes, they are required for the interest of health and environmental protection (Moss 2010). Several chemical-free weed management practices are under research by the scientists across the world owing to ecological features of the area, type and intensity of weeds, choices of the crop, effectiveness of other weed-resistant techniques, and social and economic factors. These methods keep definite limits with respect to the accessibility of labor, suitability of climatic condition, farmer's location, and capability to afford control expenditures (Kandhro et al. 2014). Crop managing techniques are typically planned to upsurge the growth of crop characters liable for resilient crop competitiveness. Better cultural approaches improve crop competitiveness and decrease weed pressure, preferring improved crop establishment and repressed weed development. The usage of better cultural approaches might enhance wheat yield up to 50–70%. Hussain et al. (2013) proposed that improvement of crop yield in main crops by weed control is the main factor in refining food safety in Pakistan.

Minimizing the weed-related losses of crop yields requires diverse and effective control weed practices. At the early stage of weed-infested situations, narrow crop spacing and higher seed rate eventually result into the increased uptake of the resources through the aggregation of biomass (Chauhan 2012). Narrower crop rows and thick plant populations work rightly in suppressing weed germination and enhancing the crop yields. For the economical production of the crop, proper weed management through a different or combination of techniques is essential. Appropriate crop row spacing shows an enhanced crop yield by minimizing the growth of the weeds at the initial stages of crop growth and development. Appropriate plant population achieved by keeping suitable row spacing is the main aspect to achieve maximum production of any crop. Additionally, narrower- rows spaced are considered to be effective in weed management as well as by preventive light pass on to the surface of the soil by increasing crop competitiveness. Furthermore, narrower spacing of the crop with a uniform plant population permits the plants to use inadequate obtainable growth factors, for example, light, space, and nutrients, extra competently over the weeds.

The reduction of the crop yield has a direct relation with the competition duration of weeds. As the competition duration of weeds with crops increases, the degree of the yield decreases, and dry weight of weeds increases and vice versa. In cereal crops, exploiting crop competition is now considered as a cost-effective and key approach for enhancing weed suppression and improving the crop yield. This approach has also been identified as future weed management research programs.

Stimulating the development of dense and closed canopy is a fundamental tool for improving the competitive ability of cereals over weeds. To understand this relationship of crop densities and their duration with weed suppression, it is important to investigate these effects on various kinds of weed species. As weed species differs in their biomass production, therefore, their responses on crop biomass, density, and yield will also vary (Olsen et al. 2005). Accordingly, in such competitions distribution of resources toward different parts of plants will also change (Hakansson 2003), and such phenotypic plasticity is an important feature that permits species to survive in a wide range of environmental conditions and may influence weed control considerably.

16.10 Biological Measures

The biological management is a corresponding implement for IWM. As per the natural and eco-friendly technique, circumvents the hazard of herbicide tolerance and surrounding contamination (Ash 2010). These living creatures are exploited for plant safety and have been described as "the utilization of an agent and complex agents or biological procedures to carry about the suppression of weed" (WSSA 2017). On the other hand, pathogens are used practically, and bioherbicides are not widely distributed due to multiple constraints (Ghosheh 2005). This method has several merits compared with other methods. Herbicide residues might contain less pollution of soil, water, and food. A lot of causes for exploiting biological method in weed science such as loss of numerous mutual herbicides due to difficulties such as strict protocols or development of herbicide tolerance in weeds; shifting in weed management such as aiming only undesirable cultivars, preserving environmentally delicate or disposed to deprivation zones, escaping adulteration owed to chemicals; and leaning to improved and sustainable cropping systems. Additionally, a biological method is measured inexpensive and autonomous if the agents unrestricted get launch effectively and replicate. Nevertheless, intrusiveness of some organisms and the impacts on non-target species have been documented (Myers and Cory 2017; Jones et al. 2017; Van Lenteren 2012; Weyl and Martin 2016; Van Wilgen et al. 2013), proposing care when selecting and liberating biological organisms in weed management. Several diverse creatures have been utilized or recommended for biological weed control extending from microscopic rhizobacteria to big mammals. For instance, *Ctenopharyngodon idella* Val., a fish, is used to manage marine weeds (Domingues et al. 2016). Procedures included in the preparation of biological weed management agents and executions of biological weed management have been a complicated singularity. Additional cost, research, and practical demos are needed to create biological control and satisfactory technique of weed control. Different pathogens have exposed different grades of virulence against *E. colona*, *E. crus-galli*, and *E. glabrescens*. *Exserohilum* species were established answerable for leaf blight of *E. crus-galli* and, thus, professed as possible biocontrol agent (Chung et al. 1990). Huang et al. (2012) stated that pathogenic fungi, with *Exserohilum monoceras* and *Drechslera monoceras*, were operative in overwhelming *E. crus-galli* seedlings. In the alternative investigation, the *E. longirostratum* repressed *E. crus-galli* beneath field circumstances (Ng et al. 2011). Additional fungal biocontrol agent, *Dactylaria dimorphospora*, produced slight contagion in *Echinochloa* species. Notable consequences against *E. colona* from *B. sacchari*, *C. geniculate*, and *E. monoceras* deliver a decent chance for their usage as biological agents (Zhang et al. 1996). Zhang et al. (1996) assessed the prospective of six fungal pathogens against rice and three *Echinochloa* species (*E. colona*, *E. crus-galli*, and *E. glabrescens*). The inadequate study has been accompanied on biological weed management in rice; however still few inspiring outcomes have been recorded in the last years. *Echinochloa* species host various fungal pathogens of rice (Zhang et al. 1996).

In current agriculture, weed management has been trusted on herbicides; however, practically no novel herbicide and its mode of actions have been discovered. Bio herbicides prepared from bigger plants, microscopic organisms, or micro biological phytotoxins (Lamberth 2016; Cai and Gu 2016) documented the utilized for weed control in agriculture schemes (Cordeau et al. 2016; Dayan et al. 2012). Usually, it has been measured that bioherbicides could not be an alternate to artificial herbicides; however, they can be an additional implement in weed management (Boyette et al. 2008). Exploitation of *Fusarium oxysporum* (Schlecht) to restrain *O. ficus-indica* is one of the initial instances in 1940 (Hawaii) (Rana and Rana 2016). In Russia, managing the bulk production of *Alternaria cuscutacidae* was utilized in *Cuscuta* spp. Some parasitic weeds were managed by extra fungal agent *Colletotrichum gloeosporioides* f. sp. cuscutae in China during 1963. Lubao was a profitable mycoherbicide that was prepared during those times and is still in use (Rana and Rana 2016). Efforts were started to ascertain bioherbicides to manage R. spp. in the USA (Inman 1971) and *Rubus* spp. in Chile (Oehrens 1977) during the late 1960s.

Investigation on novel formulations needs both time and money. The registration process is extra issue that harming the preparation of a brand new formulation consistent with regulations of any country (an amount of 5 years is also needed) (Auld et al. 2003). Although with several benefits, there are some perils of bioherbicides (Ash 2010). A number of those are allergic issues to people that are depiction to them, host plant expansion, side impacts on non-target organisms particularly helpful microorganisms, and the metabolites toxicity exist on mammals (Hoagland et al. 2007). In Australia, for example, *P. melampodii*, a fungus with Mexican starting point, was applied to *P. hysterophorus*, consequently pretentious marks spp. and *Helianthus annuus* (Evans 2000). Varied biological management agents have been regarded to lessen the prevalence of several weeds. Biological organisms are thought about environment beneficial and economically possible technique to manage weeds; meanwhile they leave no chemical remains that may have damaging impact on civilizations of humans or other living creatures.

16.11 Integrated Weed Control Measures

None of the weed control choice is a worldwide remedy for attaining weed management objectives in our complex ecosystems. Weeds are essential constituents of agroecosystems comprising of a complex web of inter- and intra-ecosystem interactions. An integrated weed management (IWM) approach comprises selection of the control measure, integration, and further implementation of weed management options based on ecological, economic, and social principles. Weed management choices (i.e., when, how much, what, and how to control) should be focused on optimizing the weed control, but not necessarily maximizing the weed control.

IWM is the utilization of numerous approaches to attain sustainable weed management (Harker and O'Donovan 2013). The practice of IWM for managing weeds can offer environmental and economic welfare. There is a variety of selections for non-chemical weed-resistant practices that can be selected rendering to the nature of crop, intensity of weed invasion, climate, growth stages of weeds and crops, critical duration for crop-weed competition, existing resources, and yield aims (Harker and O'Donovan 2013; Bajwa et al. 2015). There are several non-chemical control tactics existing to growers, and these are frequently exploited in IWM. But there is a necessity to comprehend how they execute in grouping and how they interrelate with flexible weather in order to exploit weed management and reduce yield damage (Barzman et al. 2015).

A holistic attention of weeds in our complex ecosystem is required. Whereas the progress of an IWM approach requires understanding the ecology of weeds, comprehensive knowledge of the biology of weeds involved, and tactics of weed management. In addition to these, a positive thinking that exploits natural regulating forces to develop novel options is also much important. Combination of various weed management choices has been shown to upturn species diversity, which has many benefits that have been revealed in studies with unmanaged communities (Clements et al. 1994). Weed manager must realize the whole area of the farm under his supervision and the surrounding areas adjacent to his farm. Weed management during a year impacts the whole agroecosystem in coming years so, temporal and spatial both features must be estimated. Development of better quality weed monitoring systems, competency to forecast losses by modeling weed population and crop yield loss relationships, establishing economic threshold(s), and a sound knowledge about the critical period of weed interference is fundamental to this approach. For the producers, effective information for weed management should be made available in an acceptable, clear, and operational form. A comprehensive weed management plan must have following approaches:

- Prevent the entry of weed plants.
- If enter, prevent further dissemination of weeds.

- Enhance the crops' ability to compete with weed plants.
- Combination of variety of weed controlling options.
- Weeds should be managed, considering their positive and negative aspects.

16.12 Conclusion

Non-chemical weed control strategies including all measures, viz., preventive, cultural, manual, mechanical, thermal, allelopathic, weed-crop interactions, biological, and integrated weed control, are very much efficient methods for the control of problematic weeds. Contrary to several concerns of chemical herbicides, like health and environmental security and resistant development in weeds and food contamination, there is no such demerit or problem with the non-chemical measures. Earlier, it was considered that non-chemical weed control approaches are not much efficient in comparison to herbicides and give control to all weeds, but with the recent advances in the field of mechanical measures, GPS and computer-operated high-tech approaches and non-chemical measures are gaining popularity day by day. Similarly, allelopathy can be potentially exploited to control the weeds by placing allelopathic crops in rotational sequence, mulching, or crop extracts. Furthermore, it is an ethical duty of all the researchers and weed scientists to devise technologies for the safe control of weeds and provision of safe food to the future generations.

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17

Beneficial Effects of Weed Endophytic Bacteria: Diversity and Potentials of Their Usage in Sustainable Agriculture

Kaniz Fatema, Nur Uddin Mahmud, and M. Tofazzal Islam

Abstract

Plant growth-promoting endophytic bacteria dwell a relatively privileged niche within the host plants and confer beneficial effects to their hosts. These plant probiotics from weed species are poorly explored but possess the tremendous potentials for application in eco-friendly sustainable agriculture. Bacteria from diverse taxonomic genera such as *Sinorhizobium*, *Bacillus*, *Pseudomonas*, *Marinorhizobium*, *Sphingomonas*, *Sphingobium*, *Herbaspirillum*, *Micrococcus*, *Microbacterium*, and *Rhodococcus* are associated with weed species. Weed-originated plant growth-promoting bacteria (PGPB) exert beneficial effects to their host plants through fixation of atmospheric nitrogen and solubilization of insoluble essential mineral elements (e.g., phosphorus) produce phytohormones (e.g., indole-3-acetic acid), induce systemic resistance (ISR) response to hosts, and secrete antimicrobial substances and other metabolites to protect their hosts from biotic and abiotic stresses. The ISR have tied to disease resistance and abiotic tolerance of plants against drought, cold, salinity, and extreme temperature. As there is no comprehensive review on weed endophytes, this study reviews taxonomic diversity and beneficial effects of weed-associated bacteria and discusses how these natural bioresources could be utilized in agricultural productivity to a new dimension.

Keywords

Weed endophytic bacteria · Nitrogen fixation · Sustainable agriculture · Biocontrol Abiotic stress tolerance

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17.1 Introduction

Useful plant species termed as "crops" are managed in agriculture to obtain products for mankind. On the contrary, plant species named "weeds" are not desirable but are found in agroecosystems. Though weed seed is not sown intentionally by the human, it is well adapted to the environment and grows or reproduces aggressively in association with crops from the beginning of agriculture (Janick 1979; Peterson and Peterson 1999). Weeds take part in yield loss by reducing the potential harvestable crops due to crop-weed competition for uptake of available resources or by reducing actual amount of harvested products due to interference in harvesting and threshing operations (Chandler 1980; Nave and Wax 1971; Bhandari and Sen 1979; Aldrich 1984; Zimdahl 1980). To gain establishment advantages over surrounding crop plants, weeds also produce allelochemicals which inhibit the germination, growth, and development of crop plants (Putnam and Weston 1986; Rice 1986). Again secretion of negative microbial allelopathies by the weeds in the rhizosphere inhibits the development of microorganism including endophytic bacteria which results in the reduction of emergence, withstanding, and growth of desirable crops (Schippers et al. 1987; Sturz and Christie 1996; Barazani and Friedman 1999). In the negative context, weeds are contemplated as interfering associates of desired crops, and their value is judged solely in terms of yield reduction. In agroecosystem, weeds are considered as unwanted intruders that compete for resources with desired crops, force to use more labor and technology to eliminate for better yield (Fickett et al. 2013). However, weeds also play an important role in agroecosystem as genetic resources for food agriculture and pharmaceutics and as indicators of biodiversity (Spahillari et al. 1999). Several lines of evidence suggest that weeds harbor diverse group of endophytic bacteria that exert beneficial effects to their weed host in various ways (Sorty et al. 2016; Samad et al. 2017a, b). Discovery of those interesting bacteria and search for their beneficial usage in crop production have been investigated (Krimi 2016; Lafi et al. 2017).

Due to climate change and other factors, production of food for the increasing population of the world is very challenging. Biotic and abiotic stresses such as drought, high temperature, salinity, etc. are also increasing. Emergence of disease is alarmingly increasing which poses a threat to future food security (Islam et al. 2016). Current synthetic agricultural inputs are very expensive, and application of these inputs seems unable to mitigate emerging challenges. Therefore, the most demanding issue in agriculture and agri-food sector is to achieve eco-friendly and sustainable development by boosting up crop productivity through biorational utilization of limited natural resources (Islam et al. 2017; Rahman et al. 2018). Adoption and management of new biotechnological approaches and crop production strategies can enhance productivity and competitiveness of agriculture (Fahey et al. 1991; Kloepper 1992). Application of endophytic plant growth-promoting bacteria (PGPB) is one of the viable biotechnological approaches toward sustainable agriculture (Turner et al. 1993). Both crop plant and weeds host the highly diverse microbial communities, which strongly interact with their hosts in various ways ranging from symbiosis, mutualism, to commensalism or pathogenic forms (Carroll

1988; Walker 1992; Newton et al. 2010; Hardoim et al. 2015). These interactions contribute to improve soil quality, plant health, and plant productivity by soil organic matter mineralization, stimulation of plant defense mechanisms, and prevention of phytopathogens (Lugtenberg and Kamilova 2009; Compant et al. 2010; Bhattacharyya and Jha 2012; Khatun et al. 2018). Considering the deleterious effects of synthetic agrochemicals to soils, environment, and even human health, application of beneficial endophytic bacteria is considered as a biorational approach for sustainable nutrition and protection of crop plants. Although a large body of literature is available on crop plant-associated PGPB, there is no comprehensive review that has so far been published on discoveries of endophytic bacteria from weeds and their potential usage in sustainable crop production. Therefore, this review attempts to explore the recent discoveries of beneficial endophytic bacteria from various weed species and discusses their effects on different crop species.

17.2 Concept of Endophytes and Their Role on Host Plant

More than 150 years ago, De Bary first coined the term “endophyte” for pathogenic fungi that enter into the tissues of plant leaves (Bary 1866). Since then, this term is redefined by many researchers, but each has its own restrictions. However, the word “endophyte” is derived from two Greek words (endon = within, phyton = plant), which means “in the plant” (Chanway 1996). The bacteria that can be detected at a particular moment within the tissue of apparently healthy plant hosts without inducing disease or organogenesis are known as endophytic bacteria (Chanway 1996). The first occurrence of the plant endophytic bacteria was reported by Trevet and Hollis (1948) in the internal tissues of a healthy potato plant. With the advancement of time, several studies were conducted to isolate the endophytic bacteria from different plants and evaluated their capability as PGPB (Hallmann et al. 1997; Kobayashi and Palumbo 2000; Sturz et al. 2000; Rosenblueth and Martínez-Romero 2006; Suman et al. 2016). Endophytic PGPB have several advantages over free-living, rhizospheric, or phyllospheric probiotic bacteria as endophytes are protected from various abiotic and biotic stresses such as extreme temperature, drought, nutrient, pH, water availability, and competition with other organisms (Loper et al. 1985; Cocking 2003). Besides, these bacteria colonize in the internal tissue and form mutualistic relationships, i.e., plants get fixed N_2 and provide nutrients in return (Richardson 2009; Reinhold-Hurek et al. 1998a, b; Santi et al. 2013). Endophytic bacteria can colonize well in rhizosphere and in variety of plant organs such as roots, leaves, stems, flowers, fruits, and seeds (James et al. 2002; Sessitsch et al. 2002; Berg et al. 2005; Okunishi et al. 2005; Compant et al. 2011; Pereira et al. 2012; Trognitz et al. 2014; Rahman et al. 2018). They can even colonize legume nodules and tubercles of mycorrhizal fungi (Benhizia et al. 2004; Paul et al. 2013). In different plant parts, the population of endophytic bacterial greatly varied from as low as hundreds to as high as billions per gram plant tissue (Jacobs et al. 1985; Misaghi and Donndelinger 1990; Sturz et al. 1997; Chi et al. 2005). Colonization of endophytic bacteria not only enhance growth but also promote quality of the produce of crop plants (Rahman et al. 2018).

Table 17.1 Taxonomic diversity of various beneficial bacteria isolated from weeds

Bacterial genera isolated from weed	Family
Agrobacterium	*Rhizobiaceae*
Arthrobacter	*Micrococcaceae*
Alkaligenes	*Alcaligenaceae*
Bacillus	*Bacillaceae*
Curtobacterium	*Microbacterium*
Caulobacter	*Caulobacteraceae*
Herbaspirillum	*Oxalobacteraceae*
Marinobacterium	*Alteromonadaceae*
Microbacterium	*Microbacteriaceae*
Micrococcus	*Micrococcaceae*
Pseudomonas	*Pseudomonadaceae*
Rhodococcus	*Nocardiaceae*
Sinorhizobium	*Rhizobiaceae*
Sphingonomas	*Sphingomonadaceae*
Stenotrophomonas	*Xanthomonadaceae*

17.3 Taxonomic Diversity of Weed Endophytes

The taxonomic diversity of weed endophytic bacteria are diverse. The endophytes isolated from different organs of weed plant showed significantly different abundances of shared taxa between bacterial species at the family as well (Table 17.1). Reviewing literature indicates that the families *Bacillaceae* and *Pseudomonadaceae* cover most of the endophytic bacteria identified from the weed.

A diverse community of bacterial endophytes was found in weed which helps in promoting plant's growth. Endophytic bacteria from a range of invasive weed, for instance, babchi, white popinac, Johnson grass, Santa-Maria, Thanet cress, nettle leaf, little clock, lambs tongue, sticky snakeroot, split-leaf lettuce, yellow-berried nightshade, wild tobacco, slough grass, and nut grass, not only fix atmospheric nitrogen and solubilize inorganic minerals in soils (such as phosphorus) but also act as biocontrol agent against notorious phytopathogens. Some of these weed endophytic bacteria also enhance stress tolerance to the host plants against drought and salinity (Table 17.2).

17.4 Mechanism of Plant Growth Promotion by Weed Endophytic Bacteria

Commensal endophytes have no apparent effects on plant activities but live on the metabolites produced by the host, whereas other endophytes (PGPB) exert several benefits to the plant such as protect the plants from invading pathogens and herbivores by antibiosis or induced resistance mechanism (Scortichini and Loreti 2007). Generally, in optimum growth condition, bacterial endophytes generally showed neutral effects to the host plant, whereas they confer beneficial effects during

Table 17.2 Name, source of isolation and their beneficial effects of endophytic bacteria isolated from the weed species

Name of the bacterial isolates	Name of the plant species	Plant part	Beneficial traits isolated bacteria	Applied crop species	References
Bacillus sp., *Sinorhizobium* sp., *Marinorhizobium* sp.	*Psoralea corylifolia*	Root nodule	Plant growth promotion under salinity stress condition	Wheat	Sorty et al. (2016)
Rhodococcus kroppenstedtii, Sphingomonas paucimobilis, microbacterium proteolyticum, Sphingomonas paucimobilis, microbacterium proteolyticum, Sphingomonas pseudosanguinis, Pseudomonas oryzihabitans	*Leucaena leucocephala*	Shoot	Degrades mimosine for N-fixation	–	Ulloa et al. (2017)
Xanthomonas melonis, agrobacterium tumefaciens, Sphingobium amiense, Pseudomonas jessenii, Caulobacter vibrioides	*Sorghum halepense*	Roots, rhizosphere	N-fixation	–	Rout and Chrzanowski (2009)
Bacillus sp.	*Parthenium hysterophorus*	Stem, root	Biocontrol agent against downy mildew	Pearl millet	Chandrashekhara (2007)
Pseudomonas viridiflava	*Lepidium draba*	Stem, root	Bicontrol agent	Vineyard	Samad (2017a)
Pseudomonas sp., *Arthrobacter* sp., *Bacillus* sp.	*Lepidium draba*	Root	Produce hydrogen cyanide, phosphate solubilization	Grape vine	Samad (2017b)
Bacillus methylotrophicus, Bacillus pumilus, Bacillus cereus, Bacillus amyloliquefaciens	*Urtica dioica*	Root	Plant growth promotion, biocontrol agent	Tomato	Krimi (2016)
Pseudomonas brassicacearum, Bacillus amyloliquefaciens	*Calendula arvensis*				
Bacillus sp.	*Plantago lanceolata*				

(continued)

Table 17.2 (continued)

Name of the bacterial isolates	Name of the plant species	Plant part	Beneficial traits isolated bacteria	Applied crop species	References
Stenotrophomonas maltophilia, S. rhizophila	*Eupatorium adenophorum*	Vascular tissue of root and stem	Plant growth promotion, bioremediation, production of secondary metabolites	Oil seed rape, sugar beet, wheat, canola, potato, poplar	Ryan et al. (2009)
Pseudomonas mendocina	*Lactuca dissecta*	Root	Plant growth promotion	Corn	Naz and Bano (2010)
Pseudomonas stutzeri	*Solanum surattense*	Root			
Pseudomonas putida	*Sonchus arvensis*	Root			
Bacillus cereus	*Nicotiana glauca*	Stem	Biocontrol		Abdallah et al. (2016)
Alcaligenes faecalis		Leaves	Agent, plant growth promotion	Tomato	
Herbaspirillum frisingense	*Spartina pectinata*	Root, stem, leaves	N- fixation	–	Kirchhof et al. (2001)
Micrococcus luteus	*Cyperus conglomeratus*	Root	Oxidative tolerance, salinity, and stress tolerance	–	Lafi et al. (2017)

various stages of the plant life cycle or under more extreme conditions. However, in case of the fungal endophytes, the fungus *Fusarium verticillioides* has a dual role both as a pathogen and as a beneficial endophyte in maize (Bacon et al. 2008). Not only the host genotype but also the abiotic stresses are responsible for such dual states. Abiotic stresses lessen the host fitness which distort the delicate balance. Disease occurrence and mycotoxin production by the fungus are also responsible for unbalancing the plant condition (Bacon et al. 2008). However, beneficial effects have also been demonstrated, e.g., several strains of *F. verticillioides* protect their host by suppressing the growth of another pathogenic fungus *Ustilago maydis* (Estrada et al. 2012).

17.4.1 Plant Growth Promotion

To date, plant growth-promoting effects attributed to endophytic bacteria have encompassed growth and developmental promotion through the enhanced availability of minerals (Frommel et al. 1993; Kloepper et al. 1980, 1991; Davison 1988; Murty and Ladha 1988), growth inhibition of pathogenic organisms (Fredrickson and Elliott 1985; Schippers et al. 1990), growth stimulation indirectly through the biocontrol of phytopathogens in the root zone, induction of phytohormone synthesis by the plant (Bakker and Schippers 1987; DéFago et al. 1990; Lazarovits and Nowak 1997), and the direct production of phytohormones (Barbieri et al. 1986; Brown 1974; Jacobson et al. 1994; Tien et al. 1979; Holland 1997; Rahman et al. 2018), altered susceptibility to frost damage (Gagné et al. 1989; Xu et al. 1998), and altered plant susceptibility to other pathogens (Fredrickson and Elliott 1985; Schippers et al. 1990).

17.4.2 Nitrogen Fixation

The major sources of nitrogen for agricultural soils are from mineral fertilizers and biological nitrogen fixation (Chanway et al. 2014). Due to the intensification of agriculture, contamination of ground and surface water by chemical fertilizers and coliform bacteria has emerged as significant human health and environmental issues (Anon 1997a, b). In case of green agriculture, while intensifying the use of legumes may serve to elevate N levels in root residues and form a source for subsequent crops. The N from root residues and easily mineralized soil organic matter will also form a source of leached N. Thus, nitrogen loss in green manuring systems can be equivalent to that from fertilizer nitrogen (Harris et al. 1994; Addiscott et al. 1991). By contrast, fertilizer inputs are expensive and nonrenewable, and excess nitrogen may lead to the production of N_2O, a "greenhouse gas." One viable approach for improving the nitrogen economy of crops can be the application of N-fixing endophytic bacteria to nonleguminous crops in rotations that they would fix atmospheric nitrogen for enhanced crop production (Sloger and Van Berkum 1992). Rout and Chrzanowski (2009) demonstrated that *Xanthomonas melonis*, *Agrobacterium* *tumefaciens*, *Sphingobium amiense*, *Pseudomonas jessenii*, and *Caulobacter vibrioides* isolated from the root and leaves of invasive plant species *Sorghum halepense* fix nitrogen through nitogenase activity. Rangel et al. (2016) found that *Rhodococcus kroppenstedtii*, *Sphingomonas paucimobilis*, *Microbacterium proteolyticum*, *S. pseudosanguinis*, and *Pseudomonas oryzihabitans* isolated from *Leucaena leucocephala* enzymatically break down mimosine into the intermediate 3-hydroxy-4-pyridone (HP) and use it as a carbon/nitrogen source where mimosine is antagonistic to a variety of plants and weeds.

17.4.3 Phosphorus Solubilization

Plant-associated bacteria solubilize insoluble phosphate complexes by releasing organic acids and form orthophosphate which is available for plant uptake and utilization. In return bacteria use root carbon mainly sugar and organic acids to maintain their life. Samad et al. (2017a, b) demonstrated that endophytic bacteria *Arthrobacter* sp., *Bacillus* sp., and *Pseudomonas* sp. isolated from *Lepidium draba* confer the ability to solubilize inorganic phosphate and make it available to the plant. *Bacillus cereus* and *Alcaligenes faecalis* isolated from *Nicotiana glauca* solubilize phosphate and make it available to the tomato plant (Abdallah et al. 2016). *Pseudomonas mendocina*, *P. stutzeri*, and *P. putida i*solated from *Lactuca dissecta*, *Solanum surattense*, and *Sonchus arvensis*, respectively, solubilize phosphate through the production of organic acids in saline soil (Naz and Bano 2010).

17.4.4 Indole Acetic Acid Production

Indole-3-acetic acid (IAA), a physiologically active auxin, is crucial for plant growth and development. It is responsible for longer root production, increasing the number of root hairs which is involved in nutrient uptake in the plants. The IAA is synthesized in L-tryptophan metabolism and produced by several microorganisms including plant endophytic bacteria (Datta and Basu 2000). Besides, IAA acts as a principle agent in controlling plant responses in case of environmental changes (Tuteja 2007; Malhotra and Srivastava 2009). *Bacillus* sp., *Sinorhizobium* sp., and *Marinobacterium* sp. isolated from the root nodule of *Psoralea corylifolia* produce IAA which enhances the germination and establishment of wheat by interacting with abscisic acid, gibberellins, and ethylene-mediated pathways under saline stress condition (Sorty et al. 2016). Samad et al. demonstrated that *Pseudomonas* sp. isolated from *Lepidium draba* produces IAA and exhibits great impact in grape vine. *Pseudomonas mendocina*, *P. stutzeri*, and *P. putida* isolated from *Lactuca dissecta*, *Solanum surattense*, and *Sonchus arvensis* produce IAA in *Zea mays* (Naz and Bano 2010). Recently, Abdallah et al. (2016) demonstrated that *Bacillus cereus and Alcaligenes faecalis* produce IAA which induces plant growth promotion.

17.4.5 Protection against Biotic and Abiotic Stresses

Endophytic bacteria occupy a great role in plants defense systems (Islam et al. 2005; Khatun et al. 2018). They evolve in the plants at a faster rate because of their short life span than the host and develop higher selection of antagonistic form. This phenomenon increases the resistance of plants against short-living pathogens and herbivores. Endophytic bacteria protect plants from pathogenic microoraginsm through production of antimicrobial compounds (Islam et al. 2005; Islam and von Tiedemann 2011) and ISR in host plants (Carroll 1991).

Endophytes induces systemic resistance (ISR), that leads to a higher tolerance of pathogens (Seilaniantz et al. 2011; Zamioudis and Pieterse 2012). At the very beginning of colonization of bacteria, the plants exert immune defense similar to pathogen. But the endophytic bacteria escape and colonize to the plants (Zamioudis, Pieterse 2012). *Pseudomonas* and *Bacillus* are two important genera of bacteria that generally exert ISR (Chanway 1998; Kloepper and Ryu 2006), although ISR induction is not exclusive to these groups (Ardanov et al. 2011; Bordiec et al. 2011). Bacterial factors responsible for ISR induction were identified which include flagella, antibiotics, *N*-acylhomoserine lactones, salicylic acid, jasmonic acid, siderophores, volatiles (e.g., acetoin), and lipopolysaccharides (Bordiec et al. 2011; Loon et al. 2008). On the other hand, *A. faecalis* S18 and *B. cereus* inhibited mycelial growth of pathogen and formed an inhibition zone via production of lytic enzymes such as chitinases and/or proteases among other substances. In fact, synthesis of lytic enzymes, such as chitinase, protease, and *β*-1,3-glucanase, is involved in cell wall degradation during antagonism (Abdallah et al. 2016). *Pseudomonas viridiflava* is a pectinolytic bacterium isolated from the weed *Lepidium draba* L., which showed inhibiting effects toward its host. *Bacillus pumilus* isolated from *Urtica dioica* and *B. methylotrophicus* isolated from *Plantago lanceolata* are the most effective against pathogenic agrobacteria strains. Two bacterial strains of *Bacillus* spp. isolated from *Euphorbia helioscopia* and *Plantago lanceolata* are most efficient in control of *Pectobacterium* spp. (Krimi et al. 2016). The potentiality of *Stenotrophomona*s spp. for the biocontrol of plant pathogens has been documented in several systems such as monocot and dicot crops as hosts. *S. maltophilia* strains have a remarkable high hydrolytic potential. They produce various enzymes such as proteases, DNases, chitinases, glucanases, RNases, lipases, and laccases (Berg et al. 1996; Galai et al. 2008; Islam 2011). Both chitinolytic and proteolytic activities of *S. maltophilia* contribute to the biocontrol activity (Zhang and Yuen. 1999, 2000a, b; Zhang et al. 2001). Chitinases might protect plants against fungal pathogens through fungal cell wall lysis but might also have a role in triggering plant defense mechanisms (Mastretta et al. 2006). A chitinase from *S. maltophilia* strain C5 was shown to suppress summer patch disease (caused by *Magnaporthe poae* Lanschoot and Jackson) in Kentucky bluegrass by the activation of disease resistance genes (Kobayashi 2002). *Bacillus* spp. isolated from *Parthenium hysterophorus* inhibit downy mildew of pearl millet by producing antimicrobial compound (Chandrashekhara et al. 2007).

Several abiotic stresses such as high temperature, salinity, and moisture deficiency etc. affect the the growth of crop plants and so forth, these stresses also affect the microbes. Plant growth-promoting endophytic bacteria (PGPB) have been identified as a group of microbes that are used for plant growth enhancement and biocontrol for management of plant diseases. The PGPB which showed beneficial effect in the laboratory can't withstand in the field due to the prevailing abiotic stresses. Therefore, for obtaining the benefits of PGPB at the field level, abiotic stress tolerance bacterial strains should be selected (Kumar et al. 2014). Lafi et al. (2017) found *Micrococcus luteus* isolated from *Cyperus conglomeratus* shows salinity and oxidative stress tolerance under salt-stress conditions. Another study showed that *Pseudomonas viridiflava* isolated from *Lepidium draba* confered metal and herbicide resistance in vineyard. *Stenotrophomonas* spp. are promising candidates for biotechnological applications in agriculture. Many *S. maltophilia* strains carried intrinsic resistance to various heavy metals. For example, the *S. maltophilia* strains Sm777 and D457R showed tolerance to various toxic heavy metals, such as mercury, cobalt, cadmium, zinc, lead, and silver (Alonso et al. 2000). When tested in tenfold diluted tryptic soy broth, strain Sm777 is additionally tolerant to 50 mM selenite, 25 mM tellurite, and 50 mM uranyl salts. These properties of *S. maltophilia* have the potential to be exploited for bioremediation purposes or to aid phytoremediation. Furthermore, *S. maltophilia* strains could be useful in the bioremediation of heavy metal polluted soils and xenobiotics. *S. maltophilia* strains also produce bioactive compounds, including antibiotics and enzymes (Pages et al. 2008; Cao et al. 2009; Siegert et al. 2007).

17.5 Concluding Remarks

A fuller understanding of the versatility, adaptation, and potential uses of the fascinating weed associated endophytic bacteria opens up a new way of utilizing them in sustainable agroculture. Global climate change is posing serious threat to crop production through increasing various biotic and abiotic stresses to crop plants. The PGPB isolated from the weeds can be also applied under stress condition to mitigate biotic and abiotic stressed as well as to supplement chemical fertilizer or pesticides for obtaining sustainable crop production. This study represents a good starting point to think and research with weed as a major component of agroecosystem and potential sources of novel endophytic bacteria. Investigation of the molecular understanding of the weed-bacterial interactions would be very interesting for further exploitation of these potential novel biologics in the nutrient management of crops growing under stressful conditions. To further understand the highly complex nature of the microbial adaptation and response to the alterated biological, chemical, and physical environment of the plant remains a significant challenge. Developing an efficient and longer shelf-life of the PGPB formulation as well as biocontrol agent is a time-demanding approach for their wider use in sustainable agriculture. Recent advances in genomic and post-genomic analytic approaches would help to understand underlying molecular mechanisms of the beneficial effects of weed endophytes and utilize them as a biorational tools for the mitigation of some challenges in crop production due to global climate change.

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Pest Management for Agronomic Crops

18

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Abstract

Agriculture is the main stay for many countries having agrarian economies in the world. Today there are major challenges to feed burgeoning population of the world. Among other causes of low productivity of agronomic crops, insect pests attack is also a major concern. However, under climate uncertainty, this issue has been much aggravated. This chapter focused that integrated pest management (IPM) proved to the best option to control insect pests of agronomic crops for increasing production and ultimately ensuring food security under climate change scenarios.

Keywords

Insect · Pest · Control · Integrated pest management · Cereals · Oilseed · Crops

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18.1 Introduction

Humans since the dawn of the agriculture have been competing with the animals for their effects on crops in terms of different types of losses. Insects outweigh all the other groups of the animals. The earliest record of the insect ravages dates back to 2625–2475 BCE from Egypt in the ancient times, when the locusts and other insects caused plagues (Ordish 1976). In the Middle Ages, little is known about the agriculture and pests; however, plagues due to locusts have also been recorded in this era. Moreover, cockroaches and rodents were noted as pests. Chinese also used bridges of bamboo sticks on citrus trees in about 800 AD to encourage predatory ants to move from one tree to another for biological control of insect pests. In the seventeenth century, there was more urbanization in Europe; therefore demands for food were increased. Consequently, due to urbanization more populations of insects were noted. Insecticidal properties of tobacco infusions and arsenic were discovered in the last part of the seventeenth century. Although people knew the toxic properties of the arsenic, the fear of hunger was more powerful than the toxicity. Here we discuss brief history of the pest management from eighteenth century to the modern times and pest management perspective of some important agronomic crops.

18.2 Pre-Insecticide Era

The important landmark in the biology was the introduction of the binomial system of the nomenclature in the eighteenth century by Carolus Linnaeus. The method of giving the standard names to the species helped in storage and retrieval of the information for biological pest control. The other important discovery was the understanding of connection between heat summation and various physiological processes of growth, development, and reproduction in insects. Scientists also came to know the plants' natural defense system against the insects which helped in increased development of botanicals. Insecticidal properties of nicotine, pyrethrin, and rotenone were discovered which are still used in pest management systems.

The first variety of apple resistant to woolly apple aphid was recorded in the UK in the beginning of the third decade of the nineteenth century. Scientists came to know that insects transported from one place to another can be pest through trade or tourism. Similarly if plants are introduced into place, the native species can also be the pests on newly introduced plant species. The grape *Phylloxera* a homopteran species was transported from North America to Europe and became serious threat for grapes in 1860s. This invasion led to first organized attempt of legislative measures to future invasion of the pests. Second decade of the twentieth century witnessed the resistance development in San Jose scale to lime sulfur. The term biological control was also coined in 1919 based on the concept that predators and parasitoids could control pest organisms.

18.3 Insecticide Era

The important landmark was the discovery of the insecticidal properties of DDT by the Swiss chemist Paul Muller in the era of the Second World War. This compound was discovered in 1874 in Germany as chemical, but its insecticidal properties were not known until 1940. Paul Muller was awarded the Nobel Prize in 1948. The production of the pesticides along with their applications in agricultural crops was increased tremendously in the 1950s (Osteen and Szmedra 1989). Newer chemical molecules were searched for their evaluation as insecticides to control the insect pests.

The earliest record of the insecticide resistance to synthetic chemicals dates back in 1946 DDT failed to control the houseflies in Denmark and Sweden (Brown and Pal 1971). Occurrence of resistance to insecticides led to the development of the new molecules which were introduced from time to time. After the discovery of insecticidal properties of organochlorines, organophosphates (OPs) and carbamates were discovered as insecticides. However, development of resistance to new molecules also went on parallel with their discoveries. The OPs completely replaced organochlorines to manage cotton pests in the early 1960s in Texas. Tobacco budworm, *Heliothis virescens* (Fabricius), was resistant to carbamates and OPs in the Lower Rio Grande Valley of Texas in the late 1960s (Perkins 1982). Resistance to OPs and carbamates was developed in *Helicoverpa armigera* (Hubner) during the early 1970s from Australia. Pyrethroids developed resistance to *H. armigera* only after 4 years of their introduction in Australia in 1979 (Forrester et al. 1993). The problem of the resistance was ubiquitous in the world to all classes of insecticides as well as diversity of the arthropod pests in 1990s (Razaq 2006). Insecticide resistance has been reported in 597 species of arthropods to 336 compounds in 14,644 cases from the world. *Plutella xylostella* (L.), *Bemisia tabaci*, and *H. armigera* are the species to which the highest numbers of compounds have developed resistance (www.irac-online.org/documents/resistance-database-team-update-2016).

Along with the resistance, other consequences of insecticides like emergence of secondary pests or replacement and resurgence were also observed. Cotton leaf perforator, *Bucculatrix thurberiella* Busck, was an obscure insect, but after the widespread use of DDT, it became major pest of cotton in the Imperial Valley (Smith and Flint 1977). Whitefly, *Bemisia tabaci* (Gennadius), was the secondary pest of cotton in Sudan and the Imperial Valley, but it became a major threat of the cotton only after the application of insecticides in both the regions. In Sudan yield of cotton decreased from 1653 kg/ha to 1020 kg/ha even after 600% increase in the cost of spraying (Johnson 1982).

Insecticides also affect the nontarget insects rendering the ecosystem services. Males of colonies of honey bees, *Apis mellifera* L., receiving neonicotinoids (clothianidin and thiamethoxam) have shown reduced reproductive capacity. As might be expected, queen failure and wild insect pollinator decline could be due to the effect of neonicotinoids on the male reproductive capacity (Straub et al. 2016). In the recent studies, it has been also proved that consumption of fruits and vegetables with high pesticide residues affects reproduction in humans (Chiu et al. 2015; Chiu et al. 2018). In China insecticide residues (of 32 insecticides) exceeded maximum residue limits detected from 20 vegetables (Yu et al. 2018).

18.4 Integrated Pest Management Era

Although consequences started to surround since the beginning of the chemical control, still all the problems prevail in almost all the regions where insecticides are applied. Stern et al. (1959) wrote a seminar paper entitled “The Integrated Control Concept” which is considered the basis of modern pest management. The concept was based on understanding of pest population development, sampling/monitoring, determining need/time for application of control measures, applying only selective insecticides, and integrating control methods. All these components are still required in any pest management system around the world. The authors emphasized that integrated control is not a panacea that can be blindly applied to any system. It was argued that our knowledge about agroecosystem alone is not sufficient to shift from intensive calendar-based application to integrated control. The effects of previous treatments of chemicals may last for several years. Moreover, biological control agents have to be reestablished where they no longer exist.

The integrated control was applied in various crops to control the pests in 1950 until 1960 like codling moth, *Cydia pomonella* (L.), and other pests on walnut. The efforts of integrating different control measures were adopted to address the problems of insecticide resistance, resurgence, and replacement. The entomologists thought to consider the whole picture of the entomology to control insect pests. Biotic factors like predators, parasitoids, and insect pathogens (bacteria, fungi, virus, etc.) causing diseases in insects were considered important to control insect populations. Likewise application of integrated control to crops the term also entrenched in the entomological literature (Michelbacher and Bacon 1952). However, the term pest management began to surface among specialists (Apple and Smith 1976). Both the terms integrated control and pest management coexisted in the literature as synonyms to each other until the middle of the 1970s. In the same decade, a term integrated pest management (IPM) was coined by the Panel of Experts of Food and Agriculture Organization (FAO). However, the term was discussed in several meetings of the committees of experts formed by the government of the USA and also in congresses of the entomologists. Several definitions of IPM were put forward, and till the last decade of the twentieth century, more than 60 definitions were proposed (Kogan 1998). However, well-accepted definition in the literature is of Kogan (1998), “IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment.”

Recently it has been argued that IPM does not come under the true meanings of sustainable because it requires inputs of various control methods continuously.

Alternate terms "environmental pest management" or "ecological pest management" have been proposed to refer to truly sustainable solutions with the emphasis that, when these will be integrated into agricultural production systems, will function without any further human interventions (Coll and Wajnberg 2017; Shennan et al. 2004). In the current scenario, IPM concept has envisaged with a focus on all the components of agroecosystem and also takes into account the economic, marketing, social, and political factors those affect IPM adoption (Bottrell and Schoenly 2018).

Integrated pest management strategies were applied in both developed and developing countries. With all the efforts, insecticides became part of any pest management system, and it was not possible to totally abandon them from the agricultural systems. However the efforts were diverted to minimize their use and toxic effects. In most of the cases, IPM was developed to deal with the consequences of the insecticides. One of the most important issues was the development of insecticide resistance to insecticides. Cotton was the worst crop in all regions where grown with respect to development of resistance in its herbivores mainly due to economic concerns. Before the introduction of the genetically modified cotton, lepidopterans belonging to genera *Heliothis* and *Helicoverpa* (Lepidoptera: Noctuidae) were almost resistant to all the available insecticides in the USA, Australia, China, Africa, India, and Pakistan (Razaq 2006).

IPM strategies had varied success in developed countries but largely failed in the majority of cases in developing countries, mainly due to lack of knowledge among the growers for compliance and also research to develop the IPM guidelines in the agroecosystem in which they exist. *Helicoverpa* spp. became resistant to the pyrethroid insecticides only 4 years after their introduction in Australia in 1983 (Forrester et al. 1993). Insecticide resistance management (IRM) strategy was developed to extend susceptibility of pyrethroids, as previously these pest species developed resistance to insecticides belonging to organochlorine, organophosphate, and carbamate groups of insecticides. The insecticide resistance management strategy based upon the rotation of unrelated chemical groups on per generation basis was implemented. Pyrethroids were allowed to spray on cotton for 42 days in mid season. The resistance was continuously monitored by discriminating dose technique based upon the larvae reared from the field-collected eggs. Later on from 1989 to 1990, pyrethroid window was reduced to 35 days. It was thought that two main reasons were contributing for reduction in resistance, i.e., susceptibles immigrating from refugia and pyrethroid selection pressure (Forrester et al. 1993). This strategy undoubtedly held pyrethroid resistance in check for number of years. But there was steady rise in proportion of population that was resistant to pyrethroids. The Australian IRM strategy was imitated and applied with successful outcomes in many agroecosystems of the world like management of *B. tabaci* in the USA (Castle et al. 1999; Ellsworth and Martinez-Carrillo 2001).

18.5 Era of Genetically Modified Crops

The major breakthrough in the history of the IPM was development of the genetically modified (GM) crops to manage insect pests and weeds. The gene of *Bacillus thuringiensis* Berliner (Bt) has been inserted in the crop plants to manage insect pests belonging to insect order Lepidoptera. Other genetically engineered crops are those which are tolerant to specific herbicides (particularly to glyphosate and to glufosinate) in cotton, canola, maize, and soybean. The plants having resistance genetically modified herbicide-tolerant (GM HT) traits allow for the spraying of such crops with broad-spectrum weedicides, to manage both the broad-leaved and narrow-leaved weeds, but do not affect the crops themselves (Brookes and Barfoot 2017). Such crop varieties were released for commercial cultivation in the last decade of the twentieth century (Naranjo 2010). Currently, genes have been stacked in some crops for both the insect resistance and herbicide tolerance.

The area under GM crops is 12% of the total agricultural crops in the world, in which 40% of these crops are grown in developing countries. Genetically modified cotton occupies 75% of the total area under cotton in the globe (Eisenring et al. 2017). These crops have reduced the 581.4 million kg of the pesticides ultimately decreasing their adverse environmental impacts. These crops have also helped in reducing fuel needed to apply the pesticides and for tillage to manage weeds resulting in decrease of the greenhouse emissions from GM cropping area. It has been estimated that in the year 2014, it was equal to decreasing ten million cars from the roads (Brookes and Barfoot 2017). Increases in grain yield and quality and decreases of the target insect *Diabrotica* spp. have been recorded in the last 21 years of its cultivation from maize. Moreover, these crops had low or no effect on the population abundance of nontarget insect and also reduce mycotoxin contents in grain minimizing economic losses in the world (Pellegrino et al. 2018).

However, the cultivation of the GM cotton witnessed problems like evolution in insects to develop resistance against genes conferring it and appearance of new hemipeteran insect pests. Since the inception of the GM cotton, efforts were directed toward managing resistance. Resistance has been successfully managed particularly by pyramiding genes and planting of susceptible refuge crop (non-Bt) to manage pink bollworm (PBW), *Pectinophora gossypiella* (Saunders), in the USA. Similarly *H. armigera* has also been managed without any losses to growers by aforementioned tactics and with some other cultural practices in Australia (see also section for “Cotton Pest Management”). Moreover Bt cotton have been failed due to development of resistance in PBW, which has become again threatening pest in China, India, and Pakistan. The major reason for its success in the developed nations is the development of strategies and their 100% compliance by the farmers to delay evolution of resistance, whereas no such strategies were employed in the developing nations.

Different control methods like cultural control, mechanical control, host plant resistance, and biological control need to be integrated in harmonious way.

18.6 Components of IPM

Around 60 years have gone by ever since the concept of integrated control was introduced by Stern et al. (1959). Idea behind this concept was to integrate insecticides and biocontrol agents in such a way that insecticides affect biocontrol agents as least as possible. For that, four basic elements, which had to be strategically assembled, were introduced. These included (1) determining thresholds for deciding control action, (2) sampling plans for assessing critical densities, (3) impact of biocontrol agents on pest suppression, and (4) the use of selective insecticides. According to Naranjo and Ellsworth (2009), integrated control concept has been the driving force in shaping up the conceptual frame work of IPM. IPM is a diverse set of various chemical and nonchemical pest control actions adopted in harmony, and insecticides must be applied when other control methods are failure.

IPM today has been dominated by single technology intervention, particularly insecticides (Thomas 1999), and originally it should consider ecological interactions of other pest control tactics. Foundation of IPM should primarily be based upon thorough understanding of individual ecology and ecological interactions between pests, biological agents, and host crop (Fitt 2000). Understanding these ecological aspects provide opportunities in exploring and integrating other pest control tactics like cultural control, host-plant resistance, and habitat manipulation (Cook et al. 2007; Douglas 2018; Shakeel et al. 2017). Moreover, emerging era of genetically modified crops (Kennedy 2008), which in integration with other nonchemical tactics, have been found effective in developing sustainable and economically acceptable IPM package, with much less reliance on pesticides (Fitt 2000). The modern IPM, which has evolved through hands and minds, has therefore gone far beyond the bounds of integrated control concept, latter mainly focused insecticides and biological agents of pest control.

Here we take the case of whitefly, *Bemisia tabaci*, as a polyphagous pest and a menace to a range of agronomic and horticultural crops, worldwide. In developing IPM against this pest, Ellsworth and Martinez-Carrillo (2001) focused three key elements including sampling, effective use of chemicals, and pest avoidance. These elements were the building blocks of IPM and represent an excellent overview of IPM components. Ellsworth and Martinez-Carrillo (2001) in their work piled these elements over each other to build a pyramid. The pyramid is a paradigm representing arrangement of elements and set of actions within each element. In this pyramid, sampling resides apex section, while avoidance and effective chemical use reside bottom and middle sections, respectively. However, variation can occur in their level of implementation.

18.6.1 Sampling

Sampling is a method of classifying population abundance of a given pest species. Sampling is used for detecting pest presence or measuring its damage – this information is subsequently utilized for deciding intervention. While sampling can vary according to species, therefore suitable sampling methods should be adopted after careful consideration. Without a well-designed sampling method, it is unlikely to have near accurate estimation of pest situation, and this also questions accountability of intervention used. Thus, sampling has tremendous impact in determining the fate of pest management and should be adopted carefully for successful implementation of IPM.

18.6.2 The Effective Use of Chemicals

This component considers three major strategies: (1) action thresholds for deciding intervention, (2) choice and effectiveness of insecticides, and (3) insecticide resistance management. Insecticides are the integral part of IPM; however, they should be used when other pest control strategies are unable to suppress pest. Insecticides should be applied when the pest has reached densities, which are damaging (i.e., action threshold). As their use is associated with nontarget effects, replacing broad-spectrum insecticides, which target wide range of insects, with selective insecticides, can conserve beneficials. Highly selective and toxic insecticides may result in complete elimination of pest, which can deprive biocontrol agents of their prey and favors inter- and intraguild predation. Further, caution is needed while selecting insecticides, because frequent use of insecticides favors natural selection in pest. This may led to insecticide resistance development in pest populations. One vital way to overcome resistance is developing and rotating new chemistries in varying mode of actions.

18.6.3 Avoidance

This is the bottom part of the pyramid and the most complex one. It deals with a wide range of pest control strategies considering crop management practices, pest biology and ecology, and area-wide management. All these are a complex set of interaction working in a way to shift competitive advantage to host over pests. These set of actions that in part, serve to keep the pest below damaging level, represent avoidance.

18.7 Pest Management in Cotton

Upland cotton, *Gossypium hirsutum* L., occupies 95% area in the world among other species. Due to the economic concerns, cotton has been exotic crop in most parts of the world; therefore, insect complexes have invaded this crop in different production systems (Castle et al. 1999; Naranjo 2010). More than 1300 arthropod species have been recorded from cotton around the globe; however, about 3 dozen species are considered as regular pests (Naranjo 2010; Trapero et al. 2016). Insect pests damaging to the cotton mainly belong to the two categories, i.e., sucking insects and bollworms. Sucking insect pests belong to the orders Hemiptera (bugs and whiteflies) and Thysanoptera (thrips) and feed on the sap. The second group belongs to the insect order Lepidoptera and their immature stages or larvae feed mostly upon the reproductive parts of the plants. Other than these two groups, insect pests include weevils, termites, crickets, grasshoppers, etc.; these insect pests are specific to the regions of the world. The earliest record of heavy losses from the insect pests to cotton dates back to the last decade of the nineteenth century by the boll weevil *Anthonomus grandis* Boheman in the USA (Frisbie et al. 1994).

Since the discovery of synthetic insecticides from the 1940s, insect pests of cotton have been managed with them. Due to the sole reliance on these chemicals, consequently their associated impacts have resulted in the development of resistance in arthropods, appearance of secondary pest, and resurgence of the species being targeted. Resistance to insecticides was reported as early as in the 1950s, and the numbers of arthropod species being resistant increased temporally. In the 1980s resistance to variety of insecticides was recorded in 26 insect pest species of cotton herbivores (Georghiou and Mellon 1983). In the last decade of the twentieth century, the silverleaf whitefly *Bemisia tabaci* (Genn.) and bollworms (*Heliothis* and *Helicoverpa* spp.) were resistant to the almost all the conventional insecticides, and their susceptibility was also being lost to new chemistry insecticides in the USA, Australia, and Asia (India, Pakistan, and Thailand) (Castle et al. 1999; Razaq 2006).

Genetically modified cotton varieties those express the toxin of *Bacillus thuringiensis* (Bt), which controls lepidopteran pests (bollworms *Heliothis* or *Helicoverpa* spp., *Pectinophora* sp., and *Earias* sp.), were introduced in 1995 for commercial cultivation. Bt cotton helped in managing resistant populations of bollworms that were not being controlled with insecticides (Wilson et al. 2004). In 2013, Bt cotton approximately occupied two third area of the total area in the world (James 2015).

After the introduction of Bt cotton, there was substantial reduction in insecticide use with negligible effects on nontargets (Whitehouse et al. 2014). Until 2008, 141 million kilograms of synthetic insecticides were saved, and those were applied to manage bollworm species before the adoption of Bt cotton. In the USA 44% reduction in insecticides was recorded on Bt cotton as compared to pre Bt era. In Australia after the introduction of Bollgard II, 80–90% to 65–70% reductions in the active ingredients per hectare were noted (Naranjo 2010; Fitt and Wilson 2012).

The primary challenge to the continued success, which was given due consideration even before the introduction of the genetically modified cotton, was the evolution of resistance by insect pests (Carpenter 2010). Populations of the *Helicoverpa armigera* (Hubner), *Helicoverpa punctigera* (Wallengren), *Heliothis virescens* (F.), and *Pectinophora gossypiella* (Saunders) from Australia, China, and the USA during the first 22 years after the introduction of Bt cotton have been recorded to sustain susceptibility against genetically modified cotton varieties. Susceptibility in the target species of the Bt cotton was due to adoption of preemptive insecticide resistance management (IRM) strategies (Catarino et al. 2015). However in developing countries, where IRM strategies were not developed or even in the regions where farmers did not comply with guidelines of Bt resistance management program, cotton crop had reached to crisis phase due to development of resistance in target herbivores. In India and Pakistan, *P. gossypiella* is a redundant pest of Bt cotton only due to the development of resistance in the absence of the IRM strategies (Mohan et al. 2016).

Integrated pest management requires continuous stewardship to sustain its effectiveness, which requires research as well as extension services and their compliance (Bottrell and Schoenly 2018). Here we briefly discuss the success of Bt cotton in the USA and Australia due to both aforementioned reasons. To counter the resistance first of all pyramids of Bt crop were developed Bt toxin to those expressing two or more Bt toxins. This combination of toxins is called “pyramiding.” The Bt varieties of cotton were developed having Cry1Ac and Cry2Ab toxins. Pests resistant to toxin Cry1Ac were susceptible to Cry2Ab; moreover, there was no cross resistance across the two toxins, as both these toxins have different binding sites in the midgut of the larvae (Carrière et al. 2006; Tabashnik et al. 2009).

The resistance to *P. gossypiella* has been encountered by developing and adoption of the refuge strategy by the growers in the USA. In this strategy farmers have to plant specified area of the non-Bt cotton with Bt cotton (Huang et al. 2011). This strategy provides Bt-resistant pests chances of random mating with abundant populations of Bt-susceptible pests from the susceptible refuge crop, thus reducing the chance of selection of Bt-resistance in pest populations. Moreover, several studies proved that Bt-resistance in Cry1Ac and pyramids of Bt cotton in *P. gossypiella* is a recessive trait, therefore all heterozygotes will die when they will feed on cotton plants having Bt toxin. The resistant individuals are also biologically deficit on non-Bt plants of the cotton crop (Carrière et al. 2015; Fabrick et al. 2015; Gassmann et al. 2009). Release of sterile moths in cotton fields of cotton in the USA in 2006 also contributed in delaying resistance in *P. gossypiella* (Tabashnik et al. 2012).

In Australia, resistance development has been delayed in *H. armigera* and *H. punctigera* with a preemptive IRM strategy. This strategy include the following: (1) it is compulsory to grow 10% of non-sprayed refuge crops of non-Bt cotton; (2) destruction of ratoon crop plants; (3) planting cotton recommended time; (4) minimizing sowing of Bt cotton expressing foliar toxins; and (5) obligatory to destroy pupae of both the species of *Helicoverpa* when the crop is over (Baker et al. 2008). The major reason for the success of sustained susceptibility was complete compliance of the growers with recommendations besides increasing their cost of production and inconvenience particularly for size and distance of sowing of non-Bt cotton in Australia and in the USA, respectively (Carrière et al. 2004; Wilson et al. 2004).

The second problem with Bt cotton was the emergence of sucking pests (e.g., the bug complex) when the insecticides used against lepidopteran bollworms were reduced, which had indirectly controlled these secondary pests. These emergent pests were managed coincidently with the insecticides that had been used to manage bollworms. The reliance on insecticides to control these sucking pests since the introduction of Bt cotton led to the problem of resistance in these pests in Australia (Trapero et al. 2016).

Commercial plantation of Bt cotton also suffered from substantial increase in the damage by secondary pests due to reduction in use of pesticides applied to manage lepidopteran pests in Australia, China, India, and Pakistan (Lu et al. 2010; Naranjo

2010; Saeed et al. 2015; Wilson et al. 2013). These secondary pests belong to the Hemiptera (aphids, leafhoppers, and bugs). These pests are being managed with proper use of insecticides and with other (IPM) tactics, with no further problems in the USA (Catarino et al. 2015).

18.8 Pest Management in Cereal Crops

Cereal crops are grown for their edible starchy seeds and by far considered to be the most important source of concentrated carbohydrates both for humans and animals (Leonard and Martin 1963). Cereals are the main items in the diet of much of world's population and accounts for the 70% of harvested acreage in the world (Janick et al. 1969). Cereals including wheat and corn are being utilized for food and feed and also as biofuels (e.g., ethanol) (Wolf et al. 2018). There are many insect pests reported to infest underground and aboveground parts of wheat including Hessian fly, *Mayetiola destructor* (Say), in the USA (Gallun et al. 1975); wheat stem sawfly, *Cephus cinctus* (Norton), in North America (Weiss and Morrill 1992); sunn pest, *Eurygaster integriceps* (Puton), in West and Central Asia and East European countries (El Bouhssini et al. 2009); cereal leaf beetle, *Oulema melanopus*, in Tajikistan (Landis et al. 2016); the orange wheat blossom midge, *Sitodiplosis mosellana* (Gehin) (Diptera: Cecidomyiidae), in the northern hemisphere (Chavalle et al. 2015); saddle gall midge, *Haplodiplosis marginata* (von Roser), in Belgium and several other European countries (Censier et al. 2016); and several species of aphids (Hemiptera: Aphididae) including English grain aphid, *Sitobion avenae* (Fabricius); corn leaf aphid, *Rhopalosiphum maidis* (Fitch); bird cherry-oat aphid, *Rhopalosiphum padi* (L.); greenbug, *Schizaphis graminum* (Rondani) (Walker); *Rhopalosiphum rufiabdominale* (S.) (Hashmi et al. 1983); and Russian wheat aphid, *Diuraphis noxia* (Mordvilko) (Inayatullah et al. 1993).

Among these species, aphids are considered as the most severe pest of wheat crop in Asian countries as well as across the globe. Three species, *Sitobion avenae* (F.), *Rhopalosiphum padi* (L.), and *Schizaphis graminum* (R.), are major insect pests of wheat (Kannan 1999; Shah et al. 2017). Aphid inflicts significant economic losses to wheat and other cereals by direct feeding on phloem sap (Kindler et al. 2002) or indirectly by carrying and spreading plant viruses, especially barley yellow dwarf virus between crops (Gray et al. 1996). Moreover, secretion of honeydew on leaves interferes with photosynthetic and respirational functions of plants and consequently boosts leaf senescence (Bardner and Fletcher 1974). Aphids can cause 35–40% loss directly by sucking sap and 20–80% indirectly by transmission of fungal and viral diseases (Kieckhefer and Gellner 1992; Rossing et al. 1994).

Biocontrol agents such as parasitoids, lady beetles, hover flies, green lacewing, and spiders can considerably contribute to the pest management worldwide (Ali et al. 2018; Saeed and Razaq 2015). In Pakistan, coccinellids, mainly *Coccinella septempunctata* L. and *Coccinella undecimpunctata* L. (Coleoptera: Coccinellidae); syrphids, mainly *Ischiodon scutellaris* F. (Diptera: Syrphidae); spiders, mainly *Oxyopes javanus* T. (Araneae: Oxyopidae) and *Pardosa birmanica* S. (Araneae:

lycosidae); and aphid parasitoids, *Aphidius colemani* V. (Hymenoptera: Braconidae), are the important aphid natural enemies (Shah et al. 2017). Natural enemies may act as strong top-down forces in suppressing aphid population. However, predator efficiency and their development are affected by various factors such as competency for prey resource, intraguild predation (Mirande et al. 2015), and/or temperature (Ali et al. 2014), which under unfavorable circumstances could compromise predator efficiency. As the aphids can inflict huge economic losses, various studies have evaluated synthetic insecticides against wheat aphids (Shahzad et al. 2013; Wang et al. 2017). Insecticides have been evaluated along with cultural practices, such as through the involvement of planting dates (Royer et al. 2005; Shahzad et al. 2013). However, due to concern on synthetic chemical use in wheat, the current emphasis on developing environment-friendly pest control alternative such as integrating azadirachtin-based neem-derived products in pest management. Neem-derived compounds have been found promising and compatible with natural enemies (Aziz et al. 2013) and even can increase the susceptibility of pest toward biological control agents by affecting diverse array of performance-related parameters of target pests (Charleston et al. 2006).

18.9 Pest Management in Oilseed Crops

The oilseed crop sector is regarded as a most dynamic parts of world agriculture that grew at 4.3% as compared with an average of 2.1% for all agriculture until first decade of the twenty-first century. One of the reasons for the growth of this sector is the use of vegetable oil for non-food purposes particularly in industries. However, the major reason for the rapid growth of oilseed crops is their consumption as food in the developing countries due to high-calorie contents of oil products (Alexandratos and Bruinsma 2012). Soybean, oil palm, rapeseed, sunflower, groundnut, coconuts, cotton seed, and sesame seed are the oilseed of the world (Alexandratos and Bruinsma 2012).

Developing countries cannot meet their total requirements of the oil from their domestic production; therefore they need the import of the edible oil. Rapeseed crops rank third in the world among all the other crops; moreover, these are also important in developing countries as these are used for multiple purposes like fodder, humans food (both as plants and oil), and cattle feed in the form of the oilseed cake. Canola, *Brassica napus* L., is also grown in almost all the continents. Here we shall focus on the pest management problems of the rapeseed and mustard and particularly those of *B. napus*.

Rapeseed and mustard crops are invaded by the variety of the insect pests. However, their damage varies in the different countries where these are grown. In Australia, 30 species of the arthropods have been recorded. The insect pests belong to the insect orders Hemiptera (aphids, bugs), Lepidoptera (*Helicoverpa punctigera*, *Plutella xylostella*), and Coleoptera (*Phyllotreta cruciferae*) (Aslam and Razaq 2007; Gu et al. 2007; Tangtrakulwanich et al. 2014).

Cabbage aphid, *Brevicoryne brassicae* (L.); turnip aphid, *Lipaphis erysimi* (Kaltenbach); and green peach aphid, *Myzus persicae* (Sulzer), are the primary insect pests of oilseed *Brassica*. These have been reported to cause damage in 33 states of the USA and several Asian countries, such as Bangladesh, Iran, India, and Pakistan (Adhab and Schoelz 2015). In case of the severe infestation, these aphid species may cause complete failure of the crop particularly from Asian countries with up to 11% reduction in oil contents.

Although aphids can feed on all the reproductive parts of the plants, reproductive parts like rosettes and flowers are preferred. Aphid feeding on *Brassica* crops at vegetative stage distorts leaves, prevents vegetative growth of plants, and inhibits flowering and finally pod formation (Gu et al. 2007; Weiss 1983). Damage at flowering stage causes wilting of flowers as *Lipaphis erysimi* and *B. brassicae* reduce photosynthetic rate and chlorophyll contents Razaq et al. 2014; (Hussain et al. 2015).

Among the nonchemical control methods, rigorous screening attempts in India and Pakistan proved lack of the resistance in the varieties development programs. Many species of the coccinellids and chrysopids are reported as the predators of the aphids (Amer et al. 2009). Among the parasitoids *Diaeretiella rapae* (M'Intosh) is reported from the different parts of the world. But both these kind of natural enemies are unable to keep the populations of aphids below the status of the pest (Aslam and Razaq 2007). Action threshold levels can reduce enormous quantities of insecticides need to determined yet.

18.10 Pest Management in Pulses

Pulses are the second only to the cereals and the important source of proteins in the human diet, predominately for the world's vegetarian population (Kochhar 2016). Several crops such as pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medic.) and chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan*), mungbean (*Vigna radiata*), and urdbean (*Vigna mungo*) are the important pulse crops grown in the USA and Asian countries. While pulses are attacked by a great diversity of insects, a few in these are economically important, and the economic status of pests may vary geographically (Singh and Emden 1979). In the USA and Canada, several pest species are characterized as major pests of pulses. These include seedcorn maggot (*Delia platura* Meigen), a complex of wireworms (*Limonius californicus* (Mannerheim), *Limonius infuscatus* Motschulsky, *Limonius canus* LeCount, *Hypnoidus bicolor* Eschscholtz, *Aeolus mellillus* Saylor, and *Selatosomus aeripennis* Kirby), cutworms (*Euxoa auxiliary* Guenée, *Agrotis orthogonia* Morrison, and *Feltia jaculifera* Guenée), pea leaf weevil (*Sitona lineatus* L.), pea aphid (*Acyrthosiphon pisum* Harris), lygus bugs (*Lygus hesperus* Knight and *Lygus lineolaris* Palisot de Beauvois), and grasshoppers, mainly the omnivorous *Melanoplus sanguinipes* Say, *Melanoplus differentialis* Thomas, *Melanoplus bivittatus* Say, and *Camnula pellucida* Scudder (Jaronski 2018). In Asian countries, pulse are attacked by borer, *Helicoverpa armigera*; pod bug, *Clavigralla gibbosa*; pod fly, *Melanagromyza obtusa*; blister beetle, *Mylabris* spp.; hairy caterpillars, *Spilosoma* *obliqua* and *Amsacta moorei*; jassids/leafhoppers, in particular *Amrasca biguttala biguttala* (Ishida) (*Amrasca devastans* Dist.) (Hemiptera: Cicadellidae) (Soundaryarajan and Chitra 2012); termites, *Odontotermes obesus* and *Microtermes obesi*; pod borer, *Etiella zinckenella*; and, whitefly, *Bemissia tabaci* (Roshan and Rohilla 2007). Feeding damage by these species may occur on aboveground plant parts of the infested plants such as on the roots, root nodules, pods, flowers, and seeds (Knodel and Shrestha 2018) as well as belowground plant parts by soil-dwelling pests (Zvereva and Kozlov 2012).

Pea leaf weevil, *Sitona lineatus* L., is a serious pest of peas and faba beans (Cárcamo et al. 2018). *Sitona lineatus* is a univoltine species. Adult stage passes winters in state of quiescence alongside field margin. Adults, at the time of emergence, are oligophagous on several members of Fabaceae (Landona et al. 1995), whereas their reproductive phase has a clear preference for faba bean (Nielsen and Jensen 1993) and peas (Landona et al. 1995). Characteristics symptoms of adult feeding appear as U-shaped notches along the leaf margins (Jackson and Macdougall 1920); however, their infestation can rarely destroy young shoots (Williams et al. 1995). However, larval stage is critical, in addition to feeding on nodules, and larvae can feed on nitrogen-fixing bacteria within root nodules, thus reducing nitrogen availability for the infested plant (Cárcamo et al. 2015). Larvae are abundant in numbers, reaching up to 5000 per m^2 in field plots in southern Alberta, and their infestation may lead to destruction of approximately 90% nodules (Cárcamo and Vankosky 2011).

To avoid damage by pests, cultural, biological, and chemical control methods have been developed. For the cultural control, adapting crop rotation has been a key component of traditional pest management. As *S. lineatus* adults are very mobile and can move between fields, it is crucial to maintain reasonable distance between fields within seasons (Vankosky et al. 2009). Another approach that has been investigated against this pest for over 20 years has been employing crop plant resistance to manage this pest. Field pea varieties have varying amount of wax layers on leaves due to genotypic variation (Chang et al. 2004; White and Eigenbrode 2000), and manipulation of these genotypes may have potential in producing resistant varieties. *S. lineatus* prefers leaves and stipules with thinner wax layer compared to those that have thicker wax layer (White and Eigenbrode 2000). In Europe and elsewhere between 1960 and 1980, a significant amount of work was done in an effort to identify and develop field pea with *S. lineatus* resistance (Auld et al. 1980; Tulisalo and Markkula 1970), but these efforts met with limited success (reviewed by Vankosky et al. (2009)). New field pea and faba bean varieties and new tools for screening and introducing genetic-based resistance into plant populations may allow plant breeders to overcome past hurdles. Other avenues of investigation with respect to host plant resistance may include studying the effects of plant volatiles that modify pest behavior.

Another promising approach employed against *S. lineatus* is the utilization of biological control agents. These include several species of parasitoids, predators, entomopathogenic fungi, and nematodes. Although, none of the identified biological control agent of this pests is a specialist, however, a few species of parasitoid attacking *S. lineatus* in its native range have been released in North America for management of other *Sitona* spp. and other weevil species [e.g., *Hypera postica* (Gyllenhal) Coleoptera: Curculionidae]; however, their establishment was variable (Loan 1975). The most promising was *Anaphes diana* (Girault; Hymenoptera: Mymaridae), an egg parasitoid of *Sitona* weevils that was established in the eastern USA (Dysart 1990). No parasitoids attacking *S. lineatus* have yet been found in Alberta where the pest has been present since at least 1997 (Vankosky et al. 2009). There is no biological control program for any *Sitona* species, in Canada (Cárcamo and Vankosky 2013). The impact of generalist predators on *S. lineatus* populations is not well documented.

Several insecticides have been evaluated for the management of this species since 1980s. Earlier, foliar insecticide active ingredients were evaluated, and these include phorate (King 1981), cyhalothrin-lambda (Van De Steene et al. 1999), permethrin (McEwen et al. 1981), and imidacloprid (Van De Steene et al. 1999). Several other compounds such as carbaryl, cyfluthrin, phosmet, and cypermethrin are available depending on the jurisdiction. For example, in North Dakota as of 2017, the list included over ten active ingredients or mixtures. Foliar insecticides can reduce adult weevil populations and foliar damage, but may not protect yields (Vankosky et al. 2009). Cyhalothrin-lambda treatment reduced adult weevils by 56% (Van De Steene et al. 1999). Application of permethrin (pyrethroid insecticide) decreased larval populations by approximately 50% (Bardner et al. 1983), likely due to mortality of adult females, as contact foliar insecticides have no direct impacts on eggs or larvae (Van De Steene et al. 1999). Some products have improved yields only slightly. For example, plots treated with permethrin yielded 2.4% more than untreated plots (Bardner et al. 1983). Properly timing the application of foliar insecticides is difficult, as they must be applied immediately following the detection of weevil invasion to prevent adult females from laying eggs in the host crop (Bardner et al. 1983; King 1981). To ensure adequate plant protection, multiple foliar applications may be required over the course of the dispersal period of *S. lineatus*, depending on the residual time of the insecticide product and rainfall events. For these reasons, producers generally favor the use of systemic insecticides for management of this pest.

Another method is coating seeds with systemic insecticides for *S. lineatus* management in field peas. There is consensus that systemic insecticides are more effective than foliar applications (Dysart 1990). Many of the seed treatments such as carbofuran or related compounds, effective in Europe 30 years ago, are no longer available in most jurisdictions. Over the last two decades, these compounds were replaced by neonicotinoids, which in turn have been restricted in some jurisdictions or phased out. In western Canada and the USA, for now, neonicotinoids are still used in field peas, and its mechanism of crop protection is well known at least for thiamethoxam (CáRcamo et al. 2012). This chemical only kills around 30% of the adults, but there is a significant reduction in adult feeding damage (50%), less oviposition by survivors, and only about half of the larvae survive in plants grown from seeds coated with this chemical (CáRcamo et al. 2012). The authors cautioned that under situations of high weevil outbreaks, the surviving larvae still cause damage to reduce yields of peas, and this may explain the inconsistent yield protection observed in some studies (e.g., Vankosky et al. 2011).

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Integrated Pest and Disease Management for Better Agronomic Crop Production

19

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Abstract

The disease and pest infestation is considered as one of the major constraints in better agronomic crop production for attaining anticipated yield to cater food security in the world. As agronomic crops (particularly cereals and pulses) are the leading sources of food in the world, management of their catastrophic pests and diseases needs special emphasis. At present, pests and diseases of agronomic crops are managed by various chemical control measures by using pesticides and fungicides. However, the disquiets regarding agronomic sustainability have instigated a wide and comprehensive utilization of integrated pest and disease management approaches. The said program is considered as an ecologically safer tactic for the control of various dreadful pests and diseases. Integration of approaches is aimed at reducing the health and ecological damages in response to chemicals by adopting certain cultural, mechanical, and biocontrol measures to manage various pests and diseases. However, efficacy of the control measure generally depends upon their effective utilization. Several cultural control measures such as cover crops, intercropping, trap crops, tillage practices, and planting time can reduce population of pests and disease severity but are not viable commercially under field conditions. Similarly, applicability of the biocontrol agents and plant extracts at large scale is also questionable. However, their efficacy may be increased by combination of other methods such as integrated use of the said cultural practices with reduced chemical applications. Therefore, in order to ensure better control and ecological sustainability, it is suggested that

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use of chemicals should be minimized by adopting integrated management strategies of pests and diseases.

Keywords

Agronomic crops · Biological control · Biofabricated nanoparticles · Deleterious pests · Food security

Abbreviations

AULRP	area under leaf rust progress curve
BioMA	biophysical model applications
CLCu	cotton leaf curl
CLCV	cotton leaf curl virus
CRISPR	clustered regularly interspaced short palindromic repeat
DNA	deoxyribonucleic acid
GMO	genetically modified organism
IBA	indolebutyric acid
JA	jasmonic acids
PGPR	plant growth-promoting rhizobacteria
PGR	plant growth regulators
SA	salicylic acid
PPO	polyphenol oxidase
POD	peroxidase
PCR	polymerase chain reaction
QTL	quantitative trait locus
RNAi	RNA interference
UV	ultraviolet

19.1 Introduction

The losses of agronomic crops due to diseases and pests are leading threats to the rural families for getting optimum income and to ensure worldwide food security (Savary and Willocquet 2014; Avelino et al. 2015). The information on quantitative loss in crop production is prerequisite for the understanding of the imperative pest and disease control drivers such as evaluation of crop protection practice efficiency; ecological system sustainability assessment; decisions for better adoption of the integrated pest and disease management schemes; and evaluation of the regulation of pest or disease control effectiveness as ecosystem sustainability regulation (Oerke 2006; Cooke 2006; Savary et al. 2006; Avelino et al. 2011).

Various types of pests and diseases have been reported affecting different crops from seeds to field conditions. Seed-borne, fungal, bacterial, and nematode-induced diseases as well as various types of insect pests are the major causes of reduced yield and increased losses of agronomic crops in the world. Moreover, occurrence and severity of various diseases and/or pests is generally associated with planting time, genotypes, and environmental conditions (Sharma and Sharma 1999). So, in order to reduce disease- and pest-induced agronomic crop losses, some appropriate and effective strategies are required (Sharma et al. 2015).

The pest and disease infestation is known as one of the leading limitations in achieving higher yield of agronomic crops to cater food security in the world (Igarashi et al. 2004). As agronomic crops (particularly cereals and pulses) are the major sources of food around the globe, management of their ruinous pests and diseases requires special importance. At present, pests and diseases of various crops are controlled or managed with different chemicals such as fungicides and pesticides (Rodrigues et al. 2013; Fromme et al. 2017). However, the disquiets regarding agronomic sustainability have instigated a comprehensive and wide application of integrated pest and disease management approaches. The said program is considered ecologically safe for control of dreadful pests and diseases of agronomic crops. Moreover, integrated pest and disease management has been known as one of the most robust paradigms to arise in agricultural production (Pretty and Bharucha 2015). It is an extensive strategy to cope with deleterious pests and diseases with wise utilization of cultural, mechanical, genetic, and biological ways by considering chemical control measures as a last option in a harmonious and compatible way to impede harmful inhabitants such as pests and diseases of agronomic crops (Barzman et al. 2015).

Different pests and diseases of agronomic crops can be controlled effectively. However, efficacy of the control measures generally depends on the used control measure. Several cultural control measures such as cover crops, intercropping, trap crops, tillage practices, and planting time can reduce population of pests and disease severity but are not appropriate as chemical applications at commercial scale under field conditions. Their control efficacy may be increased by combination of other control methods such as integrated use of the said cultural practices with reduced chemical applications. So, the present chapter summarizes various strategies and control measures for the integrated management of pests and diseases for the better production of agronomic crops.

19.2 Pest and Disease Effects on Global Food Security

Insect pests and plant diseases are anthropocentric perceptions. A microorganism or insect reduces (considered as a pest/pathogen) the quality and yield of food. These microorganisms, insects, and nematodes work synergistically to cause different diseases on the plants. These kinds of relationships are very dynamic and complicated for the food chain in nature. The global food security became a major threat to human population. Averagely, pests are moving about 3 km/year toward North and

South Pole, with an estimate of 10% to 16% loss in crop production globally. Rice has attained the 2nd position in global production and became more important since it is used as staple food for about half of the world's population. Every year, 10–30% loss in rice production has been recorded due to *Pyricularia oryzae*-induced rice blast disease (Talbot 2003). *Pyricularia oryzae* or other similar species (*P. setariae)* also affected the cereal crops including finger millet and wheat causing the complete loss of yield (Ekwamu 1991). Similarly, species of *Pyricularia* have been reported as a serious threat to wheat, and severe outbreaks have occurred with significant food losses (Igarashi et al. 2004). Several fungal pathogens also lead to production of mycotoxins, making the food, such as maize, unfit for human consumption. It has been reported that more than 700 identified plant viruses cause devastating diseases. Barley yellow dwarf viruses are spread globally and infect more than 150 Poaceae species, including most of the staple crops such as wheat, barley, oats, rye, rice, and maize (Gelderblom et al. 1988). So, pests and diseases of agronomic crops are the leading handicaps in securing global food security.

19.3 Pest and Disease Detection and Diagnosis

The crop losses can be minimized by timely identification and correct diagnosis of disease, followed by specific control measure. The visual examination is a traditional method for identification of plant pathogens. Mostly, it's possible only when major destruction has already been done to the crop; so treatments will be of limited or no use. For protection from these kinds of damages by pathogens, farmers should be able to recognize the infections at early stages. In addition to the traditional method, advance technology like direct microscopic observation of pathogens and their manipulation is essential for timely and effective control. The use of polymerase chain reaction (PCR) has a significant impact on plant disease diagnosis. Moreover, nucleic acid technology is the only option for detecting pathogens; yet, those have not been cultured. However, DNA-based methods have not completely replaced classical microbiology and visual inspection. These methods provide complementary evidence for accurate disease identification and diagnosis (Martinelli et al. 2015). Although the nucleic acid techniques based on PCR, hybridization, and biochemical assays are very accurate, sensitive, and effective for confirming the visual investigation, these are untrustworthy, as compared to screening tests to monitor the status of plant health before the appearance of the symptoms. These methods need detailed sampling techniques and expensive infrastructure and may garble the real status of infections. In addition, these techniques can only be efficient when used for a limited number of plants (Martinelli et al. 2015). Present and upcoming methods for plant disease detection include proximate detection, immunological and DNA-based assays, and study of volatile compounds and genes as biomarkers of disease diagnosis. Similarly, use of remote sensing technologies combined with spectroscopy-based systems and sensors based on phage display and bio-photonics could also be used (Schaad and Frederick 2002; Bock et al. 2010; Sankaran et al.

2010). In contrast, insect pests can be easily identified with visual observation in the field.

19.4 Integrated Pest and Disease Management

Integrated pest and disease management has been known as one of the most robust paradigms to arise in agricultural production science in the recent years. It is an extensive strategy to manage deleterious pests and diseases by wisely using the suitable skills, practices, and techniques including mechanical, cultural, genetic, and biological ways by considering chemical control measures as a last choice in compatible and harmonious manner to inhibit harmful inhabitants (pests and diseases) (Barzman et al. 2015; Pretty and Bharucha 2015). The effective integrated pest and disease management, however, depends upon the appropriate monitoring, inspection, and control. The integrated pest and disease management strategy has been recognized worldwide for attaining sustainable and ecologically stable agricultural production system. The increased globalization of the markets and enhanced traveling of the masses over the world allowed increased intensity and frequency of the invasive organisms to be brought into various other countries. Therefore, suitable and effective management strategies are required for these invasive pests and pathogens. For effective implementation of integrated pest and disease management program, it is also imperative to consider that the option chosen should be least threatening while bringing about maximum benefits to the farming community. The concept of integrated pest and disease management has progressively attained reasonable acceptance and has been adopted during the last two decades as an eco-friendly strategy which is considered important for the sustainable production of agronomic crops in the world.

19.5 General Principles of Integrated Pest and Disease Management

The integrated pest and disease management generally includes four major principles (Barzman et al. 2015). (a) The standardization of action thresholds is very critical before adoption of any disease or pest control measure. It is important to first find an optimum action threshold. The action threshold is a point where environmental conditions or pest populations indicate that a control action must be adopted. (b) It is important to know that not all weeds, insects, pests, diseases, and certain other organisms need to be controlled. Various organisms are either innocuous or even are surely beneficial for the crops of economic significance. So, it is imperative to monitor and thoroughly identify pests and diseases before adopting any control action. (c) As a first line of action in the control of pests and diseases, integrated approach works to efficiently manage outbreak of any pest or disease to prevent them becoming a major threat for the agronomic crops. It may be done by adopting certain cultural methods, e.g., rotation, planting resistant genotypes, and use of pest-/disease-free planting material. (d) Once monitoring, identification, and threshold action indicate that disease or pest control is indispensable and a preventive method is not available or effective, then certain control measures become essential. The control measures should be effective, ecologically viable, and environment friendly.

19.6 Modeling for Pest and Disease Prediction

The main focus of modern agricultural research is to increase the quality food production with reduced pest and disease attack. The "naked eye method" is usually used for detection and identification of pest and plant diseases at small scale with constant monitoring. In contrast, for a large farm, it's not precise and time-consuming. So, digital systems are widely used for inspection of plant diseases and pests. It generally identifies the affected area upon color changing. Automatic detection of plant diseases with the assistance of image processing technique offers more accurate pest detection and guidance for disease management (Rajan 2016). This software has been successfully used for detection of rice disease (Phadikar and Sil 2008). In this software, both image processing and soft computing skills are applied. The features include region segmentation and spot and boundary detection. Self-organizing map neural system has also been employed for classification. For satisfactory classification about test images, the simple computationally efficient technique is used for zooming algorithm extracts of the images. Likewise, BioMA modeling framework is composed of four extensible software libraries, targeting the modeling of generic fungal plant diseases. It provides input/output data structures and models to simulate a polycyclic fungal plant epidemic and to quantify its impact on crop growth. This technique has been used for major diseases of wheat (brown rust) and rice (leaf blast) to test model behavior under heterogeneous weather conditions according to changes in parameter values (Bregaglio et al. 2015). Bregaglio et al. (2015) documented a study about the extension and application of disease-based modeling that reproduces the field data of the annual fluctuations of disease epidemics for timely and accurate disease prediction.

19.7 Management of Pests and Diseases of Agronomic Crops

Pests and diseases of various agronomic crops can be managed with suitable control measures. The control measures could be cultural, chemical, biological, or combination of more than one strategy. However, the exact efficacy generally depends upon the nature of control measure being adopted. The pests and diseases of agronomic crops may be controlled/managed by employing different combinations of following measures.

19.7.1 Soil Fumigation

Soil-borne pests and diseases are the major cause of reduced yield and increased losses of agronomic crops in the world. So, in order to reduce disease- and pest-induced losses, some appropriate soil disinfestation treatments are required for getting higher yield (Rokunuzzaman et al. 2016; Mihajlović et al. 2017). Different chemicals such as ethylene dibromide, metham, and methyl bromide can effectively be used to disinfect soils from soil-borne pathogens. Soil fumigation with 1,3-dichloropropene or chloropicrin controlled the fusarium root-knot complex of nematode in cotton (Jorgenson et al. 1978). The combinational treatment with ethylene dibromide and fenamiphos significantly reduced the nematode population with concomitant higher yield of sugarcane (Chandler 1984). The application of methyl bromide reduced *Pythium*-induced infection with markedly improved vegetative growth and increased yield of grain in clean tilled winter wheat (Scott et al. 1992). The fumigation with paraformaldehyde efficiently reduced the leaf-cutting bee population of alfalfa (Goerzen 1992). The soil treatment with mancozeb strongly suppressed the dematiaceous root colonization and exhibited substantially higher sugarcane growth (Magarey and Bull 2003). Similarly, soil fumigation with methyl bromide markedly suppressed the nematode population of sugarcane having increased crop yield (Stirling et al. 2001). Likewise, soil fumigation with seed meal of mustard effectively checked the growth of soybean pathogenic fungi (Fayzalla et al. 2009). The combination of soil fumigation and *Trichoderma viride* significantly reduced the fungal diseases such as *Macrophomina phaseolina* and *Fusarium oxysporum* of sesame (Elewa et al. 2011). Soil fumigation with chloropicrin and methyl bromide showed reduced *Fusarium oxysporum*-induced infection in cotton (Bennett et al. 2011). In the same way, soil fumigation with methyl bromide efficiently reduced *Fusarium oxysporum* pathogens of chickpea (Mabrouk and Belhadj 2012). The Vapam soil fumigation suppressed *Plasmodiophora brassicae*-induced clubroot infection and enhanced the vegetative growth of canola (Hwang et al. 2014a, b). The soil treatment of sugarcane with silicon also reduced the incidence of stalk borer attack (Nikpay 2016). The bio-fumigation of the soil with *Brassica alba* extract suppressed *Fusarium* wilt of chickpea (Prasad and Kumar 2017).

19.7.2 Crop Rotation

Growing of same types of crops on same field over longer period of time ultimately leads to excessive disease outbreak or insect-pest infestation during the coming years. So, growing of suitable alternate crops is beneficial to reduce the pathogen or pest infestation in the forthcoming years (Bankina et al. 2015). Rotation scheme with corn/soybean/triticale-alfalfa/alfalfa checked the activity of carabid (O'Rourke et al. 2008). Growing of corn as a rotation practice markedly reduced the incidence of *Armadillidium vulgare* in soybean crop (Johnson et al. 2012). Adoption of fescue rotation and reduced tillage inhibited corn rootworm severity on peanut pods with increased population of collembolans, heteropterans, hymenopterans, and acarina under reduced till system (Cardoza et al. 2015). The rotation and summer fallow in combination with neonicotinoids seed treatment reduced wireworm incidence and increased yield of winter wheat up to 24–30% (Esser et al. 2015). Rotation of tobacco with rice significantly reduced plant hopper and brown plant hopper of rice (Zhang et al. 2015). Crop rotation of legumes and perennial sod or annual cereal grains in combination with moldboard or chisel plow cultivation system increased beneficial arthropods especially tiger and ground beetles in maize/soybean (Jabbour et al. 2016). A 3-year rotation as corn, soybean, and wheat resulted in reduced pests due to increased population of detritivore and granivore predators (Dunbar et al. 2016).

It has been reported that monoculture cultivation of wheat encourages aphids, thrips, wireworms, and some rust-related diseases in the cotton crop (Andow 1983; Cunfer et al. 2006). The crop rotation with corn, cowpeas, mung bean, rice, or sorghum increased yield and reduced *Pratylenchus zeae* infestation of rice (Aung and Prot 1990). The single year canola growing as rotation is suitable to efficiently reduce *Sclerotinia* stem rot and to prevent *Phoma* blackleg attack of canola (Kharbanda and Tewari 1996; Cunfer et al. 2006). The 4-year rotation by using canola, flax, and wheat significantly reduced diseased stem severity and incidence of canola blackleg under zero or conventional tillage system (Guo et al. 2005). The rotation of herbicide-tolerant canola reduced its maggot-induced root damage with better seed quality and yield (Dosdall et al. 2012). The rotation of lentil with cumin, anise, onions, and garlic considerably reduced root rot and damping-off disease with its substantially higher yield (Abdel-Monaim and Abo-Elyousr 2012). The 1-year sorghum and 2-year cotton rotation cultivation resulted in reduced *Verticillium* wilt of cotton under central pivot irrigation scheme (Wheeler et al. 2012). The rotation with barley, camelina, and spring pea showed reduced incidence of *P. thornei* and *P. neglectus* in winter wheat fields (Smiley et al. 2013). A cropping scheme of corn, soybean, and wheat combined with fungicide showed reduced *Fusarium graminearum* population; however, no effect was noted on *Fusarium oxysporum* or *Fusarium virguliforme* (Marburger et al. 2015). The cultivation of soybean with corn-soybean rotation scheme showed significantly reduced *Fusarium virguliforme*-induced sudden death syndrome of soybean (Navi and Yang 2016). The maize, pea, soybean, and sunflower growing scheme reduced Western corn rootworm infestation and *Fusarium graminearum* having better seedling health of maize (Benitez et al. 2017). The 1-year rotation of soybean with wheat crop increased its yield, whereas rotation with cotton had no positive effect (Ashworth et al. 2017).

19.7.3 Seed Treatment

Seed-borne diseases or pest infestation is the major cause of reduced yield and increased losses of agronomic crops in the world. So, in order to reduce disease- and pest-induced agronomic crop losses, some appropriate seed treatments are required for getting higher yield (Sharma et al. 2015). Several types of chemicals are being used for seed treatments (Table 19.1). Treatment of cotton seeds with metalaxyl and *Trichoderma virens* resulted in increased seedling stand and reduced disease

Table 19.1 Chemical compounds currently used as small grain cereal seed treatments

Captan	N-Trichloromethylthio-4-cyclohexene-1,2dicarboximide	Dicarboximide, Agrosol, Agrox, Granox, Orthocide
Carboxin	5,6-Dihydro-2-methyl-N-phenyl-1,4-oxathiin-3carboxamide	Vitavax
Difenoconazole	cis,trans-3-chloro-4-[4-methyl-2-(1H-1,2,4triazol-1-ulmethyl)-1,3-dioxolan-2-yl] phenyl 4chlorophenyl ether	Dividend
Imazalil	(+)-Allyl 1-(2,4-dichlorophenyl)-2-imidazol-1ylethyl ether	FloPro IMZ, Double R, Deccozil, Nuzone, Fungaflor
Mancozeb	Zinc manganese ethylenebisdithiocarbamate	Dithane M-45, Mankocide, Mansul, Penncozeb
Maneb	Manganese ethylenebisdithiocarbamate	DB Green, Granol NM, Trinox, Pro-Tex
Metalaxyl	Methyl N-(2-methoxyacetyl)-N-(2,6-xylyl)-DLalaninate	Apron, Allegiance
PCNB	Pentachloronitrobenzene	Terrachlor, Parflo, Terra-flo, Terrazan
Tebuconazole	(RS)-1-(4-chlorophenyl)4,4-dimethyl-3-(1H1,2,4-triazol-1-ulmethyl) pentan-3-ol	Raxil, Preventol, Tebuject
Thiabendazole	2-(4-Thiazolyl)-benzimidazole	TBZ, Mertect, Metasol
Thiram	Tetramethylthiuram disulfide	Arasan, Vertagard, Thiramad
Triadimenol	(1RS, 2RS; 1RS, 2SR)-1-(r-chlorophenoxy)-3,3dimethyl-1-(1H-1,2,4-triazol-1-yl) butan-2-ol	Baytan
Triticonazole	(+)-(E)-5-(4-chlorobenzylidene)-2-dimethyl-1(1H-1,2,4-triazol-1-ylmethyl) cyclopentanol	Charter

Source: Mathre et al. (2001) and Sharma et al. (2015)

incidence under field conditions (Howell et al. 1997). Seed and foliar treatment with fungicides controlled black point disease of wheat (Malaker and Mian 2009). Seed treatment with abamectin and sedaxane alone or in combination was highly effective in controlling *Pratylenchus penetrants* and *Rhizoctonia solani* disease complex under greenhouse conditions. The treatment also significantly enhanced seedling health as well as shoots and root growth of maize (Silva et al. 2017). Aerated steam therapy of sugarcane sets at 50 °C for 1 h showed high efficacy in controlling its grassy shoot disease with increased germination and cane yield (Viswanathan 2001). The incidence of anthracnose and sorghum smut was effectively reduced in response to metalaxyl seed treatment. It also increased the grain yield of sorghum particularly in late-maturing sorghum cultivars (Gwary et al. 2007). Similarly, seed treatment with *Trichoderma harzianum* reduced the incidence of *Macrophomina phaseolina* disease and increased its germination vigor index, plant height, and leaf growth characteristics under field conditions (Anis et al. 2013). Plant extract treatment of lentil seeds increased germination and reduced its associated mycoflora

(Mahal 2014). Similarly, combined treatment of seed with *Trichoderma hamatum* and metalaxyl reduced damping-off disease incidence of soybean along with increased germination percentage (Hudge 2015). The treatment of sugarcane sets with triadimefon and propiconazole effectively inhibited its smut incidence having higher harvestable yield under field conditions (Bhuiyan et al. 2015). Similarly, seed treatment with triadimenol alone or in combination with thiram effectively controlled leaf blight of spring wheat with higher grain yield (Sharma-Poundyal et al. 2016).

19.7.4 Planting Time

The occurrence and severity of various diseases and crop-specific pest attack is generally associated with planting time, genotype, growth stage, and environmental conditions. Atmospheric temperature and relative humidity are the key components for the epidemic spread of pests or diseases. Therefore, sowing date is of particular importance which determines the subsequent crop growth stages (Sharma and Sharma 1999).

The fall planting with lower plant density significantly decreased flea beetle attack with better growth and early maturity of canola (Lloyd and Stevenson 2005). Attack of thrips and *Maruca testulalis* was found to be higher during late sown crop of cowpea (Ezuch 1982). The incidence and severity of thrips was found maximum in early-planted crop, whereas lowest was noted on the late sown planting of black gram (Prodhan et al. 2008). Delayed planting in combination with insecticide spray showed reduced invasion of pod feeding bugs of cowpea (Kamara et al. 2010). Early sowing of soybean showed reduced or even escape of attack of whitefly and aphids when mixture of mung bean, sunflower, and maize was grown as border trap crop (Abdallah 2012). The population severity of dusky cotton bug was found lowest during 3rd week of July while surpassed economic threshold in August on transgenic cotton (Iqbal et al. 2017a, b). The early planting under high, medium, and low density as single, double, or triple rows showed higher incidence of cornstalk borer and armyworm in sweet sorghum (Cherry et al. 2013). Invasion of red cotton and dusky bugs was significantly higher in early sown, as compared to its normal or late plantation (Shahid et al. 2014). Early sown Bt cotton showed less incidence of sucking pests such as leaf hopper, aphid, and whitefly, in contrast to late-planted crop (Zala et al. 2014). However, early planting, combined with insecticide sprays during late July or mid-July, exhibited reduced thrips, legume pod borer, and pod sucking bugs in cowpea along with improved yield (Abudulai et al. 2017). The population of tobacco caterpillar was found to be substantially higher in the crop sown at 20 July, in contrast to 5 July or 20 June having increased leaf damage with lower yield of groundnut (Nath et al. 2017).

The cotton crop that was sown comparatively earlier during December had more yield than late cultivation (Gilio 2014). The incidence and severity of ramularia leaf spot of cotton was significantly lower when the crop was planted during the month of December, as compared to January sowing time (Ascari et al. 2016). Host fitness with environmental conditions during specific plant growth stage can be reduced by either change of sowing date or through costs of defense (Creissen et al. 2016). Ali et al. (2014) found that early sowing of cotton not only minimizes the CLCV incidence but also improved the boll weight, seed cotton yield, seed index, ginning out turn, number of nodes per plant, and other quality parameters of cotton crop. Moreover, Rashid et al. (2013) reported that disease incidence of mung bean yellow mosaic virus and cercospora leaf spot of mung bean was also associated with planting time. Early sowing (1 March) showed less disease infestation and high yield (2131.00 kg/ha), in contrast to late sowing (1 April). Similarly, Getaneh and Agu (2008) found significant loss of grain yield (6.9–40.2%), thousand kernel weight (5.9–27.6%), and kernels per spike (0–16.5%) caused by *Puccinia hordei* due to late sowing in barley. Leaf rust (*Puccinia triticina*) is a widely distributed fungal disease in wheat and is considered an unremitting dilemma due to its epidemic nature. Atiq et al. (2017) found that commonly used disease severity indicator "area under leaf rust progress curve (AULRP)" was minimum for early sowing (30 October) of wheat, while it was maximum for late sowing (30 November). In addition to this, certain diseases are spread through specific vectors (carriers) such as cotton leaf curl (CLCu) disease which is transmitted by whitefly (*Bemisia tabaci*) (Sharma et al. 2006), and this disease is responsible for low yield in cotton. Maharshi et al. (2017) found that besides changing the cultural practices, planting date is an effective method to avoid the excessive population of whiteflies, thus reducing the incidence of CLCu disease. It was also noted that Bt cotton hybrids are susceptible to CLCu virus and there is significantly positive correlation between sunshine with whitefly population and incidence of CLCuD. Hence, early plantation of Bt cotton minimizes the chances of coincidence of susceptible crop growth stage and CLCuD favorable environmental conditions.

19.7.5 Plant Spacing

Planting of sweet sorghum as single, double, or triple rows under high, medium, and low density either had no or little effect on population of cornstalk borer and armyworm (Cherry et al. 2013). Plants did not affect flowering thrips, sucking bugs, pod borers, and beetles in cowpea in response to different time of plantings (Alghali 1991). Planting of cowpea at 20 × 30 and 20 × 60 cm in combination with insecticide treatment controlled its pest infestation (Karungi et al. 2000). Reduced fall planting density decreased the attack of flea beetles with better growth and early maturity of canola crop (Lloyd and Stevenson 2005). Planting of cotton at 38 cm apart resulted in significantly reduced population of whitefly, jassid, and thrips. The incidence of the said pests was increased with decreased plant pacing (Arif et al. 2006). Planting of sunflower at 100 × 75 cm led to lowest incidence of beetle, variegated grasshopper, sunflower stem weevil, and spittlebug attack (Akinkunmi et al. 2012). The planting of cowpea at wider spacing significantly reduced the incidence of ramularia leaf spot of cotton with markedly higher vegetative growth and yield than closer planting scheme. Moreover, high plant density ensured high cotton productivity during the severe attack of CLCV (Iqbal et al. 2012; Singh et al. 2017). It has been observed that pest population (*Aphis craccivora*) enhances after 2 weeks of cowpea sowing, and this colony increases in size between 8 and 13 weeks after sowing to coincide with flower budding (Omongo et al. 1997). Most importantly, these colonies take the advantage of dense plantation to hinder below the leaves. Found that aphids (*Aphis craccivora*) and foliage beetles (*Ootheca mutabilis*) on cowpea can be controlled by regularly weeding after every 3–6 weeks and maintaining low plant density (152,174 plants/ha). Soybean was cultivated to optimize the rows and plant spacing. It was found that 40 cm row spacing with 5 cm plant spacing within a row can be used for high productivity and low weed infestation of soybean (Worku and Astatkie 2015). Akinkunmi et al. (2012) found that sunflower plants grown at normal distance (100 × 75 cm) had lowest population of various insects including sunflower beetle (*Zygogramma exclamationis*), spittlebug (*Poophilus adustus*), variegated grasshopper (*Zonocerus variegatus*), and sunflower stem weevil (*Cylindrocopturus adspersus*). Likewise, plant spacing at 65 × 75 cm damaged leaves, stems, and flower heads and caused severe economic loss to sunflower crop. However, Adipala et al. (1995) didn't found significant incidence of northern leaf blight (*Exserohilum turcicum*) incidence. Denser plantation caused high level of disease severity and subsequent loss in grain yield. Also reported similar observations about soybean crop which was cultivated at different plant-to-plant and row-to-row spacing. Plants with widest spacing (40 × 10 cm) produced lowest leaf area and shoot biomass. Chickpea crop also showed similar results under dense cultivation (Shamsi 2010). Rice sheath blight is a well-known devastating disease of rice which can be overcome by exogenous application of silicon with suitable plant geometry. The normal row spacing is 20 × 15 cm, and rice crop becomes prone to sheath blight easily. However, Khaing et al. (2015) found that widening the plant and row distance significantly enhances disease resistance and produced 32% more grain yield, than control.

19.7.6 Intercropping

Intercropping of maize, faba bean, and cabbage with sugar beet significantly reduced the population of aphid, whitefly, *Pegomyia mixta*, and *Cassida vittata*, as compared to non-intercropped field. However, no significant impact of relay intercropping was observed when winter wheat, alfalfa, and cotton were used as intercrops or green bugs and ladybeetles in sorghum (Phoofolo et al. 2010). Intercropping of basil in cotton significantly reduced the invasion of pink bollworm in cotton that eventually led to increased yield (Schader et al. 2005). Intercropping of groundnut, soybean, or common beans markedly reduced attack of termites with enhanced beneficial predatory nesting in fields of maize (Sekamatte et al. 2003). Intercropping of spring cereal in field beans significantly checked the attack and severity of black bean aphids (Hansen et al. 2008). Intercropping of sorghum resulted in markedly increased population of predatory lady beetles that eventually reduced the attack of sucking insects on cotton (Tillman and Cottrell 2012).

Intercropping has been extensively reported to reduce the incidence of various bacterial diseases (Yu 1999), fungal infections (Hao et al. 2010), and insect pests (Basha et al. 2017) during simultaneous growth of two or more component crops together. The intercropping of cowpea in cotton significantly reduced the incidence of ramularia leaf spot of cotton with markedly higher vegetative growth and yield. Kinane and Lyngkjaer (2002) also found significant reduction in occurrences of various diseases like net blotch (*Pyrenophora teres*), powdery mildew (*Blumeria graminisf*), and brown rust (*Puccinia recondite*) in barley crop which was intercropped with either of legumes (lupin, pea, and faba beans). Intercropping is also supposed to be an efficient agricultural management practice and sustainable ecological strategy since it has also been reported to overcome the soil-borne plant diseases. Moreover, the complete eradication of pathogen is very difficult in soil-borne diseases; hence substitutive economically best agricultural practice is preferred (Zhu et al. 2000). Maize-soybean intercrop suppressed the incidence of red crown rot in soybean caused by *Cylindrocladium parasiticum*. Scientists found excessive accumulation of five kinds of phenolic acids, particularly cinnamic acid, among plant root exudates of intercropped maize-soybean. Furthermore, the biosynthesis of cinnamic acid was closely associated with row-to-row distance between different intercrops. Similarly, intercropping has been successfully implemented to suppress *Fusarium* wilt in watermelon-rice intercropping system (Hao et al. 2010). Heterogeneous crop cultivation pattern significantly reduced the prevalence of crop specific pests and consequently minimized the extensive application of petrochemical-based pesticides. Intercropping of chickpea with either mustard, wheat, or barley delayed the attack of pod borer and thus enhanced the economic return by reducing the cost of production (Basha et al. 2017). However, further studies should be subjected to elucidate the detailed mechanism of pathogen or pest-host interaction among heterogeneous components of intercrop that determines the occurrence and the severity of diseases or pest levels.

19.7.7 Cover Crops

Growing of cover crops is important to check the growth of weeds and to conserve soil moisture contents. Besides, cover crops may also be used to reduce the outbreak of certain pathogenic fungi and insects. Moreover, the roots of certain cover crops also serve as a source of symbiotic mechanism in which some saprotrophic fungi grow and colonize to help in inhibiting the growth of pathogenic fungi (Harman et al. 2004). Use of grass (*Elymus trachycaulus*) as a cover crop significantly checked the population of Western corn root worm under zero tillage production system. Moreover, use of the said cover crop also enhanced the population of arthropods, beneficial for pollination. Cultivation of rye and crimson clover increased the population of natural predators that eventually reduced flower bugs on cotton under conservation tillage (Tillman et al. 2004). Cultivation of rye as autumn seeded cover crop substantially suppressed the outbreak of leafhopper, aphids, and leaf beetles in soybean (Koch et al. 2012). In the same way, plantation of rye cover crop also suppressed the attack of soybean aphids (Koch et al. 2015).

The growing of wheat, oat, marigold, and forage peanuts as cover crops significantly inhibited the reproduction of sugarcane parasitic nematodes (Berry et al. 2011). The population of pathogenic fungi was markedly reduced when perennial chicory, rye grass, red clover, and white clover were grown in spring wheat and winter barley. Moreover, these cover crops also positively enhanced the activities of the beneficial arbuscular mycorrhizal fungi (Detheridge et al. 2016). The small terminated grain crops and combination of aldicarb reduced the *Meloidogyne incognita* population with no negative effects on cotton yield (Wheeler et al. 2008). The growing of pearl millet, arugula, cowpea, mustard, jack bean, tomato, and sunflower as cover crops was tested against *Meloidogyne* complex under anaerobic soil disinfestation system. Among these, sorghum-Sudan grass, cowpea, and arugula had lowest occurrence of *Meloidogyne*-induced root disease complex (Kokalis-Burelle et al. 2013). In another work, mulatto grass, forage sorghum, and oil radish showed lowest *Rotylenchulus reniformis* nematode densities when grown in cotton as cover crops under greenhouse and field conditions (Asmus et al. 2008). The growing of rye as cover crop increased the incidence of *Fusarium oxysporum*, *F. graminearum*, *Pythium sylvaticum*, and *Pythium torulosum* in corn (Bakker et al. 2016). Winter canola and hairy vetch reduced the incidence of corn root diseases when used as cover crops in combination with fungicidal treatment (Schenck et al. 2017). The rapeseed and cereal reduced the population of soybean cyst nematodes and *Rhizoctonia solani* with uniform crop stand and higher yield (Wen et al. 2017).

19.7.8 Trap Crops

The growing of trap crops is a strategy in which pests are repelled away from the main crop of interest (Ratnadass et al. 2012). There are certain diseases which are spread by the vectors feeding on the infected crops. Likewise, many insect pests attack crop plants of economic importance eventually leading to severe qualitative and quantitative losses. The growing of taro was effective to attract armyworm (*Spodoptera litura*) in tobacco crop. However, it is important to mention that taro plants should be planted 20–30 days before tobacco to efficiently control the attack of armyworm as it was not effective to attract the said pest at seedling stage (Zhou et al. 2010). Soybean and pea were used as trap crops to manage soybean cyst nematode in corn (Chen et al. 2001). The attack of leafhopper was significantly reduced in cotton where okra and castor bean or sunflower were used as trap crops (Hormchan et al. 2009). In another work, soybean planting as trap crop more efficiently reduced boll injury and density of stink bugs in cotton than peanut (Tillman et al. 2015).

19.7.9 Tillage Practices

Different tillage systems have been used in growing of agronomic crops. It has been reported that the tillage practices and methods significantly affect diseases and pest of various agronomic crops. Use of cover crop of grass (*Elymus trachycaulus*) significantly checked the population of Western corn root worm of maize under zero tillage production system. Moreover, use of the said cover crop also enhanced arthropods beneficial for pollination. Cultivation of rye and crimson clover increased the population of natural predators that eventually reduced flower bugs on cotton under conservation tillage (Tillman et al. 2004). Reduced tillage abridged corn rootworm severity on pods with increased population of collembolans, heteropterans, hymenopterans, and acarina in peanut (Cardoza et al. 2015). Cultivation with moldboard or chisel plow increased beneficial arthropods particularly tiger and ground beetles in maize/soybean under legumes and perennial sod or annual cereal grain rotation scheme (Jabbour et al. 2016).

The growing of common bean under no tillage system significantly reduced fusarium wilt incidence and had higher yield, as compared to its conventional cultivation (Toledo-Souza et al. 2012). The cultivation of peanut under maize, soybean, and peanut system increased the population of biocontrol agents (*Trichoderma* and *Gliocladium* spp.) which eventually reduced the soil-borne fungal pathogens under no tillage cultivation system (Gil et al. 2008). The incidence of wheat leaf spot and root diseases was markedly reduced in zero tillage in comparison to conventional tillage (Bailey 1996). Root and stalk rot of sorghum was significantly lower in minimal tillage system, than plow-planted crop (Flett 1996). The cultivation under strip tillage system combined with rye cover crop significantly reduced the population of immature thrips on cotton and peanut. Moreover, it also lowered the incidence of tomato spotted wilt virus in peanut concomitant with higher yield in both crops (Knight et al. 2017). The conservation tillage effectively reduced immature and adult populations of thrips in combination with thiamethoxam seed treatment and cover crop of rolled rye along with higher yield in peanut and cotton. Furthermore, the incidence of tomato spotted wilt virus was also significantly reduced in peanut (Knight et al. 2015). The no-tillage cultivation system significantly reduced severity of fusarium blight with higher pod yield of soybean (Joseph et al. 2016). The eye spot incidence of winter wheat was significantly reduced when it was grown under no tillage combined with mulching having better nutrient use efficiency (Váňová et al. 2011). The tillage with moldboard plow reduced the incidence and severity of wheat fusarium head blight (Dill-Macky and Jones 2000). Tillage practice markedly lowered the infection of seminal roots and crown roots in wheat under winter wheat-barley-winter canola rotation scheme compared to its continuous mono-cultivation (Paulitz et al. 2010).

19.7.10 Fertilizer Application

The doses and application of nutrients may significantly influence infestation of insect pests and diseases. Excessive or reduced application may either increase or decrease incidence of diseases and population of pests depending upon crops and their growth stages. The combined application of nitrogen (N) and silicon significantly reduced attack of leaf folder, dead hearts, and stem borer along with inhibited leaf blight, grain discoloration, and brown spot of low land rice (Malav and Ramani 2015). Application of biochar increased vegetative growth that eventually increased the attack of white backed plant hopper of rice due to changes in jasmonic acid biosynthesis. However, response was found to be cultivar dependent as higher intensity of plant hopper infestation was noted in vigorously growing rice cultivar (Waqas et al. 2018). Application of N, phosphorous (P), or potassium (K) led to significant changes in concentration of soluble sugars, proteins, and silicon. Among these, application of K reduced soluble proteins, free sugars, N, and silicon in the tissues of plants and led to significant reduction of brown plant hopper attack on rice (Rashid et al. 2016a, b). Application of nutrients especially N also influences the feeding habit and oviposition for egg laying. Higher level of N, soluble proteins, and free sugars in plant tissues will increase the egg laying capacity and infestation of brown plant hopper of rice (Rashid et al. 2017a). Higher dose of N, P, or K fertilizers increases vegetative growth and yield of crop plant. However at the same time, higher doses of NPK also increase the development and survival rate of brown plant hopper of rice (Rashid et al. 2017b). The incidence of rice borer was reduced with adequate application of K with improved crop productivity (Sarwar 2012).

It has been reported that some nutrients such as magnesium (Mg) and calcium (Ca) specifically act in a particular pathogen-host interaction and alter their expression symptoms as noted in infection of alfalfa mosaic virus on common bean. In this case, Mg and Ca increased formation of alfalfa mosaic virus lesions in contrast to systemic infections (Tu 1978). Root and foliar application of silicon either as potassium silicate (40 g L^{-1}) or calcium silicate (1.25 k kg^{-1}) significantly reduced the development and severity of brown spot in rice. However, efficacy of foliar application was less than soil treatment (Rezende et al. 2009). Application of silicon (2 mM) reduced anthracnose of sorghum by increasing carbon fixation and antioxidative system due to enhanced free radical scavenging activity (Resende et al. 2012). In the same way, silicon treatment enhanced the activity of defensive enzymes such as PPO and POD against biotic stresses, ultimately leading to inhibition of *Colletotrichum sublineolum*-induced anthracnose of sorghum (Resende et al. 2013). Combined application of NPK and foliar spray of Zn, Cu, and Mn reduced the severity of fusarium head blight with lower levels of mycotoxins in winter rye (Cwalina-Ambroziak et al. 2017). Foliar treatment of B and Cu (20 + 20 mg L^{-1}) reduced fungal disease infestation along with increased number of spikelets, productive tillers, percentage of filled grains, and yield of rice (Liew et al. 2012). Application of P (90 or 120 kg ha^{-1}) significantly suppressed severity and incidence of brown blotch disease of cowpea along with enhanced vegetative growth, leaf area, nodules, pods, and overall yield (Owolade et al. 2006). Likewise, application of Ca (carbonate and silicate) markedly reduced the occurrence of downy mildew, frog eye, and Asian rust in soybean (Nolla et al. 2006). In the same way, optimum application of K or P, in combination with fungicide, reduced the severity of leaf rust with ultimate increase in yield of winter wheat (Sweeney et al. 2000). Application of Zn, Cu, and silicon inhibited rice sheath blight disease and minimized the yield loss (Khaing et al. 2014). Supplemental application of calcium silicate and calcium chloride significantly reduced white mold disease intensity in dry beans (Júnior et al. 2009). Dark spot disease was significantly suppressed with increasing N availability due to enhanced acetic acid emission which acted as antifungal volatile agent in *Brassica napus*. Availability of N also influenced pollen beetles and seed weevils infestation as well as levels of their parasitoids (Veromann et al. 2013).

19.7.11 Biological Control

Use of muscadine fungal strain (*Cotesia flavipes)* was highly effective in controlling stem and moth borers of sugarcane (Suasaard and Charernsom 1996; Suasaard et al. 2001) (Table 19.2). The release of *M. mediator* was effective to manage cotton bollworm larval population in the field conditions (Luo et al. 2014). Wheat aphids were biologically controlled with ladybeetle. However, intensity of control was dependent upon the abundance of lady beetles in the field (Yang et al. 2018). The population of sugarcane borers was significantly controlled with *Trichogramma chilonis* in the farmer's field conditions (Nadeem and Hamed 2011). *Tryporyza incertulas* being parasitoid of rice lepidopterous pests can be used to suppress the population of rice stem borers (Guo et al. 2002). Ootheca, aphids, and stem maggot were efficiently managed with combination of agronomic and biological control measures (Mwanauta et al. 2015). Planting of sesame as nectar crop increased the number of lepidopterous egg and plant hopper egg parasitoids that ultimately checked the population of the said pests of rice (Zhu et al. 2017).

The use of *Bacillus* genus effectively inhibited the incidence of *Exserohilum turcicum*-induced northern leaf blight of maize under greenhouse conditions (Sartori et al. 2017a). Likewise, *Bacillus* spp. also significantly inhibited *Puccinia sorghi*- and *Exserohilum turcicum*-induced common rust and northern leaf blight of maize under field conditions (Sartori et al. 2017b). Seed treatment with *Trichoderma harzianum* was found suitable in reducing *Rhizoctonia solani*-induced tobacco root rot disease in greenhouse conditions (Gveroska and Ziberoski 2011a, b). *Bacillus subtilis* and *Pseudomonas fluorescens* significantly reduced bacterial blight in cotton under greenhouse as well as field conditions (Salaheddin et al. 2010). Soil application and seed treatment with *Trichoderma viride* inhibited the growth of wheat root rot (*Bipolaris sorokiniana*) along with significantly enhanced plant height as well as shoot and root fresh and dry biomass than uninoculated control (Salehpour et al. 2005). *Trichoderma harzianum* and *Macrophomina phaseolina* suppressed root rot and enhanced grain yield of mung bean (Shahid and Khan 2016). Similarly, incidence of charcoal rot (*Macrophomina phaseolina*) was inhibited with combined treatment of *Trichoderma harzianum* and *Sisymbrium irio* leaf powder. Moreover, the same combinational treatment also significantly improved leaf chlorophyll, sugar contents, proteins, and activity of catalase enzyme of mung bean (Javaid et al.

Table 19.2 Effect of biocontrol agents for control of pest and diseases of agronomic crops

Biocontrol agents	Crop pests and diseases	References
	Pests	
Cotesia flavipes	Sugarcane stem borer	Suasaard et al. (2001)
H. armigera, *M. mediator*	Cotton bollworm	Luo et al. (2014)
Trichogramma chilonis	Sugarcane stem borer	Nadeem and Hamed (2011)
Tryporyza incertulas	Rice borer	Guo et al. (2002)
Aenasius bambawalei	Cotton mealybug	Ram and Saini (2010)
	Diseases	
Bacillus spp.	Maize leaf blight	Sartori et al. (2017a)
Bacillus spp.	Maize rust and leaf blight	Sartori et al. (2017b)
Trichoderma harzianum	Tobacco root rot	Gveroska and Ziberoski (2011a, b)
Bacillus subtilis, *Pseudomonas fluorescens*	Cotton bacterial blight	Salaheddin et al. (2010)
Trichoderma viride	Wheat root rot	Salehpour et al. (2005)
Trichoderma harzianum, *Macrophomina phaseolina*	Mung bean root rot	Shahid and Khan (2016)
Trichoderma harzianum and *Sisymbrium irio*	Mung bean charcoal rot	Javaid et al. (2017)
Pseudomonas sp. and *Bacillus* sp.	Sunflower necrosis virus	Srinivasan et al. (2009)
Trichoderma harzianum	Cowpea rust	Arafa et al. (2016)
Trichoderma spp.	Cowpea charcoal rot	Singh et al. (2012)
Trichoderma harzianum	Tobacco rot	Gveroska and Ziberoski (2011a, b)
Trichoderma harzianum	Rice brown spots	Khalili et al. (2012)
Bacillus spp.	Rice bacterial leaf blight	Ahmed et al. (2015)
Trichoderma viride and *Pseudomonas fluorescens*	Groundnut stem rot	Karthikeyan et al. (2006)
Trichoderma viride	Bean anthracnose	Padder and Sharma (2011)
Trichoderma harzianum	Tobacco bacterial wilt	Yuan et al. (2016)

2017). *Pseudomonas* sp. and *Bacillus* sp. competently reduced the incidence of sunflower necrosis virus disease (Table 19.2). Furthermore, these also increased seedling vigor and germination percentage (Srinivasan et al. 2009). The application of *Trichoderma harzianum* substantially reduced rust and positively increased growth and yield of cowpea grown in sandy soil conditions (Arafa et al. 2016). Groundnut stem rot was significantly reduced in response to *Pseudomonas* cf. *monteilii* 9, compared to control (Rakh et al. 2011). Charcoal rot incidence of soybean was effectively inhibited with *Trichoderma* having increased stem length, root elongation, and thousand kernel weight (Khalili et al. 2016). Cowpea charcoal rot was markedly inhibited with *Bacillus firmus*. It also significantly enhanced nodulation with better growth of plants (Singh et al. 2012). Tobacco *Alternaria alternata* disease was significantly checked with *Trichoderma harzianum* biocontrol agent (Gveroska and Ziberoski 2011a, b). Similarly, *Trichoderma harzianum* effectively inhibited rice blast incidence of direct seeded crop under low rain-fed conditions (Singh et al. 2012). Likewise, same biological control agent was also found effective in inhibiting brown spot disease and enhanced the growth of rice plants (Khalili et al. 2012). The plant growth was significantly enhanced with suppression of bacterial leaf blight of rice with rhizobacterial *Bacillus* strains (Ahmed et al. 2015). Similarly, combined application of *Pseudomonas fluorescens* and *Trichoderma* strains controlled rice blast with improved plant growth and yield under greenhouse and field (Subhalakshmi and Devi 2017). Treatment with *Trichoderma viride* and *Pseudomonas fluorescens* enhanced activities of defensive enzymes such as polyphenol oxidase and peroxidase which ultimately inhibited stem rot of groundnut (Karthikeyan et al. 2006). The incidence of CLCV was significantly decreased in response to *Pseudomonas* and *Bacillus* spp. under greenhouse conditions (Ramzan et al. 2016). Application of *Trichoderma viride* resulted in maximum germination percentage and control of bean anthracnose (Padder and Sharma 2011). Combined application of bioorganic fertilizer and *Trichoderma harzianum* was highly effective in controlling tobacco bacterial wilt owing to higher expression of peroxidase, phenylalanine ammonia lyase, and polyphenol oxidase activities (Yuan et al. 2016). *Aenasius bambawalei* parasitoid significantly reduced the incidence of mealybug in cotton (Ram and Saini 2010).

19.7.12 Plant Extracts

The infestation of thrips (*Megalurothrips sjostedti*) on cowpea flowers was inhibited in response to eucalyptus tree bark and *Gmelina arborea* extract application (Table 19.3). Similarly, *Gmelina arborea* and African marigold leaf extract mixture was also as effective as synthetic insecticide treatment. The application of these extracts resulted in increased pod yield due to lower infestation of thrips (Mbonu 2006). Ethyl acetate and methanolic extracts of *Sida acuta* increased the mortality of red cotton bug with dose-dependent concentration (Gadewad and Pardeshi 2018). *Copaifera langsdorffii* bark and leaf extracts significantly reduced larval weight and food intake and led to delayed larval development of *Spodoptera frugiperda* of maize (Samia et al. 2016). *Piper aduncum* leaf extract acted as natural insecticide as it effectively reduced reproduction and survival of soybean stink bug (Piton et al. 2014). The treatment of yard-long beans with tobacco extract showed reduced attack of aphids with increased beans biomass (Bahar et al. 2007). Application of neem seed extract and neem oil showed markedly higher yield with reduced incidence of thrips, jassids, and whitefly of cotton (Rashid et al. 2012). Treatment of sets with Chulai, Absinthe, and Babchi extracts significantly suppressed sugarcane foraging termites (Ahmed et al. 2007). Application of neem, datura, and tobacco extracts significantly suppressed infestation of pink bollworm in non-Bt and Bt cotton. However, efficacy of tobacco extract was much higher, than others

Table 19.3 Effect of natural plant extracts for control of pest and diseases of agronomic crops

Plant extracts	Crop pests and diseases	References
	Pests	
Eucalyptus globulus and *Gmelina arborea*	Cow thrips	Mbonu (2006)
Sida acuta	Red cotton bug	Gadewad and Pardeshi (2018)
Copaifera langsdorffii	Maize *Spodoptera frugiperda*	Samia et al. (2016)
Piper aduncum	Soybean stink bug	Piton et al. (2014)
Nicotiana tabacum	Beans aphids	Bahar et al. (2007)
Azadirachta indica	Cotton thrips, jassids and whitefly	Rashid et al. (2012)
Amaranthus viridis, *Artemisia absinthium, and Psoralea corylifolia*	Sugarcane termites	Ahmed et al. (2007)
Azadirachta indica, *Datura stramonium*, and *Nicotiana tabacum*	Cotton pink bollworm	Rajput et al. (2017)
	Diseases	
Croton heliotropiifolius	Maize weevil	Silva et al. (2013)
Azadirachta indica	Rice *N. lugens*, *N. virescens*, *L. oratorius* and *S. incertulas*	Abdullah et al. (2015)
Azadirachta indica and *Gossypium hirsutum*	Cotton aphids	Pinto et al. (2013)
Allium sativum	Faba beans root rot, wilt, and chocolate spot	Eisa et al. (2006)
Curvularia lunata	Maize leaf spot	Akinbode (2010)
Ziziphus mucronata and *Lippia multiflora*	Groundnut leaf spot disease, necrotic leaf area	Koita et al. (2017)
Garcinia kola, *Aloe vera*, *Zingiber officinale*, and *Azadirachta indica*	Cowpea root rot	Suleiman and Emua (2009)
Vernonia amygdalina and *Maesa lanceolata*	Sorghum smut	Sisay et al. (2012)
Datura stramonium, *Jatropha gossypifolia*, and *Ricinus communis*	Cowpea anthracnose	Falade et al. (2018)
Azadirachta indica	Cotton bacterial blight	Rashid et al. (2016)

(Rajput et al. 2017). The ethanolic extract of *Croton heliotropiifolius* flowers showed contact avoidance of maize weevil (*Sitophilus zeamais*) (Silva et al. 2013). Neem seed extract significantly reduced the insect pests of rice such as *N. lugens*, *N. virescens*, *L. oratorius*, and *S. incertulas* and was found as effective as chlorpyrifos and deltamethrin (Abdullah et al. 2015). The application of *A. indica* bark and *P. guineense* seed extract reduced the severity of pest attack on jute (Okunlola and Ofuya 2013). Similarly, neem oil and oil of cotton seed reduced aphid attack on cotton, but control was less effective than thiamethoxam insecticide (Pinto et al. 2013).

Foliar spray with clove, neem, and quinine extracts completely inhibited leaf rust diseases of wheat with enhanced yield under greenhouse conditions (Shabana et al. 2017). Treatment with moringa plant extract resulted in enhanced germination percentage and controlled seed-borne pathogens of sorghum (El-Dahab et al. 2016). Similarly, garlic extract significantly suppressed incidence of root rot, wilt, and chocolate spot of faba beans under in vitro conditions (Eisa et al. 2006). The extracts of *Curvularia lunata* markedly suppressed maize leaf spot disease in vitro (Akinbode 2010). Similarly, *Ziziphus mucronata* and *Lippia multiflora* aqueous extracts significantly controlled groundnut leaf spot disease and necrotic leaf area and reduced defoliation rate along with higher pod yield under field conditions (Koita et al. 2017). Bitter kola, aloe, ginger, and neem extract inhibited cowpea root rot disease under both in vivo and in vitro environment (Suleiman and Emua 2009). Seed treatment of sorghum with *Vernonia amygdalina* and *Maesa lanceolata* significantly suppressed smut disease under field conditions (Sisay et al. 2012). Application of *Datura stramonium*, *Jatropha gossypiifolia*, and *Ricinus communis* extracts controlled anthracnose infection with increased yield of cowpea under cowpea/maize intercropping scheme in field conditions (Falade et al. 2018). Similarly, application of *Azadirachta indica* controlled bacterial blight disease of cotton with higher yield of Bt cotton under field trial (Rashid et al. 2016).

19.7.13 Ultraviolet Radiation

It has been reported that the intensity of ultraviolet (UV) radiations has increased due to ozone layer depletion. The UV radiations are generally considered detrimental for the crop plants; however they can effectively suppress the activities of pests and growth of various pathogens of agronomic crops (Cheng et al. 2014; Li et al. 2018). Utilization of UV-absorbing films, with the ability to slab near-UV (300–400) light radiation, has been found highly effective to prevent entry of certain pests in the greenhouses (Nakagaki et al. 1984). The coverage of greenhouse with UV-absorbing films appeared to be dark for certain pests. The incidence of various insect pests including thrips, aphids, and whiteflies was reduced where UV-absorbing films were used (Costa et al. 2002; Ohta and Kitamura 2006; Nguyen et al. 2009). So, use of UV-absorbing films/sheets may be an effective way to reduce the population of various pests of agronomic crops. The population and growth rate of *Anticarsia gemmatalis* was markedly reduced when these were forced to eat UV-B (315 nm)-irradiated leaves of soybean. However, UV-B-irradiated soybean leaves had higher concentration of soluble phenols and lower lignin contents (Zavala et al. 2001).

The irradiation with UV-B (280–320 nm) reduced the susceptibility of rice plants to *Pyricularia grisea*-induced blast disease. However, the response was cultivar dependent under glasshouse conditions (Finckh et al. 1995). UV-B treatment significantly reduced wheat stripe rust. Among the three races of *Puccinia striiformis*, CYR-31 was found to be more vulnerable, and CYR-33 was comparatively resistant and survived the UV-B exposure (Cheng et al. 2014). The artificially enhanced UV-B radiation significantly inhibited incidence and severity of *Magnaporthe oryzae*-induced rice blast. Moreover, UV-B-treated rice plants also had higher activities of disease-resistant enzymes such as lipoxygenase, chitinase, phenylalanine ammonia lyase, and β-1,3-glucanase (Li et al. 2018). The increased concentration of UV-A and UV-B (0.15–11.66 MJ m^{-2}) decreased the disease development of soybean rust owing to increased urediniospore mortality. The treated soybean plants also had increased height and leaf area index (Young et al. 201). Exposure of tobacco leaves to UV-B radiation enhanced endogenous production of salicylic acid that eventually enhanced phenylalanine ammonia lyase and signal transduction to activate defense-related protein in the pathogen infection process (Fujibe et al. 2000). So, it is evident that UV radiation can effectively decrease certain diseases of agronomic crops.

19.7.14 Ozone Treatment

The application of 150 ppb O_3 reduced the population of aphids (Telesnicki et al. 2015). In the same way, O_3 treatment reduced the population of aphids in Italian ryegrass (Ueno et al. 2015). The treatment of wheat grains with O_3 at the rate of 5 g/m^3 for 5 h significantly reduced the incidence of grain moth (*Sitotroga cerealella*) (El-Ghaffar et al. 2016).

The spot blotch disease of wheat was markedly reduced in response to ozone (O_3) treatment. The activity of chitinase enzyme and pathogenesis-related protein expression was enhanced, and *Bipolaris sorokiniana*-induced disease incidence was inhibited (Mina et al. 2016). Treatment of sunflower seeds with 0.24 g h^{-1} substantially reduced fungal population of *Fusarium*, *Aspergillus*, *Penicillium*, and *Alternaria* spp., without negatively influencing its physiological potential (Rodrigues et al. 2015). The application of 0.47 g kg^{-1} O_3 to soil completely inhibited *Phytophthora sojae*-induced stem and root rot disease of soybeans. Similarly, 490 μgm^{3}significantly inhibited the *Pseudomonas glycinea*-induced infection on primary as well as trifoliate soybean leaves (Laurence and Wood 1978).

19.7.15 Plant Growth-Promoting Rhizobacteria

The group of bacteria with beneficial effects on the growth of plants is known as plant growth-promoting rhizobacteria (PGPR). PGPR may also effectively check the dynamics of fungi, bacteria, nematodes, and certain pests with improved growth (Fig. 19.1). PGPR induce systemic acquired resistance in plants against certain disease causing microorganisms and pests (Yadav et al. 2015).

Pseudomonas maltophilia substantially reduced the *Helicoverpa zea* larval stage in corn earworm. The said PGPR strain also reduced the emergence of pupae and ultimately adults from the treated larvae (Bong and Sikorowski 1991). Likewise, *H. armigera* population was reduced in *P. gladioli* PGPR-treated cotton plants due to increased terpenoid and polyphenol contents (Qingwen et al. 1998). Similarly, 526 strain of *P. fluorescens* substantially reduced hornworm population in tobacco (Stock et al. 1990). PGPR *Bacillus amyloliquefaciens* in combination with compost reduced the incidence of pink bollworm, leaf roller, bugs, and aphids with consequent increase in cotton yield. The highest reduction was obtained for aphids with significantly enhanced cotton yield (Alavo et al. 2015).

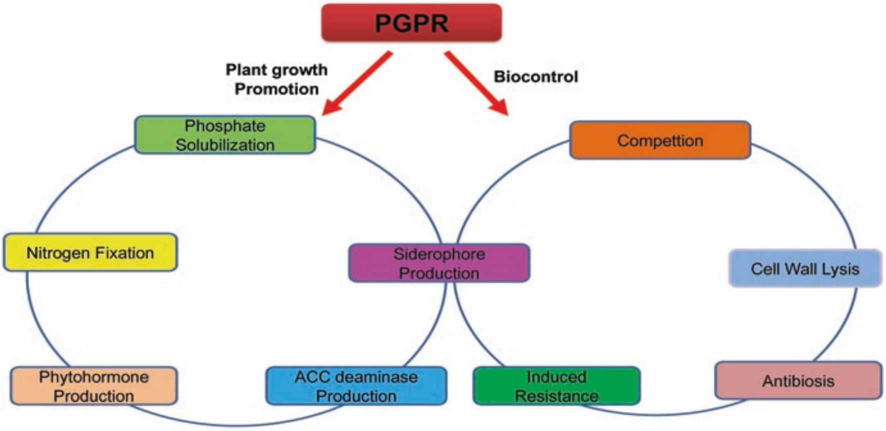

Fig. 19.1 Mode of action of PGPR on growth promotion and biocontrol of various pests and disease of agronomic crops. (Adopted from Shaikh et al. 2016)

Dip and foliar treatment with Pf1 and FP7 strains of *P. fluorescens* showed ISR induction against *Rhizoctonia solani*-induced sheath blight of rice (Vidhyasekaran and Muthamilan 1999). In the same way, PGPR induced ISR against red rot disease of sugarcane. The soil application of *P. fluorescens* exhibited ISR against tobacco necrosis virus (Maurhofer et al. 1994; Maurhofer et al. 1998). *P. fluorescens*-induced ISR inhibited cyst nematode (*Heterodera schachtii*) of sugar beet (Oostendorp and Sikora 1990). Likewise, *B. subtilis* increased protection against *Meloidogyne incognita* and *Meloidogyne arenaria* of cotton crop (Sikora 1988). It has also been reported that combination of PGPR with neem cake and chitin markedly reduced rice root nematode infestation (Swarnakumari and Lakshmanan 1999). *P. fluorescens*-treated rice seeds revealed disease resistance against *X. oryzae* pv. *oryzae* (Vidhyasekaran et al. 2001). The combined treatment with *P. fluorescens* and silica significantly inhibited rice blast incidence (Karpagavalli et al. 2002). Similarly, *P. fluorescens* application found to be effective in inhibiting sorghum root rot disease (Idris et al. 2008). The combined use of *P. fluorescens* with pesticides controlled black gram dry root rot (Siddiqui et al. 1998). The root rot disease incidence of *Vigna mungo* was markedly inhibited in response to *P. fluorescens* treatment (Latha et al. 2000). In the same way, chickpea root rot disease was substantially controlled with *P. fluorescens* application (Ahamad et al. 2000). The incidence of soybean cyst nematode was inhibited in response to *Bacillus* strain with significant increase in plant biomass, early growth, plant height, and yield (Xiang et al. 2017a). Similarly, *Bacillus* strain of PGPR efficiently controlled *Meloidogyne incognita* with improved plant biomass and yield of cotton (Xiang et al. 2017b). Tobacco growth was also substantially enhanced with concomitant protection against blue mold disease (Zhang et al. 2004).

19.7.16 Seaweed/Marine Macroalgae Extracts

At present, natural algal or seaweed extracts are considered more pertinent in agriculture. One of the benefits of these natural extracts is that they control plant infections with increased safety having almost negligible influence on environment. Application of *Sargassum tenerrimum* and *Padina pavonic*a seaweed extracts showed effective insecticidal activity as it reduced the population of *Dysdercus cingulatus* in cotton (Sahayaraj and Kalidas 2011; Sahayaraj and Jeeva 2012). The use of brown algae extract acted as insecticide and reduced *Dysdercus cingulatus* bug population in cotton (Asaraja and Sahayaraj 2013). The combined application of organic fertilizer and seaweed extract reduced the populations of *Bemisia tabaci*, *Liriomyza trifolii*, and *Aphis gossypii* infestation with increased yield and better fiber quality of cotton (Gencsoylu 2016).

The application of extracts of *U. armoricana* reduced the incidence of bean powdery mildew (Jaulneau et al. 2011). Similarly, application of *Sargassum swartzii* and red seaweed extracts efficiently controlled *Rhizoctonia solani*-induced sheath blight disease of rice due to increased accumulation of phytoalexin and phenolic compounds (Raj et al. 2016a, b). Green *Ulva fasciata* extract reduced the severity of anthracnose and enhanced the growth of common bean (Paulert et al. 2009). Seaweed application showed effective reduction of *Fusarium* spp.-, *Macrophomina phaseolina*-, and *Rhizoctonia solani*-induced root rot incidence of sunflower with reduced galls and penetration of the nematodes (Sultana et al. 2011). *Ulva fasciata* and sulfated polysaccharide significantly inhibited anthracnose and improved the growth of common bean (Paulert et al. 2009). Priming of wheat and barley seeds with *Ulva fasciata* extract enhanced the resistance against powdery mildew and improved plant growth (Paulert et al. 2010). Red algae-obtained kappa-/beta-carrageenan markedly suppressed the tobacco mosaic virus in the leaves of Xanthi-nc tobacco (Nagorskaia et al. 2008).

19.7.17 Plant Growth Regulators

The plant growth regulators (PGRs) are natural or synthetic organic compounds, known as biostimulants as well as bioinhibitors which play key roles in plant metabolism. Various growth regulators have been reported to enhance the productivity of plants (Morgan 1979) and improve their resistance against pests and pathogens, when applied exogenously (El-Hai 2015). These compounds (natural or synthetic) have been known to modify crop growth rate during several stages of development (from germination to maturity). Use of pesticides or fungicides is the major and traditional approach for the management of pests or diseases (Dogimont et al. 2010). Several elicitors have been proposed to develop acquired plant resistance. PGRs are also effective in the development of defense mechanism against biotic stresses (Thaler et al. 1999; Boughton et al. 2006; Ryals et al. 1996). War and Sharma (2014) investigated the effect of salicylic acid (SA) and jasmonic acids (JA) to induce resistance in groundnut against *Helicoverpa armigera*. Similarly aphid, a destructive pest of canola crop, is controlled by excessive use of environment-unfriendly insecticides. SA application (50 mg L^{-1}) was found effective in reducing aphid population in the field conditions (Elhamahmy et al. 2016).

JA and SA application reduced the attack of stem borer in sorghum crop and strengthen the defense system against herbivores (Hussain et al. 2014; Thakur et al. 2016). Nickell (1982) observed mixed response regarding metabolic functioning of plants in accordance with disease control in response to PGR applications. It has been observed that some auxins respond positively while GA_3 have the tendency to either decrease or increase the disease inoculum. Moreover, growth regulators (auxins and gibberellins) along with growth retardants (ethrel and PBZ) are used as alternatives to formal fungicide and showed effective control of fungal diseases of agronomic crops (Abdalla 2001; Khalifa 2003; Metwally et al. 2006; El-Hai et al. 2010). El-Hai (2015) found that IBA and GA_3 along with PBZ or ethrel showed effective control against *Alternaria* leaf spot disease. The ethrel and PBZ at 150 mg L^{-1} completely reduced the growth of fungal infection, as compared to fungicide with improved growth and yield of "faba bean."

The application of 100 mg L^{-1} kinetin suppressed the root rot diseases, particularly damping-off incidence in lentil. The treatment also improved the vegetative growth, increased leaf area and photosynthetic pigments, and enhanced yield of lentil (El-Hai et al. 2017). Similarly, the application of methyl jasmonate induced basal resistance in bread wheat against fungal pathogen "*Fusarium culmorum*" causing serious diseases such as root and crown rot.

The use of chlormequat chloride and ethephon at different concentrations, i.e., 750 g L^{-1} and 480 g L^{-1}, was evaluated against *Fusarium* fungi of wheat (Mankeviciene et al. 2008). The application of SA reduced incidence of fusarium head blight of wheat and barley (Makandar et al. 2012; Aldesuquy et al. 2015). Mbazia et al. (2016) also explored the effect of various growth-regulating compounds such as citric acid, oxalic acid, SA, and ascorbic acids with one fungicide on the control of "chocolate spot disease" in faba bean. It was found that application of SA was highly effective in vivo and in vitro and considerably inhibited fungal growth after 6 days of incubation (48%) followed by oxalic acid (39%), ascorbic acid (33%), and citric acid (10%) while the fungicide "carbendazim" provided partial protection of plant. Ali et al. (2013) investigated the effect of brassinosteroids on the resistance development of barley against fusarium disease. Application of brassinosteroids reduced severity of head blight (86%) and reduced grain loss of weight. SA treatment induced resistance against pathogens either biotrophic or hemibiotrophic. The application of SA significantly inhibited the mycelial growth of *Fusarium graminearum* of wheat (Qi et al. 2012).

19.7.18 Coating Materials

Different coating materials have reasonable potential to check the spread of certain pests and diseases of various agronomic crops. Coatings may be applied as seed treatment or as foliar sprays during production phases of the crops. The coatings have high anti-pest and antimicrobial properties that ultimately help to manage the outbreak of pests and diseases in agronomic crops. However, the efficacy of coating material is better against fungal diseases, as compared to insect pests or bacteria (Kong et al. 2010). Chitosan seed treatment effectively controlled pod borer and aphids of soybean. The treatment was also effective to increase the germination potential and growth of soybean seedlings. Application of chitin derivative showed 100% mortality of cotton leafworm larva (Rabea et al. 2005). In the same way, addition of chitosan showed significant control of chiefly moths and aphids of cotton (Badawy and El-Aswad 2012).

Application of chitosan as nanoparticles significantly reduced the incidence of downy mildew in pearl millet by regulating the defensive enzymes and nitric oxide generation. Chitosan treatment also led to higher expression of pathogenesis-related PR-1 and PR-5 proteins under greenhouse conditions (Manjunatha et al. 2008; Siddaiah et al. 2018). Gum arabic coating application significantly controlled *Rhizoctonia solani*-, *Macrophomina phaseolina*-, and *Fusarium* spp.-induced root rot infection with markedly better growth and yield of sunflower (Dawar et al. 2008). Similarly, seed coating with *Prosopis juliflora* extract combined with *Pseudomonas aeruginosa* and *Trichoderma harzianum* significantly enhanced the germination percentage and subsequent vegetative growth with effective control of root rot incidence of mung bean and cowpea (Ikram and Dawar 2013). Combined seed treatment with propiconazole and Genius Coat™ or Disco AG Blue L-237 increased the emergence percentage, tiller number, flowering, and yield exhibiting significantly lower loose smut incidence of barley under field conditions (Zegeye et al. 2017). Treatment with chitosan (low molecular weight) inhibited tobacco mosaic virus-induced necrosis (Davydova et al. 2011). Soil amendment with chitin effectively controlled *Meloidogyne arenaria* of peanut plant (Mian et al. 1982). Similarly, chitin application inhibited the growth of cyst nematodes of soybean crop (Rodriguez-Kabana et al. 1984). Combinational treatment with chemical fertilizer and chitosan significantly controlled rice dirty panicle disease. Moreover, the said treatment also markedly enhanced plant height, leaf greenness, panicle number, dry matter accumulation, and grain yield (Boonreung and Boonlertnirum 2013). Use of Cu-chitosan as nanoparticle significantly increased defense mechanism and reduced the *Curvularia* leaf spot disease of maize. It also improved growth and grain yield in pot experiment (Choudhary et al. 2017).

19.7.19 Biofabricated Nanoparticles

It has been reported that crop pests and diseases are major causes of reduced yield and increased economic losses in the world. Among various crops, wheat, rice, sugarcane, cotton, barley, beans, and groundnut are particularly susceptible to various pests and diseases. Therefore, in order to curb these deleterious ailments, myriad traditional fungicides are being used in the world posing countless harmful effects to sustainable ecosystem. Hence, some alternative approaches like nanoparticles are being developed to combat major pests and diseases of agronomic crops (Mishra et al. 2014).

Nanoparticle-coated halofenozide and tebufenozide checked the population of leafworm (*Spodoptera littoralis*) of Egyptian cotton (Elek et al. 2010). Nanoparticle-coated chitosan showed effective pesticidal activity as it controlled the population of *Aphis gossypii* of soybean under semi-field conditions (Sahab et al. 2015). Nanoparticles of biogenic showed strong larvicidal activity against *Mythimna separata* of rice (Buhroo et al. 2017).

It has been found that use of silver nanoparticles was highly effective to control *Magnaporthe grisea*-induced blast disease of rice (Jo et al. 2009; Rabab and El-Shafey 2013). Similarly, application of biofabricated silver nanoparticles checked the growth of *Bipolaris sorokiniana*-induced spot blotch disease of wheat (Jo et al. 2009; Mishra et al. 2014). Use of silver nanoparticles showed significant nematicidal activity by checking the growth of *Meloidogyne incognita* root-knot nematode of cotton (Abbassy et al. 2017). Silver nanoparticle triggered the phenolic biosynthesis and increased lignifications, which checked the *Sclerotium rolfsii*-induced chickpea collar rot disease under greenhouse conditions (Mishra et al. 2017).

19.7.20 Chemical Control

Different pests and diseases may be controlled with either curative or preventive applications (pesticides or fungicides). The efficiency of curative and preventive schemes depends upon nature of pathogens and chemicals applied (Sarnaik et al. 2006; Anuradha et al. 2015; Fromme et al. 2017).

Legume pests and diseases were significantly inhibited in response to application of dimethoate and mixture of copper oxychloride with subsequent increased growth and yield of plants (Muthomi et al. 2008). Cowpea crop encounters serious insect pest infestation such as pod borers and pod-sucking bugs that can be controlled with various applications of certain insecticides (Dzemo et al. 2010). Similarly, rice spiders were efficiently managed with pyrethroid and lambda-cyhalothrin insecticides under field conditions (Rodrigues et al. 2013). The use of pesticides may be minimized by cultivating genetically modified (GM) crops. Stem borer is the destructive pest of maize crop causing significant economic losses to the grower. Various insecticides in foliar, granular, and seed dresser form were tested under field condition. Attack of stem borer was significantly controlled in response to fipronil (granular) and imidacloprid (seeds treatment) application in maize with increased yield of crop (Iqbal et al. 2017a, b). In the same way, attack of sucking pests (whitefly, thrips, and aphids) was minimized by the application of several pesticides. However, efficacy of acetamiprid, confidor, and jazor was significantly better, than other tested chemicals (Nazir et al. 2017).

It has been reported that curative application of chlorothalonil, flutriafol, cyproconazole + trifloxystrobin, epoxiconazole + pyraclostrobin, cyproconazole + picoxystrobin and cyproconazole + azoxystrobin at 4 and 9 days after inoculation checked rust of Asian soybean. However, efficacy of chlorothalonil was found to be the lowest among all other chemicals (Reis et al. 2016). The application of azoxystrobin, flutriafol (1.0 L ha^{-1}), and pyraclostrobin (0.78 L ha^{-1}) reduced disease pressure and resulted in improved growth and development of grain sorghum (Fromme et al. 2017). The spray of trifloxystrobin and prothioconazole completely prevented grain rot of maize (Kluge et al. 2017). Triadimenol treatment completely checked brown rust of sugarcane. The treatment also lowered down the infection of rust from 36% to 16% in susceptible sugarcane variety (Zvoutete 2006). Chickpea and lentil crops majorly suffer from reduced yield due to fungal pathogens such as *Botrytis*, *Ascochyta*, and *Stemphylium*. These diseases were effectively managed with judicious application of fungicides and bactericides. Similarly, oscalid and fluazinam fungicidal treatment controlled sclerotinia blight of peanut (Woodward et al. 2015). Southern corn leaf blight is considered major disease of maize. Application of Ridomil Gold and mancozeb at 40–60 mg L^{-1} inhibited *Helminthosporium maydis*-induced foliar damage of maize (Sudisha et al. 2010).

19.8 Breeding for Resistance

Breeding for insect pest resistance is not as successful as for the development of resistance against diseases in agronomic crops. The major reason is that pest control is relatively easy to achieve by using pesticides. The major traditional methods used to develop insect pest resistance include pedigree method, mass selection, backcross, single seed descent, and recurrent selections. However, modern biotechnological techniques are more effective to create pest or herbivore resistance in agronomic crops. The expression of “Cry” toxin through genetically modified (GM) plants from *Bacillus thuringiensis* is particularly important. The resistant cultivars have been developed through GM for soybean, corn, and cotton (VanDoorn and deVos 2013). Use of molecular markers such as single nucleotide polymorphisms is of particular significance for marker-assisted selection against insect pests of rice, maize, and wheat (VanDoorn and deVos 2013). Similarly, “gene-for-gene” through R-gene-dependent resistance in which a specific chemical compound is secreted by certain insects on the plants that empowers host plants to start a defense-oriented response is also being used. However, these types of resistance are particularly suitable for sucking insect only. This is very important because sucking insects such as aphids and whiteflies spread various viral diseases in agronomic crops (VanDoorn and deVos 2013). Certain plant volatiles also attract insects for egg laying. It has been reported that herbivore-induced plant volatiles (HIPVs) fascinate natural predatory enemies for the laying of eggs at early stages. So, it could be a suitable measure for the biological control of insect pests in agronomic crops. Similarly, reduction of plant palatability through some breeding tools (modern or orthodox) could also be an option to reduce pest attack.

Naturally, plants are persistently threatened by numerous pathogens or pests. However, disease development in response to those interactions is relatively uncommon. Whether crops are suitable to certain pathogens as a host for disease development generally depends upon a number of biochemical and physiological cascades. It has been reported that resistance can be developed into the agronomic crops against various diseases through a suitable breeding program. Development of natural disease resistance holds an excellent potential to provide sustainable broad range of resistance in agronomic crops. Breeding of crops through quantitative trait locus (QTL) is an imperative tool for the incorporation of host plant resistance. For *Rhizoctonia solani*-induced sheath blight disease of rice, a novel chitinase *gene (LOC_Os11g47510)* cloned through QTL mapping contributing sheath blight disease tolerance "Tetep" rice line to *R. solani* was transformed into "Taipei-309," a japonica rice susceptible to sheath blight disease. The developed transformants were resistant to rice sheath blight. Similarly, *pGRMZM2G174449* known as inducible promoter was developed against sheath blight and banded leaf resistance in maize. Certain genome editing techniques are also available to incorporate resistance against diseases causing agents, posing significant economic losses of agronomic crops. The clustered regularly interspaced short palindromic repeat (CRISPR) is another molecular technique that helps genome-targeted amendment to develop crop with suitable traits (including pest or disease resistance) compared to traditional breeding. Similarly, technology of CRISPR/Cas9 is very advantageous to develop broad-spectrum and durable resistance against viral diseases. In the same way, RNAi (RNA interference) is a promising tool to generate the plants which can protect themselves against viruses, fungi, bacteria, nematodes, herbivorous insects, and parasites.

19.9 Conclusion and Future Prospects

Different pest and diseases of agronomic crops can be effectively controlled. However, the degree of control generally depends upon the used control measure. Several cultural control measures such as cover crops, intercropping, trap crops, tillage practices, and planting time can reduce population of pests or disease severity but are not as effective as chemical applications at commercial scale under field conditions. Similarly, applicability of biocontrol agents, PGPR, and plant extracts is also not commercially viable under field conditions. However, their efficacy may be synergized by combination of other control methods such as integrated use of the said cultural practices with reduced chemical applications. Future research should be focused on developing pest- and disease-tolerant or even pest- and disease-resistant crop varieties through modern biotechnological tools. Molecular breeding and use of QTL mapping should be further explored to incorporate resistant traits benefiting in reducing pest- or disease-induced crop losses to ensure global food security.

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Green Manuring for Soil Health and Sustainable Production of Agronomic Crops

20

Asif Tanveer, Hafiz Haider Ali, and Nabeel Ahmad Ikram

Abstract

Many countries have got self-sufficiency in food, but continuous cropping and frequent cultivation of soil result in breaking down of crumbs of soil aggregates and destruction of organic matter leading to depletion of soil fertility and productivity. There is substantial decline in use of organic manures including farm yard manure and green manure; therefore, sustainability of soil productivity has become a question. Intensive use of chemical or inorganic fertilizers degrades and emits toxicants that enter the food chain endangering the whole life sustaining system through nitrate poisoning. Applying organic matters either as farmyard manure or as green manure, recycling organic wastes, and enhancing biological nitrogen fixation combined with the use of chemical fertilizers are measures to maintain an adequate level of soil fertility for sustainable crop production. Green manuring is a low cost and effective technology in minimizing cost of inorganic fertilizers and safeguarding soil productivity. Green manuring acts as a restoration factory to maintain the soil fertility for sustainable agriculture. Initial set back may be seen in field crops after the incorporation of organic residues with wide C-N ratio. Green manures can be defined as crops or plants grown and ploughed into the soil to improve soil fertility by the addition of organic matter and nitrogen; or green manures are plants which are grown to improve the structure and nutrient content of the soil; or any crop preferably legume grown and ploughed under to improve the structure and fertility of soil, especially by the addition of organic matter is called green manure.

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Use of green manure crops in cropping system is called “green manuring” where the crop is grown in situ or brought from outside and incorporated when it is purposely grown; or green manuring is the ploughing under or soil incorporation of any green manure crop, while it is green or soon after it starts flowering. It can also be defined as the practice of growing crop, preferably legume, and ploughing it under at the start of reproductive stage of growth, for improving the structure and fertility of soil; or a practice of adding into the soil undecomposed green plant for improving the physical structure and fertility. A fundamental goal of growing green manure crop is to avoid bare soil between cash crop plantings. This not only protects soil, but also captures sunlight and produces biomass that enhances the soil quality.

Keywords
Nutrients · Crops · Organic matter · Fertility · Legume · Ploughing · Agriculture

20.1 Introduction

Many countries of the world have got self-sufficiency in food but continuous cropping and frequent cultivation of soil result in breaking down of crumbs of soil aggregates and destruction of organic matter leading to depletion of soil fertility and productivity. There is substantial decline in use of organic manures including farm yard manure and green manure; therefore sustainability of soil productivity has become a question. Intensive use of chemical or inorganic fertilizers degrades and emits toxicants that enter the food chain endangering the whole life-sustaining system through nitrate poisoning. The use of chemical fertilizers is the quickest and the shortest way of boosting crop production. But fossil fuel resources are shrinking with escalating costs, and inorganic fertilizers are becoming more expensive. Hence, there is need for alternate sources of plant nutrients.

Applying organic matters either as farm yard manure or green manure, recycling organic wastes, and enhancing biological nitrogen fixation combined with the use of chemical fertilizers are measures to maintain an adequate level of soil fertility for sustainable crop production. Green manuring is low-cost and effective technology in minimizing cost of inorganic fertilizers and safeguarding soil productivity. Value of green manuring lies in the fact that organic matter is incorporated into the soil. Green manuring acts as a restoration factory to maintain the soil fertility for sustainable agriculture. Initial setback may be seen in field crops after the incorporation of organic residues with wide C-N ratio. High lignin content which resists easy decomposition and release of higher proportion of organic acids during decomposition of green manure crops adversely affect establishment of young seedlings. It can be overcome by extra addition of nitrogen.

20.2 Green Manures

Green manures can be defined as crops or plants grown and plowed into the soil to improve soil fertility by the addition of organic matter and nitrogen or Green manures are plants which are grown to improve the structure and nutrient content of the soil or Any crop preferably legume grown and plowed under to improve the structure and fertility of soil, especially by the addition of organic matter is called green manure. Crops grown for the purpose of restoring or increasing the organic matter content in the soil are called green manure crops. Green manures are grown primarily for short-term economic gain. In other words, they are not produced for sale but rather for the benefits they provide to the production of subsequent cash crops**.** They are grown for their green leafy material which is high in nutrients and protects the soil. They are a cheap alternative to inorganic fertilizers and can be used to complement farm yard manures.

20.3 Green Manuring

Green manuring is the plowing under or soil incorporation of any green manure crop, while it is green or soon after it starts flowering. It can also be defined as the practice of growing crop preferably legume and plowing it under at the start of reproductive stage of growth, for improving the structure and fertility of soil or a practice of adding into the soil undecomposed green plant for improving the physical structure and fertility.

20.4 Why Green Manuring Is Necessary

Green manuring is a supplementary necessary practice to maintain the productive capacity of soil because.

1. Intensified and diversified cropping per unit area or time has depleted the soil physically and chemically.
2. The current jumping-up prices of inorganic fertilizers, sometimes their nonavailability, and adulteration could not withstand the fertilizer demand of high-yielding synthetic varieties and hybrids.
3. Due to mechanical cultivation, the use of animals in cultivation has decreased, and hence there is shortage of farm yard manures. To overcome their shortage, green manuring is necessary.

20.5 Objectives of Green Manuring

1. To add N to the companion or succeeding crop and add or sustain organic matter in the soil.

2. To utilize nitrates or the left over soil moisture when legumes are inter-sown in standing crop before or after harvest.
3. To shade the soil surface and prevent the rise of temperature when sown in young orchards. Otherwise, tender roots of fruit plants may be affected by the high soil temperature.
4. To cloth the surface with a vegetative cover, especially in hill slopes during the rainy season to avoid soil erosion and water runoff.
5. To take cutting of green fodder for cattle in early stages of legume and later as a green manure.
6. To enhance microbial activities in soil.
7. To increase the water holding capacity of soil.
8. To improve water permeability.
9. To make soil loose, porous and open.
10. To improve soil aeration.
11. To reduce leaching of mineral nutrients.
12. To increase availability of certain nutrients (P, K and Ca) to plants.
13. To lessen the number of cultivation.
14. To decrease the soil bulk density.
15. To improve soil tilth.
16. To improve the soil physical condition and thus rejuvenates the soil health.
17. To reduce the chances of insects attack. Guar, when in cotton fields, can eliminate the root-rot disease.
18. To increase crop yield.

20.6 Points/Characteristics Desirable for Choosing a Green Manure Crop

Almost any crop that will grow satisfactorily in a given set of climatic conditions can be used as a green manure crop. The factors which determine the suitability for use as a green manure are the cost of seed, labor, land, irrigation, and its fitness into the cropping system. When choosing which green manure plant to use, the following points should be considered:

1. It should belong to legume family.
2. It should be adapted to the climate, soil, farmer's available resources, and cropping system. This will help to keep the green manure healthy and to keep pests and diseases to a minimum.
3. Its production cost should be less.
4. Crop should rot quickly.
5. Multipurpose use.
6. Short duration, fast growing, and high nutrient accumulation ability.
7. Crop should be able to withstand abnormal conditions, i.e., tolerance to shade, flood, drought, and adverse temperatures.
8. Wide ecological adaptability.

9. High efficiency in use of water when grown in drier regions.
10. Little water is required, while still producing substantial quantities of top-growth.
11. Early onset of biological nitrogen fixation.
12. High N fixation rates.
13. Timely release of nutrients.
14. Photoperiod insensitivity.
15. High seed production.
16. High seed viability.
17. Ease in incorporation.
18. Ability to cross-inoculate or responsive to inoculation.
19. Pest and disease resistant. Species with the potential to reduce pest populations should be chosen, while those that harbor diseases or arthropod pests of the cash crops should be avoided.
20. High N sink in underground plant parts.
21. Produce abundant green foliage and succulent shoot as they provide more nutrients when buried in soil.
22. Crops that require minimal management are preferred.
23. Crops with fast germination and good seedling vigor are usually chosen because of their ability to compete with weeds.
24. Green manures should not be closely related to the following crop as they could attract pests and diseases which may affect the following crop.
25. Its seed should be easily available and affordable.
26. The length of time that land is free and how long the green manure will take to grow, bury, and rot.

Considering these points, crops like senji, berseem, sunn hemp, guar, and dhaincha can be grown for green manure either alone or intermixed with others.

20.7 Forms of Green Manuring

(a) Improved fallow: Natural fallow vegetation is replaced with green manure.
(b) Alley cropping**:** Quickly growing trees, shrubs (usually legumes), or grasses are planted in rows and are regularly cut back.
(c) Integration of trees into crop land, as found in several traditional cropping systems.
(d) Relay fallowing by sowing bush legumes among the food crops.
(e) In live mulching, in which the rows of food crops are sown into a low but dense cover crop of grasses or legumes, strips of the cover crop are removed by hand or killed by herbicides when the food crops are to be sown, thus reducing soil tillage operations to zero.
(f) Shaded green manures in fruit orchards.

20.8 Types of Green Manuring

Green manuring is of two types:

20.8.1 In Situ Green Manuring

As is obvious from the name, green manuring in situ is carried out by growing green manure crops in the field itself where their use is intended. Legume green manuring is a type of in situ green manuring. Almost any crop can be used for green manuring, but legumes are preferred because of their ability to fix nitrogen from the air. Green manuring with legumes (*Sesbania*, sun hemp, cowpea, green gram, clovers, lentils, cluster bean, etc.) is called legume green manuring. Growing a legume crop to be worked into the soil is an old agricultural practice that is gaining popularity again. It is a viable alternative to conventional lean period fallowing and can reduce the amount of chemical nitrogen fertilizer required. This crop has to be turned under the soil before the plants set seed. Legume green manuring could be profitably used on lands where it was not possible to add animal manures.

20.8.2 Ex Situ Green Manuring

Green succulent leaves or biomass of leguminous or non-leguminous plants from nearby location are collected, carted to the field, and incorporated by plowing.

It is of two types:

A. *Off-Farm Green Manure*

As an off-farm, the foliages of the shrub and herb type of weeds that grow along the roadside, water channels, and field bunds are harvested and brought in. In this type there will be more variety of species.

B. *On-Farm Green Manure*

It can be divided into:

(i) *Tree green manure*

Biomass from the farm can be generated from the legume or non-legume trees that are grown along the boundaries of the farm and along the water channels and main bunds of the fields. While preparing the main fields for the next crop, the foliage from these trees will be cut off and chopped in to small pieces and then incorporated by hoeing in the garden lands and by puddling in the wet lands.

(ii) *Live fence and hedge rows*

Some shrub species can be grown along the fence as live fence or as hedge rows along the pathways and waste patches. These life fences and the hedge rows can be trimmed off whenever needed and used. The non-legume supplies a large amount of carbohydrate material readily, but the bacteria responsible for the decay of this material must have access to N. If the N carried in the green manure crop isn't sufficient (i.e., a C:N greater than 30:1 or less than 1.5%), the bacteria will draw on the available soil N, and the newly grown crop will show a nitrogen deficiency symptoms for some time.

20.9 Benefits of Green Manuring

A fundamental goal of growing green manure crop is to avoid bare soil between cash crop plantings. This not only protects soil but captures sunlight and produces biomass that enhances soil quality. Numerous side benefits accrue from this approach as well, such as improved trafficability of fields and reduced compaction, enhanced aesthetics, and potential for animal feed production. Green manuring offers an inexpensive way of improving crop yields, and it takes little extra effort. Green manures are especially important on farms where there is not enough animal manure available, and when it is not possible to bring in natural fertilizers from elsewhere. Although the use of green manures may seem to create an extra work, they do provide a number of benefits:

(i) Reducing the impact of wind and water passing over the bare soil surface and hence reducing erosion. The roots penetrate the soil and hold it in place.
(ii) Adding organic matter to soil which improves its physical, chemical and biological properties, or structure letting more air into the soil and improving drainage.
(iii) Legume cover crops add "free" symbiotically fixed nitrogen to the cropping system.
(iv) Crops growing late in the season can capture and "recycle" soluble nutrients otherwise lost.
(v) Providing cropping system diversity which may create habitats for beneficial insects.
(vi) Reducing nutrients leaching losses.
(vii) Providing supplementary animal forage.
(viii) Promotes habitat for natural enemies.
(ix) Serves as a good food for the earthworms.
(x) Increases soil's biodiversity of beneficial microbes by providing organic matter and stimulating their growth.
(xi) Increases the water holding capacity of the soil.
(xii) Increases the nutrient holding capacity of the soil. Green manures help sandy soil hold more water and not drain so quickly.

(xiii) Green manures recycle nutrients, as they help prevent nutrients being washed out of the soil. The nutrients are taken up by the green manure and held inside the plant. When the nutrients are needed for the next crop, the plants are buried into the soil or used as mulch on top of the soil. This helps to increase crop yields. Legumes and other nitrogen fixing plants which take nitrogen from the air to the soil are particularly beneficial.

(xiv) Competing for light, water, and nutrients which may suppress weeds.

(xv) Green manure crops help to control weeds. Fallow field can become quickly overgrown with weeds which can be difficult to remove. Green manure crops cover the ground well in the off-season and stop weeds growing beneath them, by competing for different environmental resources and reducing weed proliferation and growth.

(xvi) It helps in reclamation of salt-affected soils by releasing organic acids and improving soil aeration and drainage.

(xvii) Root knot nematodes can be controlled by green manuring. Hence, green manures are a useful tool for sustainability in productivity.

20.10 Disadvantages

1. Direct cost of seed and extra cultivations.
2. Some time is lost opportunities for cash crops.
3. Extra work at busy times of the year.

20.11 Green Manure Crops

Both the legumes and non-legumes can be grown as green manure crops. The former supply N and organic matter while the latter only organic matter. Legumes have nodules on their roots which contain bacteria. These bacteria take nitrogen from the air. Plants use this to grow, but this extra nitrogen is also made available to future crops when the legumes are buried into the soil. The ability of legumes to "fix" nitrogen makes them very good green manures. However they do have limitations and non-legumes can sometimes be more suitable. Several of the leguminous species can produce a large biomass in 40–70 days and supply a considerable quantity of nitrogen under favorable soil and climatic conditions (Tables 20.1 and 20.2). Amount as high as 560 Kg of nitrogen fixed per hectare under a crop of clover has been reported from New Zealand, a country which, at present, depends almost entirely on this phenomenon for its nitrogen requirements.

The most commonly used green manure crops are dhaincha, jantar, sunn hemp, cowpeas, and guar (summer season) and berseem and senji (winter season). Among the leguminous green manure crops sunn hemp, dhaincha, and guar have been most widely used. *In choosing warm-season crops, the ability to perform well with minimal irrigation is often of primary consideration. Legume species in this category include cowpea and sunn hemp.*

Table 20.1 Nutrient composition of green manure crops

Green manure crop	N%	P%	K%	Ca%
Dhaincha	0.6	3.7	1.69	0.5
Sunn hemp	0.4–0.8	0.1	0.5	0.4
Cowpea	0.5–0.7	0.2	0.6	0.6
Senji/Indian clover	0.5	0.3	0.7	0.3
Pigeon pea	0.6–0.8	0.2	0.6	0.6
Guar/cluster bean	0.62	0.057	4.32	0.13
Berseem	0.43	0.21	4.59	2.2

Table 20.2 Amount of nitrogen and organic matter turned under by some green manure crops

Green manure crop	N turned under (Kg ha^{-1})	Organic matter (Kg ha^{-1})
Sunn hemp	75–80	18,500
Guar	60–118	18,500
Dhaincha	75–88	15,950
Senji	113	14,250
Berseem	60[a]	14,000
Arhar	45	–
Cowpea	58	–

[a] In case of berseem the first two cuttings are normally taken as fodder, while the third one is buried for green manuring

For green manuring, fast-growing legumes with more vegetative growth should be used. *Crotalaria juncea* (sunn hemp) and *Sesbania aculeata* (dhaincha) are the common green manures which produce relatively higher biomass and accumulate more nitrogen. Green manuring should be encouraged where irrigation facilities are available. For effective green manuring, legume crops are grown for 40–50 days (before flowering) to attain full vegetative growth and then plowed in the same field before sowing the next crop.

Sunn hemp is less tolerant to salinity and waterlogged conditions than dhaincha. Under good moisture conditions, dhaincha shows better response, but under limited water supply, sunn hemp performs better. Dhaincha is less tolerant to atmospheric and soil drought than sunn hemp.

Sesbania aculeata (dhaincha), a native of Africa, is more acceptable to farmers and can accumulate up to 108 kg N/ha in 60 days of growth. Dhaincha is a quick-growing succulent green manure crop, which can be incorporated at about 8–10 weeks after sowing when the crop is at flowering stage. This crop adapts to varying conditions of soil and climate. It can be grown throughout the year and withstands a wide range of soil conditions like drought, salinity, alkalinity, and waterlogging. The green matter yield is 10–20 tonnes per ha. Decomposition of crop depends upon the rainfall and irrigation after the burying of crop and depth of burying. It is recommended to bury the crop deeper in light soil than in heavy soil.

Sesbania rostrata produces effective aerial rhizobial nodules on the surface of the stem too, besides the roots. It is a quick-growing green manure tolerant to flooding and waterlogging. It is capable of producing 25 tonnes of green biomass/ha.

Sunn hemp: A quick-growing green manure-cum-fiber crop but does not withstand heavy irrigation or continuous waterlogging. It can be grown in all seasons, for green manure. It is irrigated once in 30 days. Incorporate the green mater within 45–60 DAS. Green biomass yield is 13–15 t/ha.

20.12 How Are Green Manures Used?

Farmers often see the benefits of green manure crops, but many do not use green manure crops because they do not know which green manure species to use and how to include them in their own cropping system. It is, therefore, very important to plan in advance where and when green manure crops are to be grown. Timing of sowing is important. The green manure must be ready to plow up in before the next crop is sown. There should not be a long gap between burying the green manure and planting the next crop. This is to prevent nutrients from the green manure leaching out of the soil, before being taken up by the next crop.

A. *Green Manures in Rotation*

Growing green manures as part of a crop rotation is an important part of a cropping system. Green manures can be used in rotation:

1. Whenever there is no crop in the field, rather than leaving the land fallow and allowing weeds to grow and nutrients to leach out of the soil.
2. As break crops, when there is only a short time between main crops.

B. *Green Manures and Under Sowing*

Under sowing involves growing a green manure crop at the same time as a cash crop, among the crop plants. Sometimes green manure crop is sown with the cash crop or slightly later when the crop is already growing. This reduces competition between the green manure and the cash crop. For example, under sowing is sometimes used with cotton or maize crop where a green manure is sown under the cotton or maize plants. In this way when the cotton or maize is harvested the green manure is already established and ready to grow quickly. This method means that no extra time is spent preparing the land and sowing the green manure.

C. *Long-Term Green Manures*

1. Green manure crops can be grown for more than one season and can be used when soil is very poor.
2. New land is being prepared for use, especially to help control difficult perennial weeds.

3. Land is to have a long fallow period.
4. Long-term green manures provide green material which can be cut and carried to other fields for burying such as alfalfa (*Medicago sativa*).

20.13 Time for Green Manuring

The best time for burying green manure crop is when it just starts blooming, because plants have completed their vegetative growth at that stage and more organic matter is obtained from them. Moreover, plants are tender and take less time for rotting.

20.14 Method for Burying Green Manure Crops

Irrigate the crop just at the start of flowering. When soil comes in proper moisture condition, run the heavy plank over the crop in the direction along which plowing is to be done. When the crop is laid flat, bury it in to the soil by furrow turning plow (mold board plow) in the direction of planking. Crop buried in this way takes about 4–5 weeks for rotting. If soil becomes dry then irrigate it to enhance rotting. Rotting process can be increased by application of one bag of NH_2SO_4. For complete chopping and easy rotting, rotavator should be used in standing crop.

Green manure crop should be buried after every 2 or 3 years at the start of farming and then after every 3 or 4 years. Good results of green manure crops are obtained in sandy and low fertile soils. Such results can be obtained after three to four green manuring.

20.15 Green Manuring in Different Cropping Systems

High cropping intensity, diversified cropping, warm climate, and injudicious use of chemical fertilizers are the factors which adversely affect the physical properties of the soil. During the past two decades, organic manures took a back seat in favor of chemical fertilizers that became intensified with the package of short-saturated and more fertilizer responsive varieties. The rising cost of nitrogen fertilizers, their unavailability or too late availability, kept their applications low which hinders the potential yield of modern varieties. As an alternative to inorganic or chemical fertilizers, organic manures like farmyard manure and green manure are commonly used. Organic manures and crop residues are the common sources of humus (reservoir of available nitrogen). Likewise, when farmyard manure is in limited supply, green manure is the cheapest and the best source of organic matter and nitrogen.

20.16 Green Manuring in Crop Rotations

The practice of green manuring is mostly confined to cash and food crops. The main bottleneck in its universal adaptation is the loss of one crop season. The cropping patterns should be such as to include such leguminous crops which could be raised without disturbing the main crops in rotation. Some of the important crops for which green manuring can be practiced are wheat, rice, cotton, sugarcane, and maize.

20.16.1 Wheat

Green manure crops like sunn hemp, cowpea, and guar can be raised in those areas which remain fallow during pre-wheat season. Therefore, the following rotations involving green manure crops can be implemented in such areas:

- GM-wheat-cotton
- GM-fallow-wheat-vegetables
- GM-wheat-pulses
- GM-wheat-maize-peas
- Sunflower-GM-wheat-rice

20.16.2 Rice

An existing gap of 40–70 days between wheat harvest and rice transplanting in countries with dominant rice-wheat cropping system can be utilized by growing short-duration green manure crops like dhaincha, guar, etc. It should be buried before transplanting rice. Other possible rotations in rice-based cropping systems can be considered as:

- Dhaincha-rice-berseem (fodder)-rice
- Dhaincha-rice-masoor/gram-rice
- Rice-berseem (last cutting as GM)-rice
- Rice-Indian clover (GM)-rice
- Wheat-cowpea/guar bean (GM)-rice

20.16.3 Cotton

In the cotton-growing countries, the following suitable crop rotations can be practiced:

- Maize-Indian clover (GM)-rice
- Sugarcane-(GM)-cotton

- Sunflower-mung bean-berseem (last cutting as green manure)-cotton
- Indian clover (GM)-cotton-wheat
- Maize-toria-GM-cotton

Last cutting of the berseem should be buried in soil before sowing of cotton.

20.16.4 Sugarcane

The use of green manure crops in the following rotations can ensure high productivity of sugarcane:

- Wheat-maize-Indian clover (GM)-sugarcane
- Indian clover (GM)-sugarcane-wheat
- GM-sugarcane-fallow-cotton
- Indian clover (GM)-sugarcane-maize-tobacco
- GM-sugarcane-mung bean-rice

20.17 Maize

The following crop rotations can be successful in maize growing countries:

- Guar bean (GM)-maize-wheat
- Sugarcane-GM-maize-berseem
- Indian clover (GM)-maize-sunflower
- Potato-GM-maize-pulses
- Wheat-maize-Indian clover (GM)-sugarcane

20.18 Intercropping with Green Manure Crops

A small farmer finds it difficult to produce green manure crop at the loss of cash crop which supports his family. However, it is possible to grow green manure crops in the interspaces or rows of the principal crop. In a cropping system, where sugarcane follows cotton, a good system is to grow Indian clover in standing crop of cotton in October. A little before the last picking of cotton, Indian clover is fully established. This is turned down by the end of January or early February before sugarcane planting. Similarly, berseem can be sown in the standing crop of cotton and in September-sown sugarcane crop. Another system of intercropping is the sowing of sunn hemp between the rows of February-sown sugarcane when the latter is established. This is plowed up at the time of earthing up of sugarcane. Other suitable crops are dhaincha and guar bean. Sugarcane can be sown in standing crop of berseem which is later on buried in the soil.

20.19 Residual Effects of Green Manure

Many farmers evaluate the profitability of green manuring on the bases of return obtained from the following crops, which is not good criterion. However, the yields obtained from all crops in the rotation should be taken into account rather than the yield of immediately following crop.

Experiments support the view that green manuring has a marked effect on the yields of subsequent crops in the rotation due to the residual carry over. Studies indicate that 50–80% of the nitrogen requirement of succeeding crop can be obtained from green manuring. The residual effect of green manuring remains in the plot long enough to benefit the third crop in succession. However, the persistence depends upon the kind of the green material buried, stage of burying, weather conditions, soil characteristics, and crops in succession.

The quality of green manure crop should be its ability to yield large quantity of organic matter in a short period. A legume with leafy growth, succulent foliage, ability to suppress weeds, and a well-developed deep root system forms the best green manure. Leguminous green manures commonly grow as cultivated annual legumes are given in Table 20.3. Of these, sunn hemp and dhaincha have been most widely used. The farmer is less tolerant to salinity and soil waterlogged conditions, while the latter is relatively salt tolerant and flourishes well in waterlogged, saline, sodic, and saline-sodic soils and thus is invariably used in the reclamative process as the first crop. The decomposition products of dhaincha also help in the removal of exchangeable Na from soils. Inclusion of dhaincha as a green manure crop in rice-based rotation gives better returns than its inclusion during reclamation of salt-affected soils. Thus, the role of green manure as a source of plant nutrients may, therefore, be viewed along with its other attributes.

Application of 20–27 Kg P, 10.5 Kg N, and 25–50 Kg K (depending on soil texture) per acre at the time of seed bed preparation is necessary for green manure crops.

Table 20.3 Growing of green manure crops

Common name	Botanical name	Soil type	Sowing time	Seed rate kg/acre
Sunn hemp	*Crotolaria juncea*	Well-drained sandy loam and loam soil	May	40
Cluster bean	*Cyamopsis tetragonoloba*	All types of soils in irrigated and rainfed areas. Sandy loam soil is more suitable	April	25–28
Dhaincha	*Sesbenia aculeate*	All types of soils including salt affected and water logged soils	March–July	18
Pigeon pea or red gram	*Vigna catjang*	Sandy loam, sandy, and clay soils	June–July	15
Indian clover	*Melilotus parviflora*	Light loam	September–October	10–15

20.20 Efficiency of Different Green Manures

The value of green manure crop depends upon the amount of foliage produce; N accumulates per unit time, irrigation water requirement and its growing season. An efficient green manure must contain maximum nutrients at harvest immediately preceeding the growing season of the main crop. Under good moisture conditions, dhaincha shows better response, but under limited water supply, sunn hemp performs better. Dhaincha is less tolerant to atmospheric and soil drought than sunn hemp. Despite its high water requirement, it is good accumulator of N. The nitrogen fixed by the nodule bacteria is used by the host plant and secreted partly into the soil. It follows that the contribution of dhaincha to soil N is actually more than what is added as roots and tops. It is also more efficient is mining P from lower soil depths.

The role of green manures as source of organic matters and N is well recognized. Their capacity to mobilize soil P and other nutrients are more or less universally accepted. They are readily accepted when the added green matter grows elsewhere, as in the case of green leaf manuring; but the problem arises with in situ green manures when these compete with the main crop for space, time, water, and other inputs. In situ green manure crops must grow for 8–10 weeks before incorporation.

The productivity of the traditional rice-wheat cropping system in the Indo-Gangetic Plains is poor due to adoption of this system in this region since centuries. Continuous mining of the nutrients by rice and wheat crops from a specific rooting zone presents special problems in crop management. One of the ways to overcome some of the soil fertility problems in this crop rotation is to introduce green manuring which can play an important role in improving the soil health through increasing the organic matter contents and by improving the nitrogen status of the soil.

This is possible with the use of *Sesbania* species which can fit well the fallow period between rice and wheat crops. Wheat is harvested in mid-April to early May with fallow period of 60–75 days up to the rice transplanting. *Sesbania aculeata* grown for 45 days after harvest of wheat can produce dry matter ranging 2.4–6.6 t/ha. *Sesbania rostrata* has much promise for lowland rice especially with adequate irrigation. Besides its nodules on the roots, it has nodules on the stems as well. As a result it fixes much more nitrogen as compared to *Sesbania aculeata.*This is why it looks lusher and green as compared to *Sesbania aculeata*. It contains about 3.5% nitrogen against 2.5 in *Sesbania aculatea*, and at equal level of biomass production of 2.4 t/ha, it fixes 25 kg N/ha more than *Sesbania aculeata*. *Sesbania rostrata* produces more biomass and contains 2.5–3.0 times more N than grain legumes in 60 days. Where grains are harvested, the N benefit to the following crop is reduced to the extent that the absorbed N is taken away with the grain.

With the use of *Sesbania* green manuring, rice yield increases from 15% to 60% depending on the prevailing soil conditions. These increases have been reported more in newly reclaimed soils. Addition of phosphorus to *Sesbania rostrata* resulted in fixing more nitrogen as compared to no P application. It thus resulted in producing 15% more rice yield. Green manuring with *Sesbania* looks promising and highly essential in increasing and sustaining the productivity of rice-wheat system.

The response of rice to green manure depends upon time of its application. Because of succulence and a narrow C:N ratio, a large part of green manure N is released as nitrates and tend to leach down with water during transplanting. In several experiments, it has been found that for 2-month-old dhaincha crop, the rice yield decreases as the interval between burying green manure and transplanting rice increased. The optimum crop age was found to be 2 months. Burying dhaincha 1 day before transplanting rice invariably gave more yield than a time interval of 2 weeks. Green manures when buried just before transplanting rice act as slow release fertilizers and also create reducing conditions which help in mobilizing several other nutrient elements.

Low fertility of the soil and pest attack is the important factors which reduce sugarcane productivity. During the early phase of sugarcane growth, early shoot borer is a major pest, devastating the tillers and reducing the millable cane especially in hot weather months. To overcome these two problems, dhaincha can be intercropped in the germination and early tillering phase of cane crop. Several on-farm trials revealed that when dhaincha was sown on the third day of planting cane at 15 kg per hectare and incorporated at the base of the crop with partial earthing up, the early shoot borer incidence was less, whereas in the control field, it was 39% 60 days after sowing.

The probable reason for reduction of borer incidence is that the dhaincha plant in between cane rows improved the relative humidity (above 85%) in the microclimate of cane crop. The dhaincha root nodules and its bioenergy in the soil after incorporation in the root zone of cane crop enrich soul fertility by adding biological nitrogen. As a result, dhaincha incorporated field yielded 145 tonnes of cane per hectare compared to the control field which gave only 107 tonnes per hectare.

21 Plant-Microbe Interactions in Agronomic Crops

Imran

Abstract

Crop nutrient management through integrated approach is an important aspect provided mainly by bio-, organic, and chemical fertilizers. However, it is widely accepted that the application of a balanced fertilizer with effective use of organic sources and beneficial microbes is key to achieving higher crop production and net return. Agronomist and agriculture scientists explore an alternative source to increase farm products with low-input cost and maintain soil health without affecting soil and plant environment. Plants obtain nutrients from two natural sources, organic matter and minerals and chemical fertilizers. Farmers only rely on chemical fertilizer which not only deteriorates quality of soil but also increases cost of production. Soil amendments and biofertilization are integrated approaches to reduce dependency on chemical fertilizers with the advantage of low cost of production. Crop response to biological fertilizers depends largely on crop species/strains of microbe and application method along with climatic conditions. It has been reported that using beneficial microbes reduces requirement of nitrogen 50–70% and increases yield up to 20%. Bacterial inoculation not only provides nitrogen, phosphorus, and growth hormones but also makes the plant healthy and less susceptible to pathogens. Using of beneficial microbes (soil application, seed inoculation and foliar application) along with the optimal dose of fertilizers has the ability to save about half of the recommended dose of chemical fertilizers.

Keywords

Beneficial microbes · PSB · *Trichoderma* · VAM · Root colonization · Solubilization · Mineralization · Organic acids · Soil pH · *Bacillus* · *Pseudomonas*

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21.1 Introduction

Crop nutrient management is an important aspect provided mainly by chemical fertilizers. However, it is widely accepted that the application of a balanced fertilizer with effective use of organic sources and beneficial microbes is key to achieving higher crop production (Imran et al. 2016a, b). Repeated applications of chemical fertilizers and heavy metal lead to soil degradation and cause environmental damage. Application of organic and biofertilizers can reduce these problems as useful on chemical fertilizer to improve soil fertility. Thus, it was considered appropriate to merge the three different sources of nutrients, organic, bio-, and chemical fertilizers, to get more efficient and economical result for the long terms (Imran et al. 2016a, b & Diep et al. 2016a, b). Literature on the use of organic substances along with bio- and chemical fertilizers on yield of agronomic crops are very limited. The challenges for agriculture production at the harsh and hostile environment with climate change at the twenty-first century for food and fiber only could be overcome with the application of biofertilizer (Imran 2017). Beneficial microbes application favored by the presence of high levels of plant roots, which they colonize readily act as a plant roots for nutrients uptake. Some strains are highly rhizosphere competent, i.e., able to colonize and grow on roots as they develop. The most strongly rhizosphere competent strains can be added to soil or seeds by any method. Once they come into contact with roots, they colonize the root surface or cortex, depending on the strain (Elkoca et al. 2008). Thus, if added as a seed treatment, the best strains will colonize root surfaces even when roots a meter or more below the soil surface and they can persist at useful numbers up to 18 months after application (FAO 2014). However, most strains lack this ability. Use of mineral fertilizers is faster and safer to increase grain production; however, cost and other restrictions discourage farmers to use mineral fertilizers (Dubey et al. 1997). So farmers need to take full advantage of the potential of alternative sources of plant nutrients. So, we should pay more attention on efficient use of chemical fertilizers and use these low-cost sources of nutrients such as organic matter and biological fertilizer to reduce production costs along with soil productivity and health support (Drevon and Hartwig 1997).

In addition *Trichoderma* spp. attack, parasitize, and otherwise gain nutrition from other fungi. Since *Trichoderma* spp. grow and proliferate best when there are abundant healthy roots, they have evolved numerous mechanisms for both attack of other fungi and for enhancing plant and root growth. Several new general methods both for biocontrol and for causing enhancement of plant growth have recently been demonstrated, and it is now clear that there must be hundreds of separate genes and gene products involved in these processes (Imran et al. 2015a, b, c, d, 2017).

21.1.1 How Biofertilizers Work?

Biofertilizers fix atmospheric nitrogen in the soil and root nodules of legume crops and make it available to the plants (Imran et al. 2016a, b). They solubilize the insoluble forms of phosphates like tricalcium, iron, and aluminum phosphates into

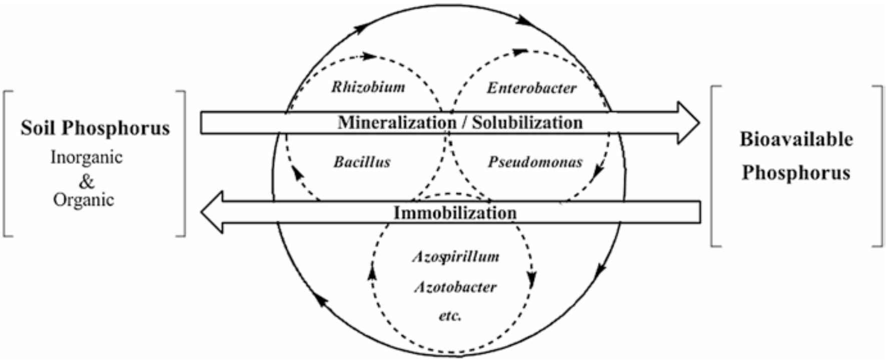

Fig. 21.1 Schematic diagram of soil phosphorus mobilization and immobilization by bacteria

available forms. They scavenge phosphate from soil layers. They produce hormones and antimetabolites which promote root growth (Imran et al. 2015a, b, c, d). They decompose organic matter help in mineralization in soil (Fig. 21.1). When applied to seed, seedlings, or soil, biofertilizers increase the availability of nutrients and improve the yields by 10–25% without adversely affecting the soil and environment (Fageria et al. 1995).

21.1.2 Properties of *Trichoderma*

The amazing properties of trichoderma fungi are enhanced further by the fact that it is nontoxic to plants, humans, and animals, nonpolluting, safe to use, and completely natural (Gao et al. 2007).

A study of *Trichoderma* applications by the Department of Pathology and Weed Science, Colorado State University, scientists observed radish growth increases of 150–250%. Similarly, in both steamed and raw soil infested with the fungus, periwinkle flowering was hastened, and the number of blooms on chrysanthemums and petunias multiplied (Khan et al. 2016). Dry weights of tomato, pepper, and cucumber plants increased, and treated pepper seeds germinated 2 days faster than the control plantings. In erosion control the faster germination and growth and heavier root system are important factors in stabilizing the soil. *Trichoderma* fungi fit perfectly into the growing trend toward biocontrol of disease and harmful fungi and reduced use of manufactured fertilizers. Research into these beneficial fungi shows promise they can be part of the answer to increasing ecological concerns (Iqbal et al. 2016).

21.1.3 Biocontrol Agents (*Trichoderma* Fungi)

As noted, these fungi are used, with or without legal registration, for the control of plant diseases. There are several reputable companies that manufacture government registered products (Akpalo et al. 2014; Imran et al. 2016a, b).

21.1.4 Plant Growth Promotion (*Trichoderma* Fungi)

Some of these abilities are likely to be quite profound. Recently, we have found that one strain increases the numbers of even deep roots (at as much as a meter below the soil surface). These deep roots cause crops, such as corn, and ornamental plants, such as turfgrass, to become more resistant to drought (Ahmad et al. 2008).

For many years, the ability of these fungi to increase the rate of plant growth and development, including, especially, their ability to cause the production of more robust roots has been known. The mechanisms for these abilities are only just now becoming known.

Perhaps even more importantly, our recent research indicates that corn whose roots are colonized by *Trichoderma* strain T-22 require about 40% less nitrogen fertilizer than maize whose roots lack the fungus. Since nitrogen fertilizer use is likely to be curtailed by federal mandate to minimize damage to estuaries and other oceanic environment. The use of this organism may provide a method for farmers to retain high agricultural productivity while still meeting new regulations likely to be imposed (Aise et al. 2011; Akhtar et al. 2013).

21.2 Pulses and Biofertilizers

Mung bean (green gram) inoculation with VAM gave the highest green forage, dry matter, and crude protein. It has been reported that highest number of plants m^{-2}, plant height (cm), number of leaves plant^{-1}, pods length (cm), numbers of seeds pod^{-1}, number of pods plants^{-1}, thousand seed weight, seed yield, and harvest index was noted with the inoculation of biofertilizer (PSB) (Imran et al. 2016a, b). Alam et al. (2007) studied beneficial microbe's inoculation with three different cultivars of mung bean and reported that growth and yield components were highest in cv. NM-92 with inoculation of *Trichoderma*. Imran et al. (2018) conducted a 2-year consecutive experiment on soybean, maize, and subsequent wheat to evaluate soybean, maize, and subsequent wheat response to biofertilizers (PSB, *Trichoderma*) and their interactions with organic sources and phosphorus levels. The author has not yet published the work that will be submitted to the Higher Education Commission of Pakistan. They reported that soybean phenological and growth characteristics were holistically improved with the inoculation of *Trichoderma*. Dry matter portioning was much higher with PSB inoculation. He concluded that *Trichoderma* are favored by the presence of high levels of plant roots, which they colonize readily. Some strains are highly rhizosphere competent, i.e., able to colonize and grow on roots as they develop. The most strongly rhizosphere competent strains can be added to soil or seeds by any method (Ansari and Sukhraj 2010). Once they come into contact with roots, they colonize the root surface or cortex, depending on the strain. Thus, if added as a seed treatment, the best strains will colonize root surfaces even when roots a meter or more below the soil surface and they can persist at useful numbers up to 18 months after application. However, most strains lack this ability. By fixing atmospheric nitrogen and solubilizing phosphates, pulses contribute to reducing the need for synthetic fertilizers and, in doing so, greatly contribute to reducing the risk of soil and water pollution, supporting soil biodiversity, and combating and building resilience to climate change (Aziz et al. 2016). Biological nitrogen fixation is particularly important for global agricultural productivity and might be considered one of the most important biological processes on the planet. It provides *circa* 100 million metric tonnes of N which leads to an annual saving of around USD10 billion in N fertilizer (Arancon et al. 2005). Lentils alone could fix nitrogen in the range of 35–100 kg ha-1. Furthermore, the reduced need for (or use of) synthetic fertilizers indirectly reduces the amount of greenhouse gases released into the atmosphere. Pulses also promote soil carbon sequestration and, ultimately, reduce soil erosion when included in intercropping farming systems and/or used as cover crops (Ancha et al. 1997). Furthermore, due to their high nutritional value, pulses are also valuable allies in fighting hunger worldwide.

Argaw (2012) reported that rhizobial inoculation alone and combined with chemical fertilizer produced significantly higher nodule number, pod number, pod weight, nut yield, and yield of groundnut as compared to uninoculated ones. Combined treatments of *Rhizobium* and fertilizers gave the highest nut and stover yield (Assioty and Sedera 2005). In summary, pulses are important food crops that can play a major role in addressing future global food security and environmental challenges, as well as in contributing to healthy diets. Pulses contain on average 19–25% protein, with over 30% in newly developed varieties (Ankamah et al. 1996). Due to their high nutritional value, pulses can improve the diet of the poorest who cannot rely on a diversified diet enriched by meat consumption. Nearly 80% of dietary protein in the developing world is plant protein, compared to 43.4% in developed countries where animal protein is mostly consumed. Diep et al. (2016a, b) conducted an experiment to study the effects of PSB on soybean. The results showed that application of PSB inoculant produced significantly higher yield component, grain yield, oil, and protein in seed than control. Aziz et al. (2016) conducted an experiment to determine the effect of bacterial inoculation on soybean. Results indicated that inoculation improved significantly height, grain, biomass yield, nodulation, and nitrogen uptake of soybean. Argaw (2012) conducted an experiment to study the effects of co-inoculation of *Bradyrhizobium japonicum* and phosphate-solubilizing bacteria on nodulation, seed yield, and yield components of soybean. The results revealed that application of PSB significantly increased plant height at harvest, number of nodules per plant, nodule volume per plant, nodule fresh weight per plant, and shoot height at late flowering and early pod setting compared to the other treatments. Ayub et al. (1994) evaluated the effect of P source in soils that need an addition of inoculums of phosphate-solubilizing microorganisms to improve the rock phosphate efficiency. The study suggested that the use of rock phosphate combined with the co-inoculation with PSB would ensure soybean production in economically profitable and environmentally friendly conditions. Bardan (2003) evaluated the effects of phosphatic biofertilizer with inorganic or organic sources of P on lentil (*Lens culinaris* Medikus). P-biofertilizers with 50% P from triple superphosphate gave the highest seed and stover yields as well as total P uptake by lentil compared to the 100% P from triple superphosphate. Argaw (2012) conducted an experiment to study the effects of co-inoculation of *Bradyrhizobium japonicum* and phosphate-solubilizing bacteria on nodulation, seed yield, and yield components of soybean. The results revealed that application of PSB significantly increased plant height at harvest, number of nodules per plant, nodule volume per plant, nodule fresh weight per plant, and shoot height at late flowering and early pod setting compared to the other treatments. Begum et al. (2015) studied the effect of *Bradyrhizobium japonicum* and PSB (*Pseudomonas* spp.) application on soybean. The results showed that application of *Bradyrhizobium japonicum* and PSB (*Pseudomonas* spp.) can enhance the number of nodules, dry weight of nodules, yield components, grain yield, soil nutrient availability, and uptake of soybean crop.

21.3 Cereals and Biofertilizers

Biopower vaccination was assessed for the growth and yield of wheat and maize by Bekere et al. (2012) in field conditions. Biopower by half and full rate of N fertilizer increased grain yields of wheat and maize over half and full rate of N fertilizer (Fig. 21.2). Imran et al. (2018) found that *beneficial microbes* or commercial

Fig. 21.2 Tangible view of maize experimental plots at ARI with (+) and without (−) bio fertilization

fertilizers greatly increase maize yield and yield relating attributes. Bellore and Mall (1975) reported that inoculation of *Rhizobia* alone or in combination with chemical fertilizers produced a much larger number of nodules, number of pod, pod weight, and yields as compared with those were not vaccinated. Combining treatments with beneficial microbes gave the highest yield. Berg and Lynd (1985) studied the effectiveness of biofertilizer in improving the availability of phosphorus. The results indicated that P concentration in maize leaf, stalk, grain, and total P uptake was much higher than non-inoculated plants. Control vs Rest plots (comparison of control with treatments asserted plots), wheat production has increased 21% and 35%, respectively, due to increased availability of phosphorus. Maize responded positively to inoculation in terms of increasing residual biomass of plants, number of cobs, and grain yield (Bhattacharya et al. 2010).

Gao et al. (2007) determined the effect of AMF inoculation on growth performance and Zn uptake by rice genotypes. A pot experiment was conducted with six aerobic rice genotypes inoculated with *Glomus mosseae* or *G. etunicatum* or without AMF on a low Zn soil. Plant growth, Zn uptake, and mycorrhizal responsiveness were determined. AMF-inoculated plants produced more biomass and took up more Zn than nonmycorrhizal controls. Mycorrhizal inoculation, however, significantly increased Zn uptake only in genotypes that had a low Zn uptake in the nonmycorrhizal condition (Cassman et al. 1981a, b; Brady 2002). They concluded that genotypes that are less efficient in Zn uptake are more responsive to AMF inoculation.

21.4 Effect of PSB on Crop Production

Phosphate rock minerals are often too insoluble to provide sufficient P for crop uptake. Use of PSMs can increase crop yields up to 70% (Carsky et al. 2001). Combined inoculation of arbuscular mycorrhiza and PSB gives better uptake of both native P from the soil and P coming from the phosphatic rock (Carvalho et al. 2011). Higher crop yields result from solubilization of fixed soil P and applied phosphates by PSB (Cassman et al. 1981a, b). Microorganisms with phosphate-solubilizing potential increase the availability of soluble phosphate and enhance the plant growth by improving biological nitrogen fixation (Fig. 21.1) (Chaturvedi 2006). *Pseudomonas* spp. enhanced the number of nodules, dry weight of nodules, yield components, grain yield, nutrient availability, and uptake in soybean crop (Chauhan et al. 1992; Chela et al. 1993). Phosphate-solubilizing bacteria enhanced the seedling length of *Cicer arietinum*, while co-inoculation of PSM and PGPR reduced P application by 50% without affecting corn yield. Inoculation with PSB increased sugarcane yield by 12.6% (Chen et al. 2006). Sole application of bacteria increased the biological yield, while the application of the same bacteria along with mycorrhizae achieved the maximum grain weight (Chen et al. 2008). Single and dual inoculation along with P fertilizer was 30–40% better than P fertilizer alone for improving grain yield of wheat, and dual inoculation without P fertilizer improved grain yield up to 20% against sole P fertilization. Mycorrhiza along with *Pseudomonas putida* increased leaf chlorophyll content in barley. Rhizospheric microorganisms can interact positively in promoting plant growth, as well as N and P uptake. Seed yield of green gram was enhanced by 24% following triple inoculation of *Bradyrhizobium* + *Glomus fasciculatum* + *Bacillus subtilis* (Chiezy and Odunze 2012). Growth and phosphorus content in two alpine *Carex* species increased by inoculation with *Pseudomonas fortinii*. Integration of half dose of NP fertilizer with biofertilizer gives crop yield as with full rate of fertilizer; and through reduced use of fertilizers, the production cost is minimized and the net return maximized (Crew 1993). Mostly on farm crops using compost may have some limitations. For example, compost could be effectively used during the establishment of nursery in the field to increase the stock and maintain health of the plant. Crop nutrient management through integrated approach is an important aspect provided mainly by bio-, organic, and chemical fertilizers. However, it is widely accepted that the application of a balanced fertilizer with effective use of organic sources and beneficial microbes is key to achieving higher crop production and net return (Imran et al. 2016a, b). Agriculture scientists explore an alternative source to increase farm products with low-input cost and maintain soil health without effecting soil and plant environment. Plants obtain nutrients from two natural sources, organic matter and minerals or chemical fertilization. Farmers only rely on chemical fertilizer which not only deteriorates quality of soil but also increases cost of production. Soil amendments and biofertilization are integrated approaches to reduce dependency on chemical fertilizers with the advantage of low cost of production (Imran 2017). Crop response to biological fertilizers depends largely on crop species/strains of microbe and application method along with climatic conditions. It has been reported that using beneficial microbes reduces requirement of nitrogen 50–70% and increases yield up to 20%. Bacterial inoculation not only provides nitrogen, phosphorus, and growth hormones but also makes the plant healthy and less susceptible to pathogens. Application of beneficial microbes has the potential to reduce dependancy on synthetic fertilizers and to save about 1/2 to 2/3 of the recommended dose of chemical fertilizers (Imran et al. 2016a, b).

21.5 Impact of Biofertilization (*Azospirillum*) on Growth, Yield, and Quality of Pepper Chili

Devi et al. (2012) studied the effect of azospirillum, nitrogen, and NAA on growth and yield of pepper chili (*Capsicum annuum*) and observed that inoculation of azospirillum in seeds, soil, and seedlings increases plant height, the number branches, tap root length, and root spread. The emergence of the flower and 50% flowering were recorded earlier with biofertilization as compared with control. The same treatment increased number of flowers and fruits weight plants^{-1}. Enlargement in length and girth of fruit, number of seeds, weight of seeds and fruits, and fresh and dry weight of fruit was noted with beneficial microbe application. It was also noted that inoculation of biofertilizer led to a better absorption of nitrogen, phosphorus, and potassium. Devi et al. (2013) assess the possibilities of azospirillum and found that azospirillum strains were effective in nitrogen fixation and synthesis of plant growth-promoting hormones and

Fig. 21.3 Tangible view of soybean experimental plots at ARI with (+) biofertilization

for proteins, enzymes, and other factors that improve uptake of essential nutrients by plants utilized in farming (Fig. 21.3). They concluded that soil amendments and biofertilization are integrated approaches to reduce dependency on chemical fertilizers with the advantage of low cost of production. Crop response to biological fertilizers depends largely on crop species/strains of microbe and application method along with climatic conditions. It has been reported that using beneficial microbes reduces requirement of nitrogen 50–70% and increases yield up to 20%.

21.6 Impact of Biofertilization (*Azotobacter*) on Growth, Yield, and Quality of Crops

Diep et al. (2016a, b) noted the impact of vaccination azotobacter in crop yields and found the effect of vaccination of seeds and roots with azotobacter and concluded that growth and yield contributing parameters enhanced with biofertilization. Soil N and other fertility traits were varied with the application of *Azotobacter* by nitrogen fixation. Chen et al. (2006) studied the response of eggplant (brinjal), tomatoes, and cabbage to *Azotobacter*. They observed that organic manure when applied in conjunction with *Azospirillum* yielded a greater number of fruits with higher girth over nitrogen with organic manure. It is due to better mobilization of plant nutrients particularly N and P during later stage of plant growth. The findings revealed that *Azotobacter* has great potential to increase the production of crops (Figs. 21.2, 21.3, 21.4, and Fig. 21.5).

Fig. 21.4 Tangible view of mung bean (green gram) experimental plots at ARI with (+) and without (−) biofertilization

Fig. 21.5 Keen and carefull observation of the crop (soybean) treated with and without biofertilization at ARI Swat for phenotyphic variation

21.7 Impact of Biofertilization (PSB) on Growth, Yield, and Quality of Field Pea

Diacono and Montemurro (2010) reported the effect of biofertilizers and chemical fertilizers on growth of garden pea (*Pisum sativum*). Application of *Rhizobium* culture and phosphate-solubilizing microorganisms and fertilizers in combination with 50% of N:P significantly increased plant height, number of branches, and leaves per plant over control and chemical fertilizers. Crew (1993) reported that inoculation of seed and seedlings with microphosphate-solubilizing biofertilizers (PSB) can provide 30 kg P_2O_5/ha by solubilizing the soil phosphorus and applied phosphorus through fertilizers. The application of *Rhizobium* + PSM in combination with 50% of N:P boosted number of pods per plant, grains per pod, and ultimately pod yield over control as well as recommended dose (20:80:40) of chemical fertilizer (Fig. 21.2). The higher green pod yield is obtained due to application of PSM with recommended dose of fertilizers. This emphasized that at least 50% of economy on fertilizer use could be affected through consecutive use of biofertilizers along with half recommended level of fertilizer nutrients.

Alam et al. (2007) evaluated the response of onion to biological and chemical fertilizers and PSB vaccination noted that PSB greatly improved growth, yield, and quality attributes of onions. All levels of chemical nitrogen with PSB inoculation increased yield and quality attributes of growth. Plant height, number of leaves, and leaf length with fresh weight were enhanced with PSB inoculation. Dry matter content recorded for the leaves and dry matter content of total soluble solids were higher than non-inoculated plots.

Chen et al. (2006) noted that the characteristics of growth and yield and quality of the pea plant affected by biofertilizers and organic amendments. Pea seed composition and carbohydrates were considerably higher as compared to conventional fertilization.

21.8 Impact of VAM (*Vesicular-Arbuscular Mycorrhizae*) on Growth, Yield, and Quality of Vegetable Crops

Chela et al. (1993) evaluated the effect of N, P, and VAM on yield and nutrient uptake in chili and Bellary onion and observed that application of VAM in combination with 75% as well as 100% of the recommended doses of N and P provided higher yield of chili fruits than yield in chili fruits obtained from the plots of those that received 100% of the recommended doses of N and P. Inoculation with 100% of recommended dose gave the highest total dry yield. N and P contents in chili pods and P content in plant were significantly influenced by the N, P, and biofertilizers. N content in straw and P and K contents in both bulb and straw were significantly influenced by the application of biofertilizers alone or in combination with inorganic fertilizers. Cassman et al. (1981a, b) recorded the effect of salinity, phosphorus, and VAM on growth and yields of potato cv. Kufri Badshah. They observed that salinity, P, and VAM interaction revealed a significant improvement over control (no

VAM and P) in fresh and dry weight of shoot, tubers, and leaf number per plant at both the stages of growth. VAM inoculation improved fresh and dry weight of shoot and tubers, number of leaves, growth, yield, P concentration, and salinity. They observed that significantly higher fresh weight of outer leaves under press mud and VAM. There was significant improvement in number of inner leaves, head weight, and diameter when press mud was applied in soil and seedlings were inoculated with VAM. Similarly significantly higher head yield over control was registered with press mud and VAM. This treatment exhibited 22.6 more head yield over control (recommended NPK only).

Another study reported three different species of *Glomus* and a mixture containing all the above three species, along with a control that formed five treatments which were tested in four replications. Mixed inoculum of all the three VAM species proved significantly superior to the control with respect to final vine length, vine fresh and dry weight, number of primary branches, and leaf area. The VAM mixture also proved significantly superior to individual species for several characters. The plants grown in the soil with mixtures of all the three VAM species and which were grown in the soil having inoculation of individual species produced significantly more number of fruits, fruit weight, and yield per hectare when compared with control.

Diep et al. (2016a, b) recorded the response of field tomatoes for pollination toward VAM fungus. Red tomatoes with VAM fungus inoculation were collectively different in terms of yield, fruit size, number of fruits plant^{-1}, days to flowering, and other traits with other tested in the field. It was found that a substantial increase in shoot dry weight, nitrogen content, phosphorus content, and yield in comparison with the control inoculated. It has been observed that VAM fungus treatment alone increased growth and yield of tomato along with nitrogen and phosphorus content. However, in combination with other organic fertilizers produces additional effects on leaf area, shoot dry weight, yield, and phosphorus content in tomato crop (Azarmi et al. 2009).

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Mycorrhiza in Sustainable Crop Production

22

S. P. Singh and M. K. Singh

Abstract

Sustainable crop production is a complex issue, and available evidences suggest that mycorrhizal association with crop plants confers yield stability. We present a schematic flow diagram to outline practices that lead unsustainability or sustainability in the crop production. We critically discussed the issue of sustainability and the role of mycorrhiza in crop production. Conventional practices are posing threat to the biological processes and agroecosystem. Arbuscular mycorrhizal fungi form symbiotic associations with wide range of agricultural crops. Management options should address primary constraints to achieve desired success. This chapter reviews the effect of various management options like tillage, soil biodiversity and fertility management, crops and cropping sequences, irrigation and agroforestry systems on the abundance and diversity of the AM fungi and the plant response. Proper understanding of mutualistic association between arbuscular mycorrhizae and plant roots needed to exploit potential benefits. Long-term studies under diverse field conditions were required to know complex interactions that occur in the mycorrhizosphere and to harness potential benefits from mycorrhizal inoculation.

Keywords

Arbuscular mycorrhizal fungi · Sustainability · Tillage, soil biodiversity · Soil fertility · Crops and cropping sequences · Agroforestry

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Abbreviations

Al	Aluminium
AMF	Arbuscular mycorrhizal fungi
Ca	Calcium
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
NO_3^-	Nitrate
P	Phosphorous
PGPR	Plant growth-promoting rhizobacteria
S	Sulphur
Zn	Zinc

22.1 Introduction

The agricultural policies with the start of modernization were primarily focussed on enhancing food grain production and farm income in an equitable way. Demand of food grains and other agricultural commodities have an increasing trend because of growing population (Pretty 2008). Continuing with narrow focus on gaining only the crop productivity may worsen the agricultural production systems. Conventional agricultural practices are based on yield maximization through more soil manipulations, greater use of fertilizers and pesticides in intensive farming regions and repeated growing of the same cropping sequences. Minimum tillage, less use of fertilizers and agrochemicals are needed steps to favour AM fungi (Plenchette et al. 2005). Management of crop production depends upon environmental factors, soil condition besides genetic adaptation of the specific plant species to the local conditions. Technology options available to enhance capacity and management to address various biotic and abiotic stresses are stress-tolerant crops, suitable cropping systems, conservation tillage and rejuvenation of soils by promoting organic manure, biofertilizers, agroforestry systems and integrated farming systems may address to the current problems (Fig. 22.1). Two major issues elucidative are low efficiencies and danger in applying inorganic fertilizers alone. Developmental pathway followed so far has ensured quantitatively but qualitative outcome become pointer indicating major concern regarding depletion of natural resources. National Research Council, Washington, DC (1989), suggested safeguarding environmental health and quality, reducing costs and improving beneficial biological interactions as important considerations for sustainable systems. Technology support through research, education to farming communities, policy planning and methodologies

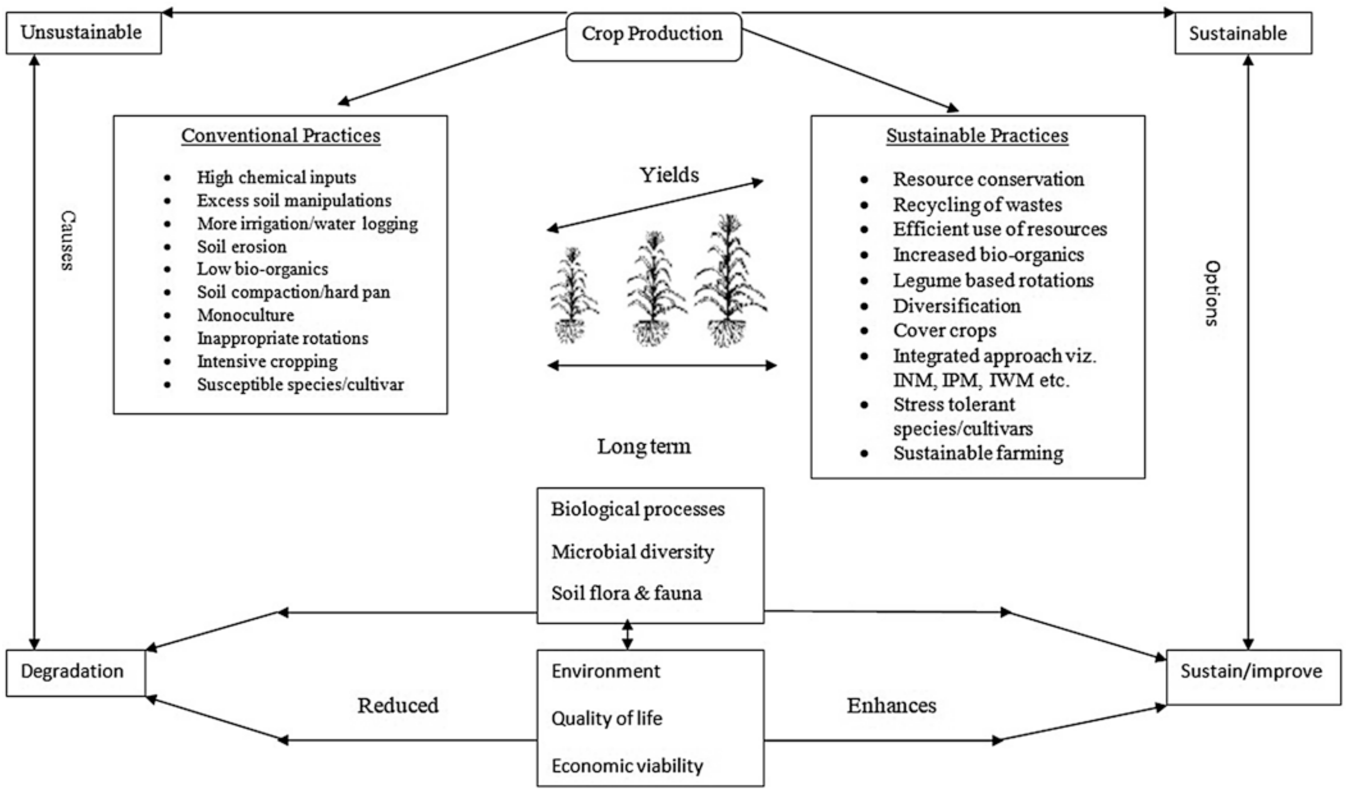

Fig. 22.1 Schematic view showing causes of unsustainable vs. sustainable crop production

designed to support extension and training systems may be the possible strategies for convergence.

22.2 Issue of Sustainability

Sustainable agriculture is a complex issue involving the effect of human-managed agricultural production systems and interaction with natural resources and systems over a long term. Efficient management of available resources may lead to sustainability of agricultural production systems over a time span. Farming systems, which maintain same level of productivity without decline in resources, economically viable to support farmer's livelihood are considered sustainable. Technology generation and its transfer models achieved self-sufficiency in production of food grains in several economies. The approaches adopted for raising crop productivity are now threatening the sustainability of the crop production systems. Sustainability in agricultural production systems will require desired changes in the current agricultural practices. No doubt, food and nutritional security has to be addressed but to sustain agricultural production, with environmental security (climate, edaphic and biotic factors) is a major challenge ahead. The apprehensions of sustainability versus production have to be clearly understood. This will need to reconsider the ground realities and to focus on multiple dimension overall improvement in agricultural production systems and their ecological functions. The goal of sustained agricultural production can be achieved through management of natural resources (sustainable use of biodiversity, land, water, vegetation, etc.). Faulty agricultural practices may cause yield reduction and adverse affect on biological processes, microbial diversity and agroecosystem (Fig. 22.1); consequentely raises question about sustainability of the agricultural production systems, its economic viability and quality of life. Sustainable crop production will largely depend upon conservation and efficient use of natural resources and their effective recycling.

22.3 Integrated Approach: A Path Towards Sustainability

Holistic approach for sustainable crop production management will depend on conservation practices, selection of appropriate cropping systems, inclusion of legumes in rotation, focus on stress-tolerant native crops and cultivars, maintenance of fertility even with reduced inorganic fertilizers, higher use of bioorganics, soil and water conservation and plant protection by cultural and biological alternatives. Integrated approach in management of nutrients, water, weed and pests may enhance sustainability of the agricultural production systems and is an important step towards sustainability. In the recent past, more emphasis is being given to the sustainable crop production systems to address the problems of stagnant and/or reduction in crop yields and to arrest or to improve continued soil and environmental degradation. With growing interest towards use of bioorganics and minimization of the chemical inputs are the targeted interventions to be attempted at wider scale. These practices may result in yield optimization, stability in production, recycling opportunities, reduced cost and enhanced profitability with overall improvement in the agroecosystem. A crop production system may be considered sustainable only when it maintains or improves the current productivity and fertility levels of soil over long term, not contributing pollution of any kind, economically viable and socially acceptable. Integration of methodological approaches needed to navigate from present hierarchical level agricultural system to a model of sustainability. Assessment of agricultural sustainability involves the farming system, cropping system, land management and agricultural sector at regional level (Zinck et al. 2002). Agricultural production systems suggested by earlier workers are based either on the complete use of biological processes or integrated approaches aim to reduce dependency on inorganic inputs by supplementation through organic and biological methods. Crop yields depend on yield building (genetics/variety, plant nutrition, site-specific precision planting for optimum population and moisture) and yield-protecting factors (control of weed, pest, lodging and harvest management). A suitable production system will require integration of yield building and yield-protecting factors. Such integration must be site and crop specific for optimization of the production system. Optimization includes environmental concerns, yields and economics (Alley 2002). Besides, soil constraints limiting productivity of the crops and the cropping systems and their management are interrelated. Crop response to the management options depends on addressing the primary constraints. Management decisions which target secondary constraints may not achieve desired success.

22.4 Soil Biodiversity and Agricultural Sustainability

Maintenance of soil fertility is the prerequisite for sustenance of crop production, and the role of microbes in nutrient management is well recognized. Biodiversity in and around the agricultural agroecosystems are of prime importance. Diversity in species of plants, vegetation, weeds, crops, varieties, livestock, pathogens, pests and predators influence crop production by their direct or indirect effects. Soil biodiversity includes a large number of microorganisms and is highly complex. Soil microorganisms are key driver for several biological processes like decomposition of organic matter, mineralization and nutrient cycling. Research challenges for agricultural sustainability are to understand soil biodiversity in resistance/resilience against stress and utilization of natural resources, management of soil biodiversity and valuing it (Brussaard et al. 2007). Strategic research aimed at utilizing and sustaining soil biodiversity for conservation of agrobiodiversity has to be streamlined (Perrings et al. 2006). Soil microbial diversity plays a key role in regulating processes of nutrient cycling and acquisition, suppressing harmful organisms and improvement in soil structure. Success in use of AM fungi for economic gain is linked with the suitable environment enabling AM fungal symbiosis development (Baar 2008). Most of the inhabitant plant species (>90%) form mutually beneficial relationship with AMF, and this association confers direct benefit in the growth and development of the host plants. Such symbiotic associations facilitate host plants for uptake of phosphorous and other minerals from soil, soil aggregation and stabilization, water uptake, protection against pathogens, reduction in stress and heavy metals pollution from soil through bioremediation. Mycorrhizal technologies may play multifarious role in future by reducing ill effects of inorganic agricultural inputs, addressing sustainable management of environment, land, diseases and in achieving profitability by low-input agricultural production systems (Aggarwal et al. 2011). Mycorrhizal fungi are biological resource used for stabilizing plant productivity and an important component for sustainable agricultural production systems. Only few plant species, viz. Proteaceae, Juncaceae, Cuperaceae and Chenopodiaceae, are non-mycorrhizal or exhibit restricted response. Molecular tools may add further to our knowledge base for successful production of the fungal inoculums at mass scale (Sharma et al. 2000). However, our current knowledge base and understanding is insufficient about the phenomenon of mycorrhizal symbiosis and its functioning in diverse ecosystems under field conditions. Long-term studies under diverse ecosystems are required based on mycorrhizal performance for the development of effective inoculants, continued long-term monitoring needed to assess their role on the ecosystem (Dodd and Thomson 1994).

Soil biodiversity confers stability against abiotic and biotic disturbance and stress in agroecosystem functioning. Studies indicate that soil microbial diversity provides protection against soilborne disease; however the management of crop and soil are also important considerations. Indirect biodiversity effect on soil fauna is apparent in modifying to nutrient and water use efficiency through effects on soil structure (Johansson et al. 2004). Physiological performance of crop, its productivity and quality depend on the rhizospheric characteristics and components. Most common mycorrhiza type is arbuscular mycorrhizal fungi (AMF), symbiotically associated with plant roots with wide variety of the crop plants and other rhizospheric microorganisms. Advance research on biotechnology techniques may open new vistas to harness potential benefits by arbuscular mycorrhizal inoculation to crops, farmers, consumers and agroecosystems (Dilean et al. 2011).

22.5 Mechanism and Role of AMF in Soil Fertility

The challenging task ahead is maintenance/improvement in soil fertility to ensure sustained agricultural productivity for generations to come (Meena et al. 2015). Mycorrhizae may be considered as an essential component while designing the sustainable agricultural systems, though these are not the sole biological alternative of fertilizers (Jhonson and Pfleger 1992). AMF association with plant is mainly mutualistic, where plant supplying sugar to obligate biotrophic fungus and fungus supplies organic mineral nutrition to plants, particularly immobile nutrient like phosphorus and zinc (Thompson et al. 2013; Lehmann et al. 2014). Actually, the AM extend their hyphae >10 cm from the root surface well beyond the P depletion zone of roots and root hairs (Jakobsen et al. 1992; Liu et al. 2007; Nayyar et al. 2009; Sheng et al. 2013; Thompson et al. 2013), thereby accessing large volume of immobile nutrients. Moreover, these hyphae also produce finer feeder extensions (~2 μm diameter) which enters into soil pores, from where roots are not able to extract the P in drier soil (Thompson et al. 2013). In fact, association with AMF provides an alternate nutrient assimilation pathway through extra- and intra-radical hyphae, arbuscules and the root apoplast interface (Parniske 2008; Smith and Read 2008; Lehmann et al. 2014). Actually, the AMF increases the plant growth and uptake of N, P, K, S, Ca, Fe, Cu and Zn (Pellegrino et al. 2015). It is essential to note that the AMF species performs differently with respect to hyphal growth, nutrient uptake and root colonization (Allen et al. 1995; Mehravaran et al. 2000; Munkvold et al. 2004) due to their diverse functional traits and life strategies (Chagnon et al. 2013).

It is noteworthy that AM fungal symbiosis mediates efficient utilization of nitrogen through transport via AMF. The crop receives small benefit by nutrition since the nitrate (NO_3^-) ions are freely mobile in the soil (Yang et al. 2014). Phosphorous, a major essential nutrient, is found deficient in about >40% of the global arable land. Soil phosphorous reserves are continuously depleted at a faster rate. The exploitable phosphorous deposits are finite and may disappear rapidly (Gilbert 2009). One of the ways to address this potential threat is to improve its uptake efficiency through mycorrhizal association. Proper management of soil phosphorous is required to sustain crop production particularly in the deficient soils by addition of organic manures, residue recycling and application of fertilizers (Balemi and Negisho 2012). AM fungi also enhance the mineralization of N from organic residues added to the soil (Hodge et al. 2001; Atul-Nayyar et al. 2009). Long-term (27 years) NP fertilization in a maize cropping system decreased AMF sporulation and diversity of AMF species. Reduced spore numbers were linked with higher phosphorous accumulation in long term. Variation in spore numbers and their relative abundance is observed among species and with sampling time. Highest occurrence of spore numbers at maize development stage for most species suggested their dependence on maize as host plant. On the basis of response to NP fertilization, AMF species were categorized as insensitive, slight sensitive and highly sensitive to fertilization. Insensitive AMF species (*Acaulospora*) found capable to colonize at a faster rate; confirmatory field studies needed under diverse farming situations to utilize such species more effectively (Bhadalung et al. 2005).

Chemical fertilizers are integral component of modern day agriculture and widely used to harvest maximum produce but are expensive. In general, application of chemical fertilizers (NPK) at recommended level showed adverse effect, while organic sources like FYM are beneficial for growth and activity of AMF. Fertilizers may affect the growth and colonization ability of AM fungi by altering concentration of soil mineral nutrition and N:P ratio of plant tissues, which in turn may stimulate the growth of AMF population (Johnson et al. 2003; Bhadalung et al. 2005; Toljander et al. 2008). Chemical fertilizers are widely used to harvest maximum produce but are expensive. Interactions between phosphorous fertilization and AMF under field conditions are not completely known. AMF application showed positive effect on yield attributes, yield and nutrient uptake (P, Zn and Fe) by maize crop. Repeated application of P at higher rate adversely affected mycorrhizal activity due to residual P (Treseder and Allen 2002; Mathimaran et al. 2007; Lekberg et al. 2008; Sheng et al. 2013), while best interacting response is observed at moderate level (Hagh et al. 2016). AMF helps in better utilization of low levels of available phosphorous (Yang et al. 2014). In fact, short-term phosphorous fertilization (<10 years) reduces the number of AMF spores in soil (Mårtensson and Carlgren 1994), but long-term fertilization (>10 years) improves the AMF spore density (Wu et al. 2011; Avio et al. 2013). Under low-nutrient environment conditions, these AMF play a significant role in phosphorous nutrition. Actually, phosphorus is transported via extra-radical hyphae of AMF as phosphate ions against a concentration gradient (Takanishi et al. 2009); these ions are converted into polyphosphate granules (Thompson et al. 2013), which are transported to the symbiotic interfaces located in root cortical cells (Thompson et al. 2013; Yang et al. 2014). Nutrient acquisition pattern by crop plants often varies with the plant species and soil conditions. Crops grown under acid soil face limited availability of K, Ca and Mg, generally more available at higher pH. Simultaneously, with rising soil acidity, there is enhanced availability and toxicity of Al, Fe and Mn. Under these situations, application of AMF, organic matter and phosphate rock enhanced the acquisition of nutrients such as P, K, Ca, Mg and S while it was reduced for Al, Fe and Mn (Alloush et al. 2000). Such practices encounter toxicities arising in the crops grown under acid soils and may avoid intensive application of phosphate fertilizers.

Invariably, Zn efficiency shown by plants varies with morphology and physiological traits of roots. For example, cereals have thinner, finer and branched root system resulted in better uptake of nutrients, but at the same time, reduced AM fungal root colonization (Newsham 1995; Tawaraya 2003). It is noteworthy that phytoavailability of Zn decline with increase in clay and organic matter content, cation exchange capacity and pH. Zinc acquisition improved by AMF associations under these situations (Armour et al. 1990; Alloway 2009). Overall, assessing the impact of AMF in Zn nutrition of plant is complicated because it has simultaneous effect on P nutrition also (Cardoso and Kuyper 2006). Enhanced P nutrition in plant resulted in improved plant growth and dilution of Zn in plant tissue (Cavagnaro 2008). Increased P nutrition leads to increased phytate content. Phytate being an anti-nutrient chelating agent reduced the bioavailability of Zn. In rice, phytate, Zn molar ratio ranges from 3.07 to 11.27; however, the ratio more than 15 is associated with reduced Zn bioavailability (Singh and Prasad 2014). But, later on, Subramanian et al. (2013) observed that AMF are able to reduce the phytate concentration vis-à-vis enhance the Zn content in maize seed; however, Ryan et al. (2008) could not detect this phenomenon under field condition. Meta-analysis of 263 trials reveals that AMF had a positive effect on Zn concentration in all tissue types and was modulated primarily by soil texture (Lehmann et al. 2014).

Organic farming systems dependent on farm organic manures and legume-based rotations are potential alternative to the conventional systems. These systems provide efficient utilization of resources and enhance floral and faunal diversity. Long-term study (21 years) showed organic systems reduced crop yields (winter wheat, potato tuber and grass-clover) by 20%, but the demand for fertilizer input (NPK) decreased from 34–53% than conventional. Moreover, organic production systems resulted in higher root colonization (40%) by mycorrhiza (Mader et al. 2002) require less external inputs and dependent on farm-generated inputs to the maximum possible extent. Future strategies for soil fertility management have to focus on less use of external inputs and exploitation of potential benefits from rhizospheric microorganisms. Mycorrhization helper bacteria, AM fungi and PGPR association with plant and their interactions had synergistic effects on mycorrhization. Development of multi-agent biofertilizer technology may be easily popularized among the farmers. However, to exploit the potential benefit of improved mycorrhization, understanding of complex interaction and mycorrhizosphere is required by field investigations (Shirmohammadi et al. 2014). Enhancing plant tolerance against environmental stresses like drought, salinity, heavy, metals, etc. and limiting growth and productivity of plants are major challenge to sustain crop productivity. AMF inoculation technology holds enormous potential to mitigate the effects of abiotic stresses. Besides all the above benefits, this technology is poorly accepted by farmers due to high product price, because of high cost of inoculums production. Thus, extensive adoption of technology will primarily require a large-scale production of AMF inoculants and its availability at the reduced cost. Therefore, technological advances to develop imperative methods and more research under multi-environment are essentially needed (Kapoor et al. 2013).

Biofertilizers play key role in augmenting soil fertility and productivity and targeted to increase the availability of nutrients particularly nitrogen and phosphorous. Synergistic effect of biofertilizers, including AMF alone or co-inoculation, on crop growth and yield has been reported by many workers. In fact, the ultimate plant response termed as synergism may be cumulative effect of several mechanisms and processes such as N-fixation, mineralization and mobilization of nutrients, growth promoting substances and production of antibiotics. Combined use of organic manures with biofertilizers increases the activity of microorganisms and ultimately the overall effect. AMF inoculation or co-inoculation (AMF + *Azospirillum*) with NPK fertilizers produced higher chlorophyll, cob and fodder yield and root biomass of winter baby corn than sole application of NPK fertilizers. Higher quantity of inorganic fertilizers reduced partial factor productivity of nutrients with or without biofertilizers but noted higher with biofertilizers. Fertilizer response doses were observed minimum when supplemented with the biofertilizers (Sharma and Banik 2014).

It is true that intensive cropping systems require huge quantities of readily available nutrients, which cannot be supplied by organic sources, but, at the same time, sole dependence on inorganic fertilizers adversely affects the soil physical and biological properties. Thus, the combined use organic and inorganic resources may address the problem of sustainability, soil health and pollution. Integrated nutrient management involves inorganic fertilizers, organic manures, biofertilizers, crop residues and inclusion of legume crops in rotation. The most critical issue to sustain production at an optimum level will depend on the fact that how best we integrate these sources. Since choice of crop and land use varies in accordance to places, ecological and socioeconomic conditons. Inorganic fertilizers supply essential nutrients quickly to the crop plants, while organic sources improve their availability slowly for prolonged period. On the other hand, organic sources play vital role in improvement of physical, chemical and biological conditions of the soil and lead to gradual build up of organic carbon. Thus, conventional systems require modification to decrease their dependency on inorganic fertilizers (Nelson and Spaner 2010). Mycorrhizal inoculation and conjunctive fertilizer use showed significant yield response and enhanced soil fertility and nutrient use efficiency over the alone use of either inorganic (NPK) or organic manures. Integrated nutrient supply at optimum dose increases the available soil phosphorous status in comparison to the suboptimal, optimal and super optimal doses of NPK. Direct supply of nutrients by inorganic fertilizer improves soil phosphorous, and the magnitude of increase is positively correlated with the level of phosphorous applied (Laxminarayana et al. 2015). Other management options are to utilize phosphate solubilizing microorganisms in an integrated manner. Exploring the possibilities of phosphorous management through biological processes and bioorganics will reduce fear of soil phosphorous depletion. Limited knowledge about microbial interactions and mechanisms associated with the AM fungi, problems in culturing, spatial and temporal variations in mycorrhizosphere are the major limitations. Improved understandings on such aspects are important for sustainable crop production and soil fertility management (Johansson et al. 2004).

22.6 AMF Response to Tillage

Agronomic activities like tillage operation significantly influence AMF activity (Säle et al. 2015). A network of hyphae is produced in root rhizosphere in association with plant roots. Early review by Miller et al. (1995) clarifies that soil disturbance by tillage reduces the effectiveness of AMF symbiosis in mycorrhizal associated crops like wheat and maize and simultaneously reduce phosphorous absorption by plants (McGonigle and Miller 1996; McGonigle et al. 1999). Disruption of extra-radical mycelium causes reduced phosphorous absorption but may not lead to a change in mycorrhizal colonization (McGonigle et al. 1990; McGonigle and Miller 1993). Species composition and diversity varies with farming system and tillage practices. Low-input and extensive land use systems have positively influenced the AMF; therefore the crops grown under such conditions may receive more benefit from the AMF (Mäder et al. 2000; Njeru et al. 2015). As Säle et al. (2015) mentioned that increase in tillage intensity reduces spore density and the community compositions are also changed. Invariably, zero till practice increased spore density and species richness in top soil than the ploughed soil (Säle et al. 2015; Brito et al. 2012). Moreover, conventional and low-input farming systems both exhibited greater colonization potential at the end of growing season in no-till compared to chisel-disc and mouldboard tillage practices (Galvez et al. 2001). It is noteworthy that zero till helps in continuity of the AM hyphal network which remains undisturbed; the succeeding crop rapidly connect to this network and thereby enhances nutrient absorption capacity (Kabir 2005). Galvez et al. (2001) seen abundant *Glomus occultum*, *G. occultum*-like spores group and *G. geosporum* in no-tilled soil with low-input application. However, *G. etunicatum* and *G. etunicatum*-like spores group were more abundant in conventional tilled soils. Avio et al. (2013) reported predominance of *Funneliformis mosseae* species sporulating in tilled soils while *G. viscosum* and *G. intraradices* prevailed in no-tilled soils. More occurrence of *Scutellospora* was found in low-tillage fields, whereas *Glomus* was dominant in high-tilled fields (Jansa et al. 2003); tillage led soil disturbance favours the growth of fast-growing species that might be less mutualistic and less efficient in improving host plant nutrient uptake (Kabir 2005). In general, there is gradual decline in mycorrhizal inoculum potential in natural and disturbed soils with increase in soil depth (Schwab and Reeves 1981; Zajicek et al. 1986). Findings of few experiments suggest more concentration of spores at comparatively greater depth of 30–45 cm (Ananth and Rickerl 1991), whereas others favour higher concentration of spores in top 8 cm under no-till and 8–15 cm soil in tilled fields (Abbott and Robson 1991). Later, it was concluded that spore population at certain depth depends on sampling time, host crops, farming system, spore type group and tillage practices (Douds et al. 1995).

22.7 AMF Association with Crops and Cropping Sequences

A sound farming system is a potential option to meet food demand and maintain/upswing agricultural growth on eco-friendly and sustainable basis. The system of production adopted in the past had been exploitative, led to degraded crop ecosystem and life supporting environment. Most of the evidences suggest that mycorrhizal association provides benefit to several plant types, viz. field crops (cereal and legumes), horticultural and transplantation crops. More occurrence of AMF in cultivated lands has been reported than in noncultivated (Gupta and Mukerji 2001). AMF may improve post planting survival rate and growth of micropropogated plantlets via bio-hardening, active uptake of nutrients, increased tolerance to drought, pest and diseases and also enhances yield of horticultural crops (Singh et al. 2015). AM biotechnology may be utilized as biofertilizers and bio-protectors to improve plant health. Development of appropriate management may cause reduction in chemical fertilizers and pesticides. To derive maximum benefits from AM inoculation, selection of efficient AM fungi and its compatibility with the host plant are important considerations (Aguilar and Barea 1997). Crop rotation is known to influence the development of mycorrhizal colonization. Selection of crops, cropping sequence and their order in rotation, cropping history, soil phosphorous concentration and synergism with rhizobia may affect AMF root colonization and sporulation in soil. Growing of nonhost crop or bare fallow leads to reduced AMF spore density in the succeeding crop. Maintenance of AMF spore density can be achieved either by growing AMF compatible crops or by application of inoculums. Variable responses are obvious in different agroecological zones. Natural nutrient cycling, microbial diversity and AMF community may be promoted by managing the cropping systems. Conventional and organic cropping systems may promote soil diversity if intercrops are grown.

Nitrogen is the most important yield-limiting primary nutrient usually found deficient in agroecosystems. Strategies through alterations in cropping system can enhance nitrogen availability mainly by inclusion of legume crops in rotation. A legume crop fixes atmospheric N through symbiotic relationship with rhizobia, and the subsequent crop also receives considerable benefits. Traditional mixed cropping, intercropping, alley cropping and lay farming (forage grass-legume mixtures) are systems known to provide benefits to non-legume companion crops involved in above systems. In forage systems based on mixture of legume and cereals, extra-radical hyphal networks of AMF facilitate the transportation of N from nitrogen fixing plant to the companion grasses (Chalk et al. 2006; Yang et al. 2014). Plant and soil microorganisms compete for the soil available N, and large hyphal network of AMF offers a pool of available N to the crop, inaccessible to the competing microorganisms (Whiteside et al. 2009; Yang et al. 2014). Growing of legume and grass mixtures together in a forage production system (Lay farming) helps in transfer of N fixed by the legumes through their extra-radical hyphal network. AM-dependent species show a competitive advantage and benefited over others. Increasing the proportional populations of legumes in pasture fields would improve the productivity and reduce dependence on N fertilizers (Yang et al. 2014). The mechanisms of N-transfer from legumes to non-legumes and their uptake by non-legumes occur in three ways, i.e. root exudates, decomposition of roots and nodules and transfer mediated by mycorrhizae. Several abiotic (soil available N, addition of fertilizers, temperature, light and water stress) and biotic factors (plant density of legumes and non-legumes, growth stage, root contact, root herbivores and defoliation) affect the below ground N-transfer. Biotic factors can be managed by agronomical practices, e.g. choice of crop species, cultivar and plant density. Finally, the selection of appropriate crop combinations with desired traits may open new avenues for improving nitrogen transfer in intercrops. Thus, holistic approach should focus identifying nitrogen transfer routes and constraints in N-transfer between donors and receivers in agroecosystems for improvement (Thilakarathna et al. 2016). Gain in biomass production and nutrient uptake (shoot N content) of turmeric noticed due to AMF inoculation in glasshouse conditions, but no such effect observed under field conditions. Hence, benefits from AMF inoculation can be obtained when native soil population is low or ineffective (Yamawaki et al. 2013). Increased growth, number of nodules, nodule weight and nutrient content are observed due to inoculation of AMF in nodulating plants. Combined application of compost with AMF inoculation can improve nodulation, mycorrhizal infections and AM propogules and is able to substitute inorganic fertilizers. Inoculation of effective AM fungi in nodulating plants may be done as a component of soil restoration strategy in nutrient poor soils to enhance N–fixation and yields (Salami 2007).

Large variations observed in AMF colonization and spores were positively related with soil P concentration. No effect of rotation found in a soybean-maize sequence and previous crop failed to influence mycorrhizal colonization in maize. However, higher mycorrhizal colonization and more diverse AMF species found in both the crops where rhizobial inoculation was done in soybean compared to non-inoculated one (Sanginga et al. 1999). Growing of cereals after legumes in sequence has been found to increase the yield of cereals. In fact, cereals in rotation with legumes had early and higher AMF infection rate and increased availability of mineral N due to N fixation than continuous cereal rotation. Performance of legume species is also found variable; thus, choice of crop is important in stabilizing cereal yields in rotation. Groundnut has been found better option than cowpea in millet-based rotation (Bagayoko et al. 2000). Enhanced growth, yield, AMF colonization and P uptake were found with soybean when grown after wheat (host) than rapeseed (nonhost). AMF colonization ratio and soybean yield had significant correlation but not with spore density. Other factors also influence AMF colonization and are not governed by spore density alone (Isobe et al. 2014). Thus, crops with stimulatory and carry-over effect up to next season (groundnut) are effective than others (cowpea and finger millet) (Harinikumar and Bagyaraj 1989).

Practice of bare fallowing for prolonged period to control weeds and maximize soil water storage during fallow period results stunted crop growth and leaf chlorosis because of ‘P’ and ‘Zn’ deficiency. Under less severe condition, poor growth during early crop phase was noticed without showing any clear symptom. This phenomenon is called ‘long fallow disorder’ found associated with poor colonization of AMF in crops after a long bare fallow period (Thompson 1987, 2013). However, the severity of problem depends on the mycorrhizal dependence of crop species, amount of AMF inoculum in soil, duration and frequency of fallow and availability of P and Zn in soil (Thompson 1991, 1994). Higher AMF colonization and subsequent improvement in maize growth reported when soybean grown as preceding crop compared to fallow (Higo et al. 2010). Keeping the field fallow for prolonged period or inclusion of a nonhost in rotation reduces AM fungi populations. Strongest effect was noticed due to breaking the cycle by growing nonhost canola as a first crop delayed mycorrhizal colonization in succeeding maize. The inhibitory effect lasts within 3 months of maize cropping (Gavito and Miller 1998). Reduced growth and biomass of early season flax noted when grown after canola compared to wheat-flax rotation. Canola-flax rotation caused reduced colonization of AM fungi. No inhibitory effect observed when flax grown after wheat crop. Maximum uptake of nutrients (copper, phosphorus and zinc) by flax occurred after wheat seems to relate nutrients immobility in soil and mycorrhizal stimulation (McGonigle et al. 2011).

Arbuscular mycorrhizal fungi are generally found in abundance in natural ecosystems than managed ecosystems. Variability in mycorrhizal root colonization and spore density in rhizosphere often found associated with the soil factors like organic carbon, pH and available nutrients. Soil characteristics, viz. soil organic carbon, available N and P, indicated positive correlation with spore density in a low-input cropping system. Results stressed that with selection of well adopted naturally occurring species, no limiting value of soil nutrients found to increase or decrease spore density (Harikumar 2015). Field survey on four cropping systems non-rice (dryland), rice (upland), flooded rice (one crop/year) and flooded rice (two crops/year) shown greater root colonization and spore density in vertisol than regosol. Flooded rice reduced colonization and spore numbers, while trend was reverse for dryland crops and upland rice. Prolonged flooding reduces AMF colonization and spore numbers though sufficient colonization occurs after transplanting of rice seedlings. Incorporating non-rice crops in rotation with flooded rice will lead to restoration of AMF populations again after rice season. Research efforts needed to find out potential crops after flooded rice in order to improve AMF colonization during non-rice season (Wangiyana 2006). Current knowledge base is limited on root dynamics and its turnover in different cropping systems. Crop root growth and its turnover differ under varied nutrients and moisture availability in soil and under stress conditions. Increased understanding about measurement of root turnover needed to judge effectiveness of cropping systems for sustainable agriculture (Goss and Watson 2003). Cropping systems and the cultivation practices are important component affecting mycorrhizal infectivity and spore density under field conditions. Large data and information's generated on conditions which favour AMF colonization. Replacement/shifting from current cropping systems are difficult. Necessary adjustments can be done within the boundaries of the cropping systems for stepping towards sustainable crop production. Development of new methodologies to judge behaviour of AM fungi and models is required based on long-term field experimentation (Plenchette et al. 2005). Long-term studies on conventional and low-input cropping systems indicated identification, isolation and culture possibilities for development of fast colonizing AMF inoculants for use in agriculture and horticulture (Vestberg et al. 2011). Application of AMF inoculums in granular form to agricultural field requires high cost. Thus, seed coating has potential to substantially reduce the cost of application vis-à-vis improves its efficiency (Oliveira et al. 2016).

22.8 AMF Response to Irrigation

Mycorrhizae association has been found to increase the survival capacity of plants under moisture stress condition, more particularly during the early growth phase (Table 22.1). AM fungi (*G. etonicatum*) produced higher total biomass and harvest index with increase in the irrigation interval in the sterilized soil (Bolandnazar et al. 2007). Inoculation of ectomycorrhizae on *Pinus* species resulted enhanced survival of seedlings at moderate frequency of irrigation. Low or high frequencies of

Table 22.1 Effect of AMF in mitigation of water stress

Crop	Beneficial response	References
Grape (*Vitis vinifera* L.)	Enhanced field survival of plantlets	Singh et al. (2011)
Citrus (*Citrus jambhiri*)	Drought, nutrient uptake and physiological and biochemical adaptation	Dutta et al. (2015)
Wheat (*Triticum aestivum*)	Higher biomass, grain yield, shoot P and Fe	Al–Karaki et al. (2004)
Citrus (*Poncirus trifoliata*)	Improved biomass and soil structure	Wu et al. (2008)
Lettuce (*Lactuca sativa*)	Enhanced growth and nutritional quality	Baslam et al. (2011)
Basil (*Ocimum grattissimum* L.)	Enhanced oil yield and chlorophyll content	Hazzoumi et al. (2015)
Millet (*Panicum miliaceum* L.)	Yield components and yield	Arab et al. (2013)

irrigation could not affect mycorrhization. Hence, mycorrhizal inoculation together with the artificial watering may be utilized to address the prolonged drought (Atala et al. 2012). Addition of AM fungi (*G. fasciculatum*) improved yield components and yield of millet under both optimum irrigation as well as drought conditions (Arab et al. 2013). Similarly, improved physiological (stomatal conductance, relative water content and photosynthetic rate) and biochemical (proline, chlorophyll a and b, total carotenoids and phenol) changes observed in *Citrus* plants after AMF inoculation under water deficit conditions (Dutta et al. 2015). Thus, results indicate the possibilities of mycorrhizal inoculation to mitigate drought stress. Jayne and Quigley (2014) carried out a meta-analysis to assess the research work conducted on the plant response under water stress which it revealed that mycorrhizal association enables plants for better growth and reproduction. Perennial vegetation responded more favourably due to improved colonization and symbiosis compared to the annuals. Improvement in the above ground biomass observed higher than the belowground (root length or dry weight).

22.9 Mycorrhizas in Agroforestry Systems

Agroforestry is a land use that involves deliberate retention, introduction or mixture of trees or other woody perennials in crop/animal production field to benefit from the resultant ecological and economical interactions (Nair 1984). In subsistence economies, destruction due to ruthless cutting of trees/shrubs continued by local farmers to fulfil their daily needs for forest products (mainly fuel wood). Such dependency poses threat to sustainable development by adversely affecting biodiversity and ecology (Bargali et al. 2008). To achieve sustainability in agricultural land use and ecology, the production system has to maintain equilibrium between utilization of natural resources as input and in optimizing the production of agricultural commodities as output. Agroforestry systems may be one of the most practical and viable option for growing shrubs/trees with agricultural crops in intimate combination. Agroforestry systems are efficient and capable to deal for sustained production, improvement in environment and ecology, economically beneficial and socially useful because of diversified products. Agroforestry systems may sustain production even on fragile land with existing low external input agriculture prevalent in many areas. These systems can contribute both protective and productive functions. Rehabilitation of degraded lands, improvement in soil fertility, stability in production and conservation of soil and water may lead to improve biodiversity and ecosystems to sustain agricultural production. Integration of trees with crops would lead to a self-sustaining and ecologically sound land use system for long term.

Agroforestry systems possess tremendous potential of efficient land utilization, recycling residues and nutrients, promoting positive interactions between crop and tree components by reducing competition and improving soil microflora and microfauna; carbon sequestration benefits minimize environmental load and optimize overall efficiencies. Appropriate management practices required to harness the maximum benefits from chosen agroforestry system. *Acacia nilotica* (age series 6–20 years) in traditional agroforestry system showed reduced biomass and yield (37.73% to 68.49%) of gram crop compared to open field. Reduction in gram yield was positively correlated with tree age, crown diameter and diameter at breast height (DBH). Study suggests regular pruning of trees to reduce the competition during the crop season (Bargali et al. 2004). The interactions between the components must be positive to the maximum possible extent. Sustainable benefits may be obtained through careful selection of its structural component species and proper considerations on its spatial and/or temporal arrangements. A critical understanding of associated components and biological interactions between them is required to derive maximum benefits and enhanced sustainability of the system. Component crops selected in an agroforestry system must be least competitive and well adapted to specific location. Benefits due to symbiotic association of AMF were found with most of the higher plant species (82%) (Brundrett 2002). Arbuscular mycorrhizal relationships with the plants are one of the most important rhizospheric interactions that significantly contribute to maintain or increase soil fertility besides plant health (Jeffries et al. 2003). Different plant species and soil parameters affect abundance of AMF. Reduction in soil nitrogen and phosphorous concentrations (moderate to low) has been found to enhance spore density and AMF root colonization than higher concentrations in rhizospheric soils. AMF colonization appeared highest for shade trees in comparison with the perennial crops intercropped. Agroforestry plants usually vary significantly to each other regarding spore density and AMF root colonization (Dobo et al. 2016). Local AMF isolates indicated better plant height and biomass of neem (*A. indica*) seedlings inoculated with consortia (mixed inoculums) than individual AMF species, though P uptake and root colonization were maximum with individual species (*G. intraradices*). Such variations among species are obvious and call for the identification of growth enhancing AMF species for various forest tree species (Banerjee et al. 2013). Seedling inoculation with AMF (*G. aggregatum*) in a phosphorous deficient soil exhibited many fold higher P concentration in shoot of multipurpose fruit trees tamarind (*Tamarindus indica*) and jujube (*Ziziphus mauritiana*) as a result of higher root colonization. Total dry weight of fruit tree species enhanced (3–4 times) than control. Such findings elucidate the need to inoculate fruit tree seedlings with specific effective AMF species identified (Guissou 2009).

Conventional agricultural practices have been found to produce inverse impact on diversity and wide occurrence of AM fungi. Diversified agricultural practices like hedge row intercropping can increase the diversity and abundance of AM fungi. However, some studies also indicate negative or zero effect on AM fungi compared to conventional agricultural systems. Diversity in AM fungal community has no relationship with soil factors and land use intensity. Thus, whether the native AMF is enough for sustainable production or not, it cannot be judged by soil conditions. Hence, farmers should inoculate their crops with specific mycorrhiza for sustainable crop production rather than to depend on native AM fungal community (Castillo et al. 2010). Large variations in agrotechniques, interaction between the component species and the prevailing agroclimatic conditions may affect mycorrhizal associations and its intensities. Overall, the tropical regions showed variable responses because of tree-based systems on AM fungal community but in general the effects are positive (Bainard et al. 2011).

22.10 Conclusion

Agricultural policies now are focussing on development of the sustainable crop production systems to safeguard agroecosystem health at a reduced cost. Faulty conventional practices are threatening to sustainability of the agricultural production systems and adversely affecting agroecosystems. Technology and management options are able to address the root causes for unsustainability of the conventional agricultural production systems. Sustainable crop production in near future will largely depend upon conservation practices, selection of site-specific appropriate crops and cropping sequences and reduction in chemical fertilizers with enhanced faith in organic and biofertilizers. Integrated approach in plant nutrition management may provide solutions to the current problems. Biodiversity of the above and below soil is of prime importance; strategic research and long-term studies under diverse condition are needed for clear understanding of rhizospheric microorganism's interaction to derive maximum benefits. The AM fungi relationship with the plant species may be efficiently utilized to address the current challenge of sustainable crop production. In fact, AMF symbiosis with crop plants mediates to mitigate abiotic stresses like drought, supply of essential nutrients and crop protection. Maximum benefits from AMF can be derived with knowledge and development of accurate inoculation technique, selection of efficient strains and compatibility with crops and cultural practices. Agroforestry systems may play significant contribution since most of the higher plant species form symbiotic association with AMF, thus, may be utilized as an important component in stabilizing plant productivity. Advance research on biotechnology techniques is required for development of imperative methods under multi-environment to harness potential benefits from AM fungi.

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The Role of Mucuna pruriens in Smallholder Farming Systems of Eastern and Southern Africa: A Review

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Abstract

Smallholder farmers in eastern and southern Africa face various food production constraints that have resulted in high food insecurity problems. The smallholder cropping systems are affected by poor rainfall distribution, high drought frequencies, poor soil fertility status, limited access to adequate inputs and lack of knowledge among others. The situation has been further worsened by increasing variability in climate. To improve food security, enhance soil conservation and fertility and boost livestock feed in different cropping systems, use of legumes such as velvet bean has been recommended. A literature study has been carried out aiming to review research findings on the roles of velvet bean (*Mucuna pruriens* L.) in African smallholder farming systems with emphasis on food and feed provision, soil fertility improvement and soil erosion control. The review found that velvet bean adapt very well within the tropical climate, but its uptake in smallholder farming systems in the region remains low. Velvet bean provides food in the form of seed grain after careful processing using different methods

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including soaking the seeds in running water for 72 h or soaking in water for 48 h with 12 h water replacements, among other methods. It can be integrated into smallholder farming systems through intercropping with other crops, crop rotations, relay cropping and as a sole crop. Velvet bean has high protein concentration (23–35%), which can help reduce the protein deficiency gaps for resource-poor farmers. It has also been used as a medicinal plant. The crop can be used as green manure cover crop to improve soil fertility and as source of soil cover which helps reduce the impact of raindrops which reduces runoff and soil erosion. Velvet bean fixes more nitrogen when compared to other legumes, 34–108 kg atmospheric nitrogen, which helps improve soil fertility. The crop may also be utilised as livestock feed through use of grain seed and the crop residues which both increase the protein availability to the animals. Velvet bean also smooths weeds due to high growth rate and biomass production, which may reduce weed density up to 92% when rotated with maize. In summary, velvet bean has multiple functions which have potential to improve smallholder farmer's livelihoods through increased livestock and crop production.

Keywords

Africa · Crop-livestock · Legumes · *Mucuna pruriens* · Smallholder farmers

Abbreviations

°C	degree Celsius
AN	ammonium nitrate
BNF	biological nitrogen fixation
C	carbon
C:N	carbon-nitrogen ratio
CA	conservation agriculture
CGIAR	Consultative Groups for International Agricultural Research
L-Dopa	L-3,4-dihydroxyphenylalanine
masl	metres above sea level
mm	millimetre
N	nitrogen
P	phosphorus
PAN	plant-available nitrogen

23.1 Introduction

African crop production and productivity needs to increase significantly by 2050 to meet the food demands of the growing population that is currently rising by 2.4% per year (Alexandratos and Bruinsma 2012). Meeting such a demand is challenging when one considers the likely impact of climate change in the smallholder farming sector. Smallholder farmers' crop yields are generally low due to various constraints such as limited access to adequate inputs, poor weed management, low and unpredictable rainfall, limited knowledge on improved cropping systems and continuous soil degradation among others (Warren 2002; Evans 2013; Muoni and Mhlanga 2014; Adhikari Umesh et al. 2015). Such problems have often resulted in food insecurity among smallholder farmers. The smallholder farming systems in eastern and southern Africa are mainly characterised by high population densities that result in high pressure on land to produce food and feed for humans and livestock (Giller et al. 2009). To address these problems, numerous solutions have been suggested which include increasing legume diversity in crop-livestock systems and promoting climate-smart agriculture to conserve and make more efficient use of natural resources (Descheemaeker et al. 2016; Ncube et al. 2016).

Increasing legume diversity in eastern and southern African smallholder farming sectors has great potential to address food, feed, income and soil degradation problems (Haque and Jutzi 1984; McIntosh and Topping 2000; Graham 2003; Mpairwe et al. 2003). Among the legume species that have great potential in offering all these functions is velvet bean (*Mucuna pruriens* L.). The crop is underutilised in Africa (Afolabi et al. 1985) although (Mhlanga and Thierfelder 2015) reported that it is one of the most studied cover crops in southern Africa. Velvet bean was originated from southern China and eastern India, where it was widely cultivated as a green vegetable crop (Tegge 1982). It is one of the most popular green crops in the tropics used as food (Lampariello et al. 2012). Velvet bean seed has been reported to be high in crude protein and carbohydrates and provides crude lipid and dietary fibre (Achinewhu 1982). However, the grain seed of velvet bean contains *L-Dopa* that has been reported to be toxic, and it must be soaked in water for 24 h replacing water every 12 h, among other methods, before it can be eaten. The plant is also used as a medicinal plant, and its chemical compound is used to treat Parkinson disease (Brain 1976; Siddhuraju et al. 1996). Velvet bean can yield approximately 3000 kg ha^{-1} of grain, in sub-Saharan Africa, which may significantly contribute to smallholder farmer's food requirements and income generation depending on market conditions (Okito et al. 2004; Maasdorp et al. 2004). The grain seed can be used to make porridge and coffee after considerable processing, thus reducing protein deficiencies in smallholder farming systems (Diallo and Berhe 2003).

Velvet bean fixes considerable amounts of atmospheric nitrogen (N) (e.g. 34–108 kg N ha^{-1}, measured in Uganda) through biological nitrogen fixation (BNF) (Kaizzi et al. 2004). Such a characteristic is important in smallholder farming systems in east and southern Africa where fertilizer use is minimal. To benefit from the fixed nitrogen, the crop residues of velvet bean have to be retained on the soil, and these will decompose to release N into the soil for uptake by plants (Prasad and

Power 1991; Erenstein 2003). In addition, retention of crop residues promotes soil biological activities that facilitate soil aggregation and soil organic matter build-up, reduce soil erosion through tumbling rainwater runoff and thus improve rainwater-use efficiency (Kumar and Goh 1999; Mutema et al. 2013; Abera et al. 2014). The velvet bean crop residues are a good source of high-quality livestock feed that has been reported to increase meat and milk production (Matenga et al. 2003). Thus, integrating velvet bean into the cropping systems has potential to improve smallholder farmers' livelihood. This paper aims at providing an overview on the potential of velvet bean in smallholder farming systems in eastern and southern Africa. The literature review focuses on past research on velvet bean and identifies its niche in smallholder farming systems.

23.2 The Agroecological Requirements of Velvet Bean

Although velvet bean has in many studies exhibited considerable tolerance to the unfavourable conditions that most smallholder farmers face, it has specific growing requirements that control its productivity. Its capacity to maintain reasonable productivity under suboptimal conditions makes it very suitable for integration into crop-livestock systems in different regions. The crop prefers hot and humid areas, which receive 1000–2500 mm rainfall annually, but the crop is also successful in areas with 400 mm annual rainfall (Whitmore 2000). Velvet bean can do well in a wide temperature range: 20–30 °C (Buckles 1995). However, compared to lablab (*Lablab purpureus*) and other legumes that can be integrated in crop-livestock systems, velvet bean has shown considerable tolerance to low temperatures and moisture levels usually experienced in early winter. In a study conducted in the subhumid parts of southern Africa, velvet bean exhibited favourable biomass productivity even when grown as a relay crop into a maize system at different periods of the season (Mhlanga 2016). In addition, velvet bean can do well in areas up to 2100 meters above sea level (masl), but to ensure a reasonable grain harvest, 1200–1500 masl is optimal. Velvet bean performs well in well-drained soils of medium to high soil fertility within 5.0–8.0 soil pH range.

23.3 The Potential Niche of Velvet Bean in the Smallholder Farming Sector

The productivity of velvet bean has been better than most other leguminous and nonleguminous cover crops across Africa; for example, its biomass productivity has been shown to be about 300% greater than cowpea [*Vigna unguiculata* (L.) Walp] in a clay soil under subhumid conditions (Mhlanga et al. 2015b). Due to its flexible characteristics described in the previous section, velvet bean is a useful legume in smallholder crop-livestock production systems. However, despite its adaptability to a wide range of environmental conditions, to increase the adoption of velvet bean within the smallholder farming system, its roles should be clearly defined through identification of its optimal niche within the system. Velvet bean can be integrated into smallholder farming systems through intercropping with other cereals, crop rotations, relay cropping and as a sole crop. All these methods of integrating velvet bean depend on farmers' preferences and the availability of land and other resources.

23.3.1 Soil Fertility and Yield Improvement

Soil degradation or poor soil fertility predisposes to rural poverty in most parts of sub-Saharan Africa (Vanlauwe et al. 2015). Velvet bean is one of the legumes that has been shown to be able to fix considerable amounts of N through BNF under various conditions (Okito et al. 2004). Kaizzi et al. (2004) reported that velvet bean accumulated about 170 kg N ha^{-1} and, of this, 57% was derived from BNF in very low potential agricultural soils of Uganda. Significant increases in maize yield of about 1 t ha^{-1} were noted in maize after a velvet bean fallow compared to maize that received 40 kg N from inorganic fertilizers (Kaizzi et al. 2004), and this shows that velvet bean is capable of improving subsequent crop yields at reduced input costs for smallholder farmers. Similar results were also reported in a study by Mhlanga et al. (2015a) where the decomposition of velvet bean residue resulted in about 170 kg N ha^{-1} of potential plant-available N (PAN). This amount of mineralised N resulted in comparable maize yields with maize that received 70 kg N ha^{-1} in the form of ammonium nitrate (AN) suggesting that in the case where farmers cannot afford AN, velvet bean can be an alternative source of N.

In a sandy soil of inherent low fertility in south America, velvet bean contributed up to 60 kg N ha^{-1} to the soil as compared to groundnuts (*Arachis hypogea*) which contributed about 40 kg N ha^{-1} (Okito et al. 2004). Thus, using velvet bean in smallholder cropping systems can facilitate soil N build-up that is essential for crop growth. In the study by Okito et al. (2004), maize-groundnut system was more attractive to the farmer since both crops have marketable produce, but a simple N balance of the system in the study confirmed that this system would, in the long run, lead to nutrient "mining". Although the maize-velvet bean system would seem less attractive, this system would lead to a soil fertility build-up over time and consequently, the subsequent maize after velvet bean outyielded maize that followed groundnut. In addition, the decomposition of velvet bean residue can also be a considerable source of N and phosphorus (P) (Dube et al. 2014).

The biomass of velvet bean is of high quality, with a low C:N ratio and low lignin, and this means that it decomposes quickly, thus releasing N into the soil for plant uptake more readily compared to other widely used legumes. In a preliminary study conducted by Mhlanga et al. (2015b), velvet bean residues decomposed much faster than other legumes on a clay soil (Fig. 23.1).

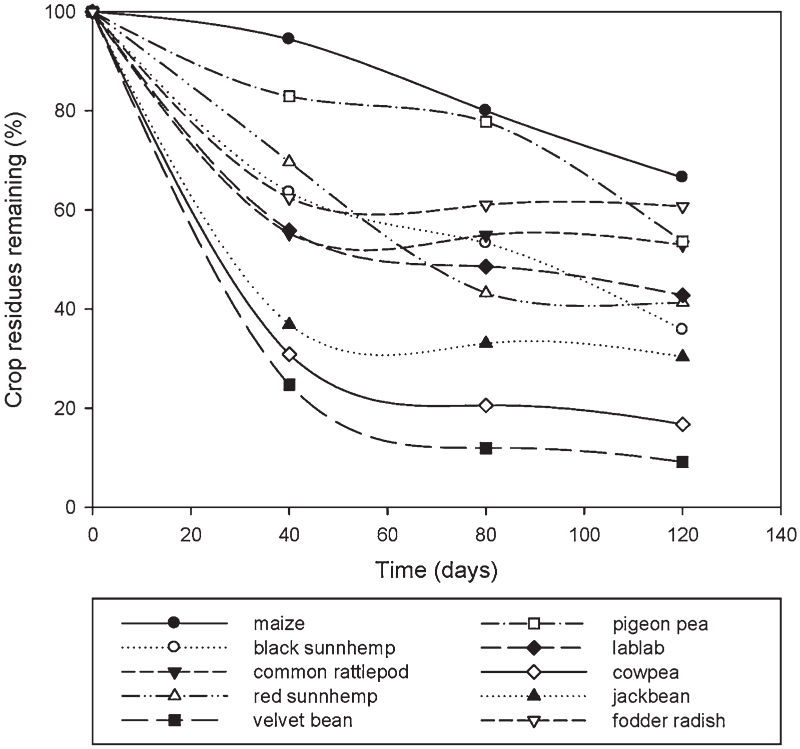

Fig. 23.1 The percentage remaining of different residues in litterbags collected over 40-day intervals on a clay soil. (Adapted from Mhlanga et al. 2015b)

23.3.2 Weed Management

Velvet bean is of fast and vigorous growth habit, thus making it an ideal tool in weed management. Due to its vigorous and fast growth habit and high biomass yields, it tends to outcompete weeds through shading them from light and competing with them for other growth elements (Teasdale 1998). The resulting weed densities after planting velvet bean are usually lower than after planting other cover crops of slower growth habit such as pigeon pea. In a study carried out in sandy soils, velvet bean yielded more biomass than pigeon pea, and in the following season, both cover crops were rotated with maize. The density of weeds in the following season was higher in the pigeon pea-maize rotation as compared to the velvet bean rotation (Fig. 23.2).

Velvet bean has been reported to produce allelochemicals that suppress growth of weeds including African yam bean (*Sphenostylis stenocarpa*) (Eucharia and Edward 2010), but damage to the companion crop can be observed (Appiah et al. 2015). The damage, however, can be avoided by growing the velvet bean after the accompanying crop has been well established or is at advanced growth stage.

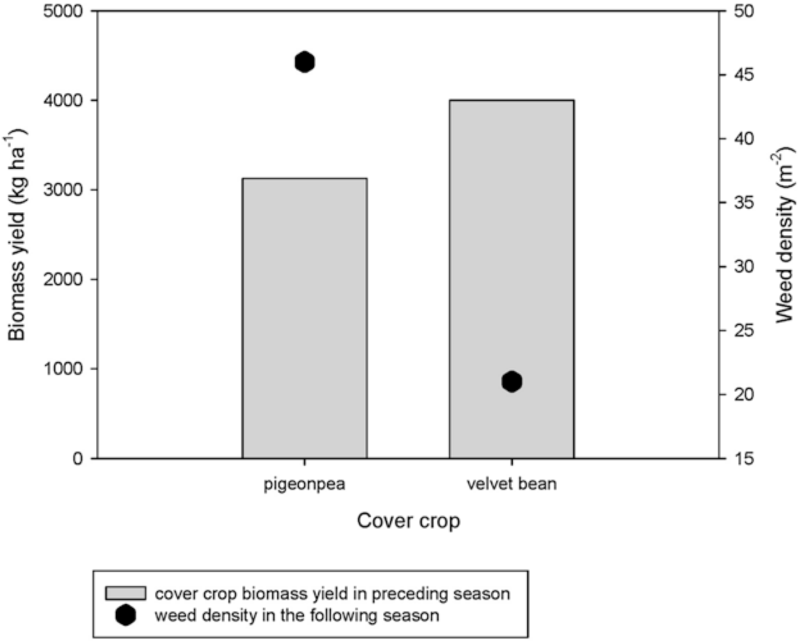

Fig. 23.2 Biomass yield of velvet bean and pigeon pea and the corresponding weed density in the following season. (Adapted from Mhlanga et al. 2015a, b)

Various studies carried out in southern Africa have shown velvet bean to be an important tool in weed management. When rotated with maize, weed densities decreased by up to 92%, and this is a significant decrease that would save farmers from reliance on expensive post-emergent herbicides (Mhlanga et al. 2015a). The diversity of weed communities in the presence of velvet bean has been reported to be high, and this reflects the reduction in numbers of dominant weed species, thus creating a flexible weeding plan for smallholder farmers (Mhlanga et al. 2015a).

23.3.3 Soil Cover

Soil cover is important to protect the soil from adverse weather conditions. Soil cover can be achieved through the retention of crop residues. However, in some instances it is difficult to achieve soil cover due to competition for the use of residues such for feeding livestock during the dry season. To reduce competition for crop residues between livestock feed and soil fertility improvement, velvet bean can produce supplementary biomass yields as high as 5 t ha^{-1} (Mhlanga 2016). This is a significant yield to supplement livestock feed during the dry season or as ground cover. For farmers that are practicing conservation agriculture where retention of crop residues for ground cover is necessary, competition for crop residue uses is high (Jaleta et al. 2013). It is in these systems that the production of supplementary biomass is necessary. Supplementary biomass is considered here as the biomass that is left after sufficient biomass is retained for 30% ground cover (minimum ground cover required for CA systems) (Mhlanga 2016). High biomass productivity of velvet bean also ensures protection of the soil against direct impact of unfavourable weather conditions. If soil surfaces are covered, raindrop impact is reduced, thus reducing soil erosion (McCarthy et al. 1993). Retention of velvet bean residues can assure contact ground cover that reaches 85% compared to maize monocrop systems with about 75%, thus reducing soil erosion significantly (Mhlanga 2016). In addition, the high ground cover from velvet bean reduces the rainfall runoff reducing the rate of soil loss.

However, due to its high quality (low C:N ratio and low fibre content), the decomposition of velvet bean is faster than for the conventionally retained maize residues resulting in reduced contact ground cover (Mhlanga 2016). A litterbag experiment setup in the subhumid region of Zimbabwe resulted in 10% remaining velvet bean residue after 120 days of field exposure compared to 60% remaining maize residue (Mhlanga 2016) (Fig. 23.1).

23.3.4 Provision of Livestock Feed

Livestock play a crucial role in smallholder farming systems in eastern and southern Africa where they contribute to food provision, draft power, manure production for crop production, employment creation and income generation among other benefits (Sansoucy et al. 1995). Due to high pressure on land, integrated crop-livestock systems have been promoted with the aim to increase the product output per unit of land. This is achieved by reducing soil erosion, increasing biological activity and nutrient cycling, intensifying land use and strengthening environmental sustainability (Gupta et al. 2012). Integrated crop-livestock systems contribute approximately 50 and 90% of the world's meat and milk requirements, respectively (Thornton and Herrero 2001). Such benefits reduce extreme hunger and poverty in smallholder farming systems in eastern and southern Africa. However, livestock production in Africa is affected by permanent or seasonal nutritional stress and other factors such as climate change, diseases and parasites (Thornton 2010; Lamy et al. 2012).

To address the problems of nutrition-related stress in smallholder farming systems, researchers have recommended introduction of new feed sources of high quality which include fodder grasses and legumes, treatment of the feed stuffs using different methods to improve crop residue quality and improved preservation and storage techniques (Sumberg 2002). Legume species such as velvet bean play an important role in improving livestock nutrition in smallholder farming (Pugalenthi et al. 2005). Velvet bean has been widely used as cattle feed in the south-eastern United States where it increased N intake and N retention and milk and meat production (Chikagwa-Malunga et al. 2009). However, velvet bean was replaced with soybean in the 1950s. Velvet bean nutritional composition is comparable to soybean and other conventional stock feeds that have high protein, minerals, lipids and other nutrients. Its crude protein can reach 300 g kg^{-1} (Chikagwa-Malunga et al. 2009, Fathima et al. 2010; Tresina and Mohan 2013), which is approximately 10 times greater than maize (*Zea mays*) crop residues, which typically have CP concentration of 30 g kg^{-1} (Abdulrazak et al. 1997).

Velvet bean provides ruminant animals with nitrogen that is needed for efficient microbial fermentation of carbohydrates to volatile fatty acids, a major source of energy in ruminants (Moran 2005). Rumen microbes are also a major source of protein in ruminant animals, after they die, which increase milk and meat productivity (McAllister et al. 1994). The hay made from velvet bean is highly digestible leading to high productivity of milk and meat (Siddhuraju et al. 1996). Anti-nutritional factors are degraded in the rumen under the action of rumen microbes (McSweeney et al. 2002). However, the use of velvet bean seed in non-ruminant animals is limited due to anti-nutritional factors (Emenalom et al. 2004). The seed should be processed to reduce the toxic component (L-Dopa) that may reduce the animal productivity. The suggested processing methods include boiling the seed for 1 h, pressure-cooking for 20 min, soaking the seed for 48 h and cracking the seed that will later be soaked and boiled (Ravindran and Ravindran 1988; Diallo and Berhe 2003; Siddhuraju and Becker 2003).

23.3.5 Human Consumption as a Source of Protein

Legumes have played an important role in cropping systems as a food resource for humans since ancient times (Li et al. 2016). Seeds of legumes such as field pea, groundnut and soybean have been consumed either directly as relish or further processed to make products including peanut butter or cooking oil. Hence, these legumes are more common than velvet bean in smallholder farms, although it has high protein concentration (23–35%). However, the seeds of velvet bean can also be consumed after careful preparation which reduces the anti-nutritional factors which may be toxic. Soaking the seeds in running water for 72 h reduced L-Dopa by approximately 95% and even lower when the seeds were cracked before soaking in Guinea (Diallo and Berhe 2003). Also, soaking velvet bean seeds in water for 48 h with water change every 12 h reduced L-Dopa to 1% in the same country. When the L-Dopa is successfully reduced, the seeds can be used to make porridge (using flour made by grinding the seeds) and coffee (Diallo and Berhe 2003).

23.3.6 Velvet Bean Adoption in Eastern and Southern Africa

Although velvet bean is relatively uncommon, some farmers in southern Africa have adopted its use. Farmers is Zimbabwe have indicated interest in using velvet bean as livestock feed although there is no data to show the number of farmers (ICRISAT 2017). This is because velvet bean produces high biomass in areas that receive low rainfall such natural region 5 in Zimbabwe, where ICRISAT was working. In some countries such as Benin, velvet bean has been adopted by farmers for weed suppression (Versteeg et al. 1998), and over 10,000 farmers adopted this crop for this reason (Manyong 1999). Farmers tend to adopt velvet bean based on functions they prefer, and these include weed control, provision of livestock feed and food. However, more research is needed to quantify the adoption of this crop.

23.4 Conclusion

Velvet bean has potential to contribute to improve smallholder farmers' livelihood in eastern and southern Africa. This is because the plant has the ability of biological nitrogen fixation that in turn contributes to high plant protein concentrations and soil fertility improvement. Most smallholder farmers in sub-Saharan Africa are resource constrained, and the use of legumes such as velvet bean reduces the reliance on inorganic fertilizers which are often unaffordable. However, to benefit from the fixed N, crop residues should be retained in the soil for further decomposition and nutrient cycling. Velvet bean plays a crucial role in reducing soil erosion in smallholder farming through provision of high ground cover that reduces raindrop impact and runoff. All these soil fertility improvement benefits result in increased crop yields that are obtained by farmers, hence improving food security status.

In addition to soil fertility improvement, velvet bean can be consumed by humans and contribute to provision of protein in their diets. This is important for smallholder farmers who cannot afford other protein alternatives. However, careful processing of the seed is necessary to reduce toxicity effects from anti-nutritional factors such as L-Dopa. The L-Dopa has various medicinal properties that need to be explored in smallholder farming systems. In addition, velvet bean plays a crucial role in provision of high-quality livestock feed that increases milk and meat production in smallholder farming systems.

To increase utilisation of velvet bean in smallholder farming systems, there is need to continue informing farmers on the benefits of using velvet bean. The crop should gain value in markets since its role is comparable to some high-value crops such as soybean. If the crop has more value at the market, farmers will be able to sell it rather than produce it and struggle to sell it. In addition, researchers should pay more attention to the crop and work on ways to reduce the anti-nutritional factors that have resulted in underutilisation of the crop. More focus should be given to developing techniques that are more labour and cost effective in aiding in the consumption of velvet bean. In this way, the underutilisation of velvet bean as food and fodder can be reversed.

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Scientific Interventions to Improve Land and Water Productivity for Climate-Smart Agriculture in South Asia

24

Rajan Bhatt, Akbar Hossain, and Pritpal Singh

Abstract

Wheat-rice cropping system in South Asia has taken a toll on the natural resources of air, water, and soil as this proves to be labor, water, capital, and energy intensive and becomes less profitable under the current scenario of climate change. Adverse effects will be further intensified under changing climate, declining underground water table, and deteriorated soil structure. The frequency of droughts, heavy rain falls, and heat waves increased under the scenario of climate change which results in higher grain production instability. Further, number of rainy days, rainfall events, postpone of monsoons, mid-season droughts, etc. have observed in recent years, affecting the land and water productivity. For enhancing the profitability, productivity, and sustainability of this system, a paradigm shift is required. To improve declining land and water productivity under the prevailing climate change, scientists developed several resource conservation technologies (RCTs), viz., direct-seeded rice, irrigation based on soil matric potential, zero tillage in wheat, and mechanical transplanting of rice under different tillage conditions, being advocated in the region, which have been studied under isolated conditions for individual crops. A single RCT might not solve the purpose of improved land and water productivity; therefore an integrated approach with agronomic and soil manipulations depending on the location, soil

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textural class, and agroclimatic condition is the need of the hour. The delineated lower WP at the farmers' fields compared to well-managed experimental plots indicates the need for a scope to improve it. However, these technologies need to be studied for complete wheat-rice cropping system in the region as a whole including the intervening periods. However, these technologies are site specific, and before selecting any particular RCT for a particular region, soil texture and agroclimatic conditions must be considered. Further, a single RCT would not be effective; therefore, an integrated approach is required. In this chapter, an attempt was made to discuss different scientific interventions and their different integrated approaches which might be used to improve land and water productivity under the climate change scenario for improving the productivity, profitability, and sustainability of RWCS in the region. But, after adopting any RCT or a set of RCTs, their residual effects need to be delineated not only during succeeding or proceeding crops but also on the soil moisture dynamics during intervening periods for finally improving the livelihoods of the poor farmers of South Asia under the scenario of climate change.

Keywords
Climate-smart agriculture · Land and water productivity · South Asia · RCTs

24.1 Introduction

Climate change is one of the main challenges in front of the sustainable agriculture as its effect adversely affecting both land and water productivities in South Asia (IPCC 2014). Water availability for agricultural and allied sectors decreased day by day due to change in the dietary habits and raised demand by industrial and residential sector. In comparison to pre-industrial base of the 1880s (1861–1900), the all-India annual mean ambient temperature is projected to increase 1.7–2.0 °C by the 2030s and 2.0–4.8 °C by the 2080s, while precipitation is projected to increase 1.2–2.4% by the 2030s and 3.5–11.3% by the 2080s (Sikka et al. 2016). Both land and water productivities influenced by the total received rainfalls during the season as around 54% area of the country are rainfed. Our grain producing ability is affected by the impacts of the climate change, viz., droughts, cyclones, extreme precipitation events, heat waves, etc. During the last 15 years, rainfall so recorded at the India level had delineated that lower, higher, and average rainfalls recorded during 7, 6, and 2 years, respectively (Rao et al. 2015). Table 24.1 clarifies the impacts of climate change on the weather events which really proves to be a challenge for practicing the climate-smart agriculture in South Asia the increased incidences of extreme weather events.

Further, agricultural sector in India has been and is likely to remain the major consumer of water, but the share of water allocated to irrigation is likely to decrease by 10–15% in the next two decades because of increasing water demand by other sectors (Elliott et al. 2014). Irrigation is the largest direct human water use,

Table 24.1 Monsoon rainfall and extreme weather events during 2001–2015 in India

Year	Deviation from the normal rainfall	Extreme events
2001	−15	Drought
2002	−19	Heat waves in Andhra Pradesh
2003	2	Extreme cold winters
2004	−13	Abnormal temperature and drought
2005	−1	Floods
2006	−1	Cold waves, floods in Rajasthan, drought in eastern regions
2007	5	Abnormal temperature during January and February
2008	−2	
2009	−23	Droughts
2010	2	Warmest year
2011	1	Failure of September rains
2012	−8	Droughts
2013	6	Floods in Uttarakhand
2014	−12	Floods in Jammu and Kashmir
2015	−14	Extreme heatwaves

Source: Sikka et al. (2016)

including large amounts of green and blue water required for producing food for the ever increasing population from the decreasing land holdings (Mancosu et al. 2015). The rice-wheat cropping system (RWCS) is the world's largest agricultural production system occupying 24 million hectares (Mha) throughout India and China alone (Kukal et al. 2014) which spreads from Punjab in the Northwest to West Bengal in the East (Singh et al. 2006). Around 12.3 Mha area in India, 0.5 Mha in Nepal, 2.2 Mha in Pakistan, and 0.8 Mha in Bangladesh are under RWCS (Ladha et al. 2003). Further, RWCS contributes more than 45% of the region's food grains and provides staple grains for nearly 42% of the total population (1.3 billion) in South Asia (Naresh et al. 2012).

Rice is normally flood irrigated during most part of the season with water pumped out from the belowground aquifers leading to a steady decline in the water table in the region since 1970s (Hira et al. 2004). The fall in water table particularly in Central Punjab has been reported to increase from 0.2 m year^{-1} during 1973–2001 to about 1.0 m year^{-1} during 2000–2006. Majority of the blocks in NE Punjab are being overexploited for pumping out groundwater (Humphreys et al. 2010), whereas in SW Punjab, problem of water logging arises as the farmers over here use canal water for irrigation because of very poor water quality. The lowering of the groundwater table in the NE Punjab has been resulting in an increase in the energy requirement, tubewell infrastructure cost, and deteriorating groundwater quality (Hira 2009).

Conventionally, rice established through repeated puddling of coarse and medium-textured soils. Large soil particles aggregate in standing water under puddled conditions burst due to the air inside; as per stroke's law first bigger particle viz., sand followed by silt came down and finally clay particles settled down and closing all the pores. This is the reason why farmers even in light-textured soils are able to cultivate paddy after creating anaerobic conditions. But on the long run, this has led to the subsurface compaction in these soils (Sur et al. 1981; Kukal and Aggarwal 2003a), which has been proving detrimental for the upland crops like wheat (Kukal and Aggarwal 2003b). The high bulk density layer at 15–20 cm depth formed due to repeated puddling restricts the root growth of wheat in addition to creating aeration stress generally known as "plough pan" (Aggarwal et al. 1995; Kukal and Aggarwal 2003b). Thus, puddle transplanted system of rice is water, capital, and energy intensive and leads to the structural deterioration of the soil. Therefore productivity, profitability, and sustainability of rice-based systems are threatened because of the inefficient use of inputs, increasing scarcity of resources especially water and labor, the emerging energy crisis, and rising fuel prices.

Another major issue related to RWCS is effective management of rice crop residue, which due to its high silica content is not fed to the animals and is normally burnt by the farmers at their fields which further led to the problem of global warming by generating the green houses gases. Annually around 500 MT of the residue is being generated through the rice-wheat cropping system in India alone. Burning of the rice residues causes environmental pollution, global warming, and killing of the beneficial insects, creates net negative nutrient balance and also degrades the soil, decreases organic matter levels, and finally results in the soil health deterioration. Hence, for avoiding the burning of rice residues, some alternate options, viz., compost preparation, for energy production as a fossil fuel substitute, ethanol production, biogas generation, electricity production, and bio-oil and biochar production, have been suggested by scientists to the farmers, and depending upon their socioeconomic and cultural status, one could choose the better option for judicious use of the straw residues (Singh and Sidhu 2014). Main emphasis is to adopt some of the above-listed alternate uses instead of burning the residues which not only causes air pollution but is also a threat to the sustainable agriculture. Thereby, disposal of crop residues by burning is not a viable option due to losses of soil organic matter, nutrients, C emissions, intense air pollution and reduced soil microbial activity (Rasmussen et al. 1980).

In order to take care of the above-said issues of declining land and water productivity, and residue management in RWCS in the region, various scientific interventions or resource conservation technologies (RCTs), viz., laser land levelling, alternate wetting and drying (AWD), irrigation system in rice on fixed day interval or soil matric potential (SMP)-based scheduling, mechanical transplanting, zero-tilled wheat and transplanted rice, direct-seeded rice, rice and wheat on raised beds, mulching, etc., are being advocated for improving the declining land and water productivity along with soil health for practicing climate-smart agriculture, the region so as to mitigate the adverse effects of the global warming. These technologies mainly focus on three fundamental principles of conservation agriculture, viz., conservation tillage, use of crop residues (Hobbs et al. 2008; Jeffrey et al. 2012) as mulch, and conservation irrigation (Kukal et al. 2005). Further, there is a need to delineate the residual effect of each applied RCT adopted for establishing a crop on not only at proceeding or succeeding crops but also on the intervening periods as this is the most neglected period as scientists are generally busy in analyzing the effect of the treatments applied. However, there is a need for the developing countries like India to also look into this intervening periods as to grow intervening crops, viz., fodders also for the animals, or to grow green manuring crops viz., moong, etc., which further on one side improve the livelihoods of the poor farmers while on other side improves the declining soil health status and land and water productivity of the rice-wheat system as a whole including the intervening periods (Bhatt and Kukal 2015a, b, c).

24.2 Techniques for Improving Livelihoods of the Farmers

24.2.1 Strategies for Sustaining Smallholders' Agricultural Production in Household Levels

A livelihood is known to a set of economic activities by which a household meets the basic needs of its member and also improves the cash income. When on tedious basis, these were performed, it is becoming a way of life of a household (Robinson 2001; Mahajan 2005). Informally, the majority people in smallholder make their living through self-employment, while in broader sense, the livelihood comprises the people, who are capable for their major basic needs such as food, revenue, and properties (Ellis 2000; Mahajan 2005), and the livelihoods of a household must be sustainable environmentally and also socially (Van Ginneken 1999).

However, under-developed and low-income countries, the maximum people are living in the urban area, and their livelihood largely depends on agricultural activities, since the agriculture mostly depends on land, water, agricultural inputs, credit, market facilities, government policies, and knowledge base (Rosegrant 2000). However, marginal and small households' in South Asia including India, Pakistan, Bangladesh, Nepal, Sri Lanka, generally farmers, are facing many problems, such as natural hazards, small size and fragmented land, soil erosion, infertile and low productive soil, scarcity of water for irrigation, lack of improved technologies, lack of infrastructure for post-harvest management, inaccessibility of credit facility during peak period of cultivation, and problem for marketing of agricultural produces (Kaspersma 2007; Kulkarni and Rao 2008; Khan and Shah 2010; Dahal and Pandey 2014). Therefore, it is necessary to solve the challenges, mostly to increase household income by expanding the agricultural productivity of small and marginal households. The following major strategies/techniques could be improved and sustain smallholders' agricultural production.

24.2.1.1 Develop and Extend Modern Agricultural Technologies for the Root Levels

Agricultural researchers should develop locations' specific new crop varieties and adaptive technologies for increasing the net income ha^{-1} at the farm level, not just increasing the crop yield ha^{-1}. Additionally, improving technologies, with a farming orientation system such as crop-livestock integrated production systems, could help to improve the household income of farmers (Singh and Pundir 2001; Parthasarathy

Rao and Birthal 2008). Rice occupies the largest area in the South Asian countries, and there are opportunities for generating more jobs and income by establishing rice bio-parks (Bishwajit et al. 2013; Chaturvedi 2016).

24.2.1.2 Enhancement of Soil Health for Increasing Soil Fertility and Productivity

Due to the intensification of cropping in a traditional way, the soil productivity and fertility of small householders' land in South Asia are decreasing day by day, while soil degradation such as soil acidity, salinity, erosion, and drought is also another major challenge to improve the agricultural yields. Therefore, the aim of researchers should increase the productive potential of soil through concurrent attention to the soil physico-biochemical properties (macro- and micronutrients and also microbiology) through following the precision nutrient management (PNM) strategy (Varinderpal-Singh et al. 2016), 4R Nutrient Stewardship Principles for nutrients/fertilizers management (Johnston and Bruulsema 2014; IPNI 2012, 2018), use of nanotechnology for sustainable crop production (Parisi et al. 2015), and the resource conservation technologies for sustaining crop production systems such as promote climate smart agricultural (CSA) policies (McCarthy et al. 2011) and introduce conservation agriculture (CA) with inclusion of legumes and crop residues (Dagar et al. 2016). Further, the adoption of CA will help in improvement of the both soil and environmental quality at the ecosystem levels (Fig. 24.1).

24.2.1.3 Improve Water Productivity in the Agricultural System

Future food demands for the increasing population in the world are projected to increase under changing climate; at the same time, water resources in the world are vulnerable, due to the lack of rainfall, water degradation, and over/misuse of water (Jury and Vaux Jr 2007; Wada and Bierkens 2014). To meet the food demand, land expansion is impossible or no longer a viable solution since most of the suitable arable land is under cultivation in around the globe (Godfray et al. 2010). Therefore, enhancing the productivity of water (IWP) is an important element for sustainable agriculture and healthy ecosystem (Rijsberman 2006; Bogardi et al. 2012) to meet the food demand of increasing population (Cosgrove and Rijsberman 2014). So, it is confirmed that IWP has been linked with food security and livelihoods (Cook et al. 2009; Cai et al. 2011). IWP means using less water or utilizing the equivalent amount of water, but the yield is more (Descheemaeker et al. 2013). Researchers were suggested the following basic methods for using the natural water resources could meet the growing food demands in future, such as continuing to expand rainfed and irrigated lands, increasing crop productivity per unit of water, trading food commodities, changing consumption practices, improving supply through rainwater harvesting, and recharging of the aquifer (Rockström et al. 2009; Descheemaeker et al. 2013; Molden 2013). Similarly, seawater farming should be promoted in coastal areas through the cultivation of mangroves, *Salicornia persica*, *Casuarina equisetifolia* and appropriate halophytic plants (Sardo 2005; Sardo and Hamdy 2005; Khan et al. 2006). The conjunctive use of rain, river, ground, sea, and treated sewage water and also improved irrigation practices, such as sprinkler and drip

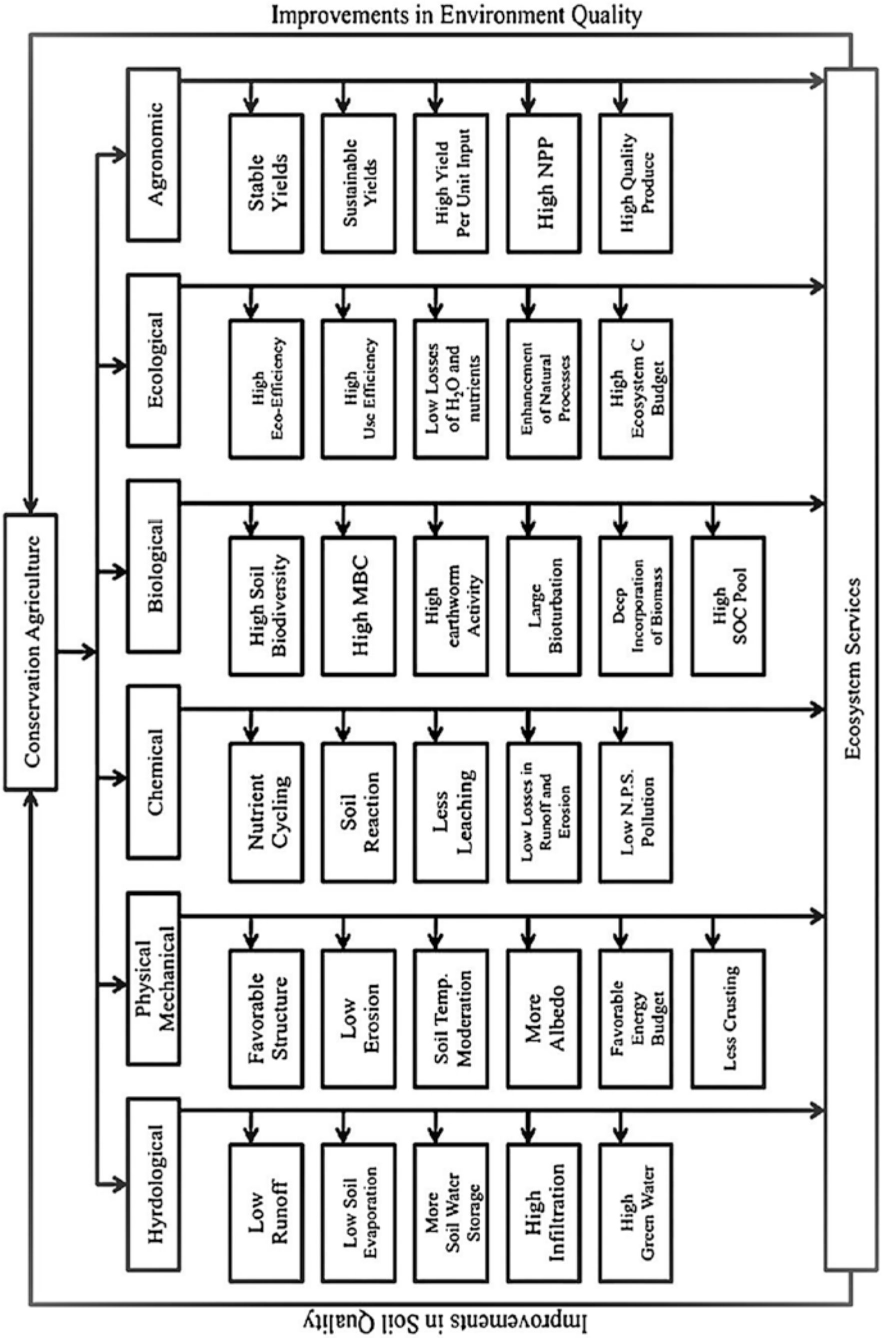

Fig. 24.1 Improved soil and environment quality through adoption of the conservation agriculture

irrigation, should take the priority attention in smallholders' level to improve crop productivity (Foster et al. 1998; Qadir et al. 2007). Figure 24.1 clearly delineates the benefits of conservation agriculture in improving the soil and environment quality through improving ecosystem services (Lal 2010).

24.2.1.4 Develop and Promote Location/Regional as Well as Farm-Specific Strategies to Improve Smallholders' Agricultural Productivity

Due to the wider variations in agroclimatic and economic conditions across the world, regions, and country as well as smallholders' level, there cannot be a single strategy of agricultural technology to be followed everywhere (Chand et al. 2011). Therefore, it is very important to develop and promote location/regional as well as farm-specific technologies/approaches to improve smallholder's agricultural productivity.

24.2.1.5 The Available Market Facility, Credit, and Insurance Improve the Farm Income

Available market provides chances to small and marginal farmers to got better price of their produce (Zeller et al. 1998; Govindasamy et al. 1999), whereas agricultural credit in peak period is the primary pathway for enhancing the small farm crops production and also minimizing the risk of agriculture (Harvey et al. 2014). The spread between the deposit and lending interest rates should be a standard level for small householders' level.

24.2.2 Concept and Importance of Precision Nutrient Management (PNM)

Soil test-based nutrient management recommendations have served the drive of improving food grain production, but have not only improved the nutrient use efficiency after a certain limit. Researchers around the globe have applicably moved to a method of nurturing the crops rather than feeding the soil, called as "precision nutrient management" (PNM) (Varinderpal-Singh et al. 2016). The PNM is one of the key mechanisms of the precision agriculture and manages all the major issues for refining agricultural productivity, protecting natural resources and avoiding any ecological or social misfortunes (Varinderpal-Singh et al. 2016). According to Jin and Jiang (2002), PNM is the science of using advanced, innovative, cutting-edge, and site-specific technologies to manage spatial and sequential erraticism in inherent nutrient supply from soil to improve production, efficacy, and cost-effectiveness of agricultural production systems and sustainability.

24.2.2.1 Tools and Techniques for Precision Nutrient Management

24.2.2.1.1 An Optical Sensor Is a Decision-Making Tool for Precision Nutrient Management (PNM)

A wide range of optical sensors such as multispectral sensors (i.e., Crop Circle (450–880 nm) and CropScan (440–1750 nm)) have wide spectral resolution (10 to

20 nm) with a limited number of wavebands (3–16)) normally used to define variation of biomass and leaf area index, due to application of nitrogen, whereas hyperspectral sensors (i.e., ASD FieldSpec) (350–2500 nm) have a fine spectral resolution (1–2 nm) with continuous wavebands (21–50), which provides details of biophysical and biochemical information of crop (Darvishzadeh et al. 2006). Many researchers have successfully used the optical sensors in various crops: rice (Bijay-Singh et al. 2015), wheat (Heege et al. 2008; Bijay-Singh et al. 2013), corn (Tremblay et al. 2009), barley (Soderstron et al. 2010), sugarcane (Singh et al. 2006; Portz et al. 2012), and cotton (Raper et al. 2013).

24.2.2.1.2 Chlorophyll Meter Is a Decision-Making Tool for Nitrogen Application in Multiple Crops

Nitrogen in plants is generally detected by testing soil sample and also is possible by plant tissue sample analysis. But, both these methods are expensive, time-consuming, and not easily accessible by farmers, while the chlorophyll meter is a quick decision-making tool for application of nitrogen in crops' field (Akhter et al. 2016). It is easily usable and no need to analyze the soil and plant tissue sample. The most popular chlorophyll meter around the world is Minolta SPAD-502, which is a quick, nondestructive portable device that was developed by Minolta Limited, Osaka, Japan (Minolta 1989). It is instantly provided with an estimate of leaf N status as chlorophyll content (Feibo et al. 1998; Boggs et al. 2003). Fieldscout CM 1000 is another type of chlorophyll meter, developed by Spectrum Technologies, Inc. (2009). It calculates a running average of multiple readings, and concurrently recording for each sample is recorded in data logger (Varinderpal-Singh et al. 2016).

24.2.2.1.3 Leaf Color Chart (LCC) Is a Decision-Making Tool for Nitrogen Application

The LCC (leaf color chart) tool is a high-quality plastic strip with different shades of light: yellowish green to dark green. Although LCC may not be as specific as the SPAD meter, but it works like the SPAD meter under field condition (Varinderpal-Singh et al. 2010). For the first time, LCC technology was used in Japan (Furuya 1987). In the year 1996, IRRI (1996) developed an upgraded version of six-panel LCC (i.e., IRRI-LCC, six-panel) in collaboration with several Asian agricultural research organizations and universities. Later (in the year 2007) researchers of IRRI (2007) further sophisticated the color panels of the IRRI-LCC and developed a four-panel IRRI-LCC (Fairhurst et al. 2007; Witt et al. 2005). In the year 2013, the researchers (Yang et al. 2003) of Zhejiang Agricultural University, China, developed an eight-panel (3, 4, 5, 5.5, 6, 6.5, 7, and 8) "ZAU-LCC" leaf color chart. Another eight-panel (1–8) UCDLCC was developed by the University of California, Davis, USA, to define per cent leaf nitrogen (Boyd 2001).

24.2.2.1.4 Precision Nutrient Management through Omission Plot Technique

For attaining a yield target, omission plot technique (OPT) is used to estimate fertilizer requirements. In this technique, all the important nutrients are applied, while nutrient of interest is omitted (do not apply). For example, Varinderpal-Singh et al.

(2016) found that if all the nutrients were applied except for P, in P-omission plot, then the yield was decreased by the indigenous supply of P. Similarly, Khurana et al. (2008) conducted an omission plot on-farm experiment in 56 locations of India with wheat crop and found that PNM through OPT improved the grain yield of wheat ranged from 4.2 to 4.8 t ha^{-1}, while accumulations of N, P, and K increased in plant by 12–20%. The gross return was 13% higher than with farmers' practice.

24.2.2.1.5 Using Nutrient Expert (NE) for Precision Nutrient Management (PNM)

The NE is a computer-based decision support program, which is generally used for PNM (Pampolino et al. 2012). It is a highly interactive computer-based tool that rapidly tells about fertilizer requirement of a particular field (Varinderpal-Singh et al. 2016). Nutrient Expert (NE) is developed based on 3–5 years of previous yield, manures and chemical fertilizers applied, realistic yield, soil fertility indicators, residue content, and information of growing environment for farmers' specific or site-specific fertilizer recommendation (Dass et al. 2014; Xu et al. 2014). The model is designed to consider spatial and time-based inconsistency in nutrient supply and confirm need-based nutrient applications (Sapkota et al. 2014, 2015).

24.2.2.1.6 Precision Nutrient Management (PNM) through Aerial Imagery and Sitemaps

Although many researchers in the world have been worked on aerial imagery and sitemaps for PNM, its application has not been established yet in many developing and low-income countries (Nadagouda and Tippannavar 2015; Varinderpal-Singh et al. 2016). However, in some advanced countries, aerial imagery/sitemap and soil survey map for PNM have been popularized since a long time ago (Plant 2001; Pinter Jr. et al. 2003; Chen et al. 2011). Generally these tools are developed based on knowledge of previous land use(s) such as previous crops, application of manures and chemical fertilizers, attainable yield, soil fertility indicators, residue content and growing environment, geologic characteristics, and/or other sources of variation (Cook and Bramley 1998; McBratney et al. 2000; Zhang et al. 2010). Varvel et al. (1999) observed that the bare soil reflectance was significantly correlated with phosphorus (P) and organic matter content by using the aerial and satellite images. Singh et al. (2006) used GIS-based mapping and found that Puse was suboptimal in all the crops, except in potato-based system, where double the dose of recommended P was applied, while P use was found also higher in potato-based cropping systems followed by a sugarcane-wheat systems.

24.2.2.2 The 4R Nutrient Stewardship Principles as the Basis of Precision Nutrient Management

Under changing climate, application of fertilizers plays a substantial role in securing the food security of increasing population in the world. It is estimated that 40–60% of all crop production fully depends on fertilizer application (Johnston, and Bruulsema 2014). Therefore, to meet future food demand for increasing population, fertilizers should be used from the right source, in the right rate, at the right time, and in the right place as the termed as four rights or 4R (Stewart et al. 2009; Mikkelsen 2011). Since, application of the right source of nutrient or product at the right rate, at the right time, and in the right place has been closely associated with agricultural sustainability (Johnston and Bruulsema 2014; IPNI 2012, 2018). The 4R concept is developed through a long history of assistance between the fertilizer industry and the scientific community as a process to guide the best management of fertilizers in all regions of the world. Details of the 4R Nutrient Stewardship Principles are described as follows:

24.2.2.2.1 Fertilizers/Nutrients Must Be Applied from "Right Source"

Selection of right fertilizer assures that appropriate nutrient for target crops to encounter the specific objectives and also avoid the unnecessary application of fertilization (Mikkelsen et al. 2009). The appropriate assortment of the source of nutrient depends on product availability in a farmer's locality, application equipment, economics, and plant requirements. Before application of any nutrients in specific field or specific crop, their interactions and quantifiable compatibility should also verified (IPNI 2011). Application of quality fertilizers have a variety of benefits in ever field crops, such as improved yields, reduced fertilization rates, and eco-friendly (Trenkel 2010).

24.2.2.2.2 Fertilizers/Nutrients Must Be Applied at "Right Rate"

Apply nutrients/fertilizers at the right rate, increase its efficiency, and also increase crop yields and optimizing farmer profitability. Therefore, for enlightening the farmers' probability, must be applied a balance and optimal nutrients for increasing its use efficiency and the finest crop productivity. The concept of applying fertilizers at the right rate is to provide just enough nutrients to meet target production and quality (Phillips et al. 2009). The maximum nutrient use efficiency always shows in the lower parts of the yield response curve (Roberts 2008). Selecting the right rate begins with first establishing judicious yield goals and evaluating the soil nutrient supply (through soil testing) and then checking the plant nutrient status with tissue analysis or field scouting (Mikkelsen 2011).

24.2.2.2.3 Fertilizers/Nutrients Must Be Applied at Right Time

Application of right fertilizers time, synchronizing the soil nutrients availability with peak periods of crop demand (Stewart et al. 2009). To get the maximum fertilizers' use efficiency, first step is to understand the necessities of crop growth and development and also know the peak periods of nutrient demand for the specific crop in the specific soil. After knowing crop growth pattern based fertilizers/nutrients demand, a variety of practices could be properly employed such as pre-plant or pre-sowing (basal at final land preparation) application, split-applications, controlled-release, fertilizers' additives for inhibition of nitrification or urease, fertigation, and foliar applications (Mikkelsen 2011). For example, Horneck and Rosen (2008) demonstrated that potato has a very high demand for nitrogen between 40 and 80 days after planting. Similarly, the peak period of potassium demand for potato is between ~60 and 90 days after planting. While, excessive dose of in the soil before the peak demand of growing plants or uptake the bulk amount could be happened a negative impact on yield, quality, and the environment (Horneck and Rosen 2008).

24.2.2.2.4 Fertilizers/Nutrients Must Be Applied in the Right Place

For improving the nutrient use efficiency, it must be applied at the place or depth of root zone of soils, where nutrients are accessible to plant roots (Murrell et al. 2009). The dynamics of soil and root interactions in fertilized areas need further exploration. The placement of fertilizer is often indicated by the soil properties, crop rooting patterns, and available technology (Randall and Hoeft 1988). However, during the placement of fertilizers/nutrients, the chemical and biological reactions of each nutrient in the soil and also their combined impact on bioavailability also need to be considered (Barber 1995; Comerford 2005). For example, nitrogen is not left on the soil surface for prolonged periods due to its susceptibility to loss through ammonia volatilization (Mikkelsen 2011), while the precision placement of fertilizer for many horticultural crops has been shown to be more effective than application as broadcast.

24.2.3 Site-Specific Nutrient Management (SSNM)

Use of chemical fertilizers in agriculture has sustained the crop production to meet the food and fiber needs of global population over last many decades. Globally, the demand of food and nonfood commodities has been estimated to increase by 75–100% between 2010 and 2050 (Keating et al. 2010; Tilman et al. 2011). The role of chemical fertilizers in increasing food production throughout the world could be ascertained from the fact that area under crop production has increased in millions of hectares that have been shifted from the natural ecosystems (Balmford et al. 2005). In South Asia, there is only a little scope for further increase in area to be further brought under cultivation, and there is no other alternative except by intensifying the existing land use and increasing the productivity of cropping system to meet ever increasing food demand.

Today’s situation is almost entirely different, with the fact that agriculture has become totally dependent of the use of chemical fertilizers. Farmers have resorted to the use of chemical fertilizers, and the dependence on traditional practice of using organic manures has lacked behind. Such a trend has resulted in excess use of chemical fertilizers in agricultural system which has further resulted in imbalanced application of plant nutrients. Nutrient management practices in many ecosystems fail to achieve congruence between nutrient supply and crop nutrient demand (Van Noordwijk and Cadisch 2002), which has resulted in decreased nutrient use efficiency, the major concern for world agriculture. Different approaches for increased nutrient use efficiency are discussed below.

SSNM is a plant-based approach which is used to address nutrient differences that exist within the fields by making adjustments in nutrient application. SSNM approach in field crops was developed to increase the fertilizer use efficiency to promote balanced use of fertilizers. It involves the estimation of field- and season-specific nutrient application rate based on indigenous soil nutrient supply, realistic yield target based on plant nutrient demand, and interaction among plant nutrients. This approach focused mainly on the management of field-specific spatial variation in indigenous nutrient (N, P, and K) supply and the temporal variability in plant N status that occur within a growing season and medium-term changes in soil P and K supply resulting from actual nutrient balance. Dobermann and White (1999) defined SSNM as a dynamic field-specific nutrient management approach for a particular cropping season to optimize the supply and demand of nutrients according to the differences in soil-plant system. SSNM primarily involved the prediction of field-specific optimal fertilizer rates and development and implementation of site-specific nutrient management strategies which account for real-time variation in crop nutrient demand at major growth stages. Therefore, this approach provides guidelines for N, P, and K fertilizer requirement depending upon cropping season, crop establishment method, and nutrient input through other sources such as residue or organic manure. To get better match between plant N requirements and fertilizer N supply, the SSNM approach provides guidelines for splitting and timing of fertilizer N applications at appropriate crop growth stage. Five key steps are involved in the calculations for field-specific fertilizer N, P, and K recommendations to the crops, which are described in detail as follows:

24.2.3.1 Realistic Yield Target Selection

A first step in SSNM is the selection of yield target that should be realistic, i.e., it should not be too less to be economically unviable, and at the same time it should not be too high to be difficult to achieve. Yield target is selected on the basis of a maximum yield potential for a specific crop variety. Yield potential is defined as the maximum possible achievable crop grain yield with an assumption that there is no other yield limiting factor, except the local climatic condition. In general, maximum potential yield is determined using crop simulation models or is estimated from the highest grain yield obtained in an experiment for a particular site under near optimal crop growth conditions.

24.2.3.2 Estimation of Crop Nutrient Requirement

SSNM advocates the generic and quantitative approach, i.e., some simulation models to estimate the relationships between grain yield and nutrient uptake that help make fertilizer recommendations. Since there are several uncertainties about N, P, and K requirement of crops owing to the internal efficiency (the amount of grain yield produced per unit of nutrient accumulated in aboveground plant dry matter) that varied greatly depending on soil, nutrient supply, crop management, and prevailing climate conditions and make it difficult to extrapolate on small field scale level, the quantitative evaluation of the fertility of tropical soils (QUEFTS) model resolves this issue, since it took into account the interactions of N, P, and K. Estimation of crop nutrient requirement depends upon nutrient uptake and yield target which is estimated using QUEFTS model that provides an empirical approach for estimating the crop nutrient requirement for a specific yield target by considering the climate-adjusted, season-specific yield potential (Chuan et al. 2013; Xu et al. 2013). The QUEFTS model guides fertilizer application, with integrated consideration of balanced inputs of all plant nutrients. QUEFTS model is an empirical relationship between grain yield and nutrient accumulation in plants following a linear-parabolic-plateau model and involves two linear boundaries to describe the range between maximum nutrient accumulation and nutrient dilution. The model regresses the yield as combined functions of N, P, and K and described the relationship between grain yield and nutrient uptake into four steps.

1. It assesses the potential indigenous nutrient supply based on the soil chemical properties.
2. It calculates the N, P, and K uptake based on their potential supply from soil. The model compared the nutrients in pairs. The relationship between the uptake and the potential nutrient supply of one nutrient (e.g., N) is calculated twice, viz., first depending on the potential supply of P and secondly of K. Similarly, P uptake depends on the potential supply of N and K and that the actual K uptake depends on the potential supply of N and P.
3. It identifies the yield range as functions of the actual nutrient (N, P, and K) uptake at maximum accumulation when the nutrient is in sufficient supply and maximum dilution when the nutrient is deficient in supply.
4. It estimates the yield based on the three yield ranges i.e. (one range each for N, P and K) and interactions between N, P and K. In this model, two boundary lines are determined, and the model then simulates a liner-parabolic-plateau curve for estimating optimal nutrient uptake (Fig. 24.2).

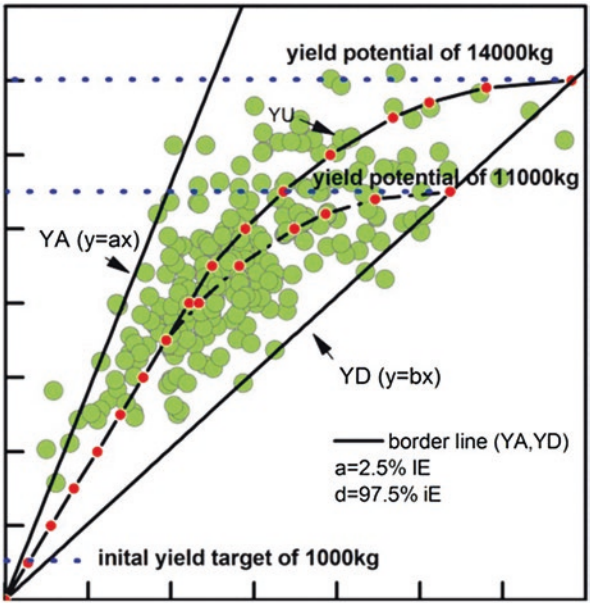

Fig. 24.2 Relationship between grain yield of maize and plant N uptake (YU, balanced N required to achieve a potential yield, and YA and YD, borderline of maximum accumulation and dilution of N in aboveground dry matter). (Source: Jiang et al. 2017)

24.2.3.3 Accounting of Indigenous Nutrient Supplies

Accounting of indigenous nutrient supplies, i.e., total amount of a particular nutrient that is available to the crop from the soil during a cropping cycle, when other nutrients are not limiting, is the most prime step in the calculations of site-specific requirements of fertilizers. It involves the estimation of nutrient (N, P, and K) supply through soil, in situ crop residue incorporation, irrigation water (groundwater or canal), and an atmospheric deposition. Nutrient omission technique is applied to calculate its uptake. For example, to measure the indigenous N supply, plant N uptake in N_0 plot (no-N) (but with the application of other nutrients in sufficient amounts) is measured at harvest so that N is the only growth limiting nutrient. Indigenous N supply capacity under well-managed field conditions can be estimated by measuring aboveground plant N uptake at crop maturity in N omission plot when all other nutrients are amply supplied (Janssen et al. 1990). Timsina et al. (2010) reported that the omission plot yield data shows the differential indigenous nutrient supplying capacity of soils; however, yield loss due to omission of N was higher compared with P and K, suggesting N as the major yield-limiting factor. Data from on-farm experiments on SSNM in maize conducted at different farmers' field locations in two different districts in northwest Bangladesh showed large variation in yield response to N application. Low grain yield in N omission plots, compared with plots with low P and K that yield very close to the yields obtained in NPK treatment, indicates large response to added N. Such variation in yield response at different locations has been ascribed to large variation in indigenous nutrient supply capacity of soils, suggesting need of SSNM to improve productivity of a cropping system (Table 24.2).

24.2.3.4 Calculation of Fertilizer Application Rates

Fertilizer application rates are calculated based on nutrient requirement of a plant at a specific yield target, estimated indigenous nutrient supply, and an expected fertilizer recovery efficiency by the plant, i.e., amount of fertilizer nutrient uptake per kg applied. Estimating indigenous nutrient supply by measuring a crop nutrient uptake in nutrient omission plots for SSNM is not feasible on a routine basis, because it involves destructive plant sampling and plant tissue analysis, which is time-consuming and expensive.

Table 24.2 Range of grain yield of winter maize from on-farm experiments on site-specific nutrient management (SSNM) at different locations in northwest Bangladesh

	Location	
Treatment	Rangpur	Rajshahi
N omission	0.5–5.1	3.4–3.9
P omission	3.9–8.3	4.5–8.5
K omission	4.1–8.1	5.3–7.9
Low K	5.5–8.8	6.2–8.9
Low P	5.8–9.8	6.5–8.6
NPK	6.0–10.3	6.7–10.8

Source: Timsina et al. (2010)

24.2.3.5 Dynamic Adjustment of Fertilizer N Application

The fertilizer application rates thus calculated are rough estimates of the amount of nutrient required to achieve a target grain yield for a particular season, assuming an occurrence of average optimal climatic conditions. But fertilizer application rates may differ depending upon climatic conditions, crop variety sown, average crop duration, irrigation water management, and crop establishment method, which are affected by timing of fertilizer application in relation to a particular crop growth stage. Field- and season-specific fertilizer rates are calculated based on indigenous soil nutrient supplies, plant nutrient demand (based on yield targets), and interactions among N, P, and K.

According to Dobermann and Fairhurst (2000), basic dose of fertilizer N is generally applied in soils with low indigenous N supply and remained in two or three splits at a crucial crop growth stage. The dose of fertilizer N to be topdressed is based on actual plant N status determined with chlorophyll meter (SPAD) or leaf color chart (LCC) (Blackmer and Schepers 1995). SSNM such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) have been developed to increase nitrogen use efficiency of irrigated rice (Peng et al. 1996; Dobermann et al. 2002). In RTNM, N is applied only when the leaf N content is below a critical level. In RTNM, if the SPAD reading is below 35, application of 30 kg N ha^{-1} is applied (Peng et al. 1996). If SPAD was below 35 around the panicle initiation stage, application of 45 kg N ha^{-1} is advocated. In this approach, the timing and number of N applications vary across seasons and locations, while the rate of each N application is fixed. On the other hand, in FTNM, the optimal amount of fertilizer N is applied before planting, with in-season upward or downward adjustments of predetermined N is topdressings at critical growth stages based on SPAD or LCC readings at a few critical growth stages (Dobermann et al. 2002).

The short-term crop response to nutrient application is assessed through five different indices (Table 24.3) that are most commonly used in research to estimate the efficiency of applied fertilizer nutrient (Cassman et al. 2002). In Asia, average grain yield increased by 11%, and average recovery efficiency increased by 9% with FTNM (Dobermann et al. 2002). N recovery efficiency (ratio of plant N to N supply) (30–35%) and agronomic N efficiency (ratio of yield to N supply) (5–10 kg kg N^{-1}) in China and other rice-growing countries with N recovery efficiency of 50–60% and agronomic N efficiency of 15–18 kg kg N^{-1}, respectively, have been reported (Peng et al. 2009). In cereals (rice, wheat, and maize), higher partial factor productivity (PFP) of 54 kg kg^{-1} in Asia has been reported compared with 50 kg kg^{-1} for Europe and America and the lowest for Africa (39 kg kg^{-1}) (Fig. 24.3).

PE_N and AE_N were also higher in Asia, followed by Europe and America, and the lowest in Africa. The average fertilizer N application rate of 115 kg N ha^{-1} (in Asia), 100 kg N ha^{-1} (in Europe), and 111 kg N ha^{-1} (in America) is much lower compared with 139 kg N ha^{-1} in Africa (Dobermann 2007). Among these cereals grown under at research stations under irrigated and rainfed condition across the world, maize (PFP = 72 kg kg^{-1}) and rice (62 kg kg^{-1}) had higher PFP_N, compared with wheat (45 kg kg^{-1}) (Fig. 24.4).

Table 24.3 Commonly used indices for nutrient use efficiency, their calculation, and range for different cereal crops

Index	Method used for calculation	Interpretation
Agronomic efficiency (AE) (kg yield increase per kg nutrient applied)	AE = $(Y-Y_C)/A$	AE indicates how the applied nutrient resulted in a change in grain yield and depends on management practices which affect RE and PE
Partial factor productivity (PFP) of applied nutrient (kg harvested product per kg nutrient applied)	PFP = Y/A	It is the most important indices because it integrates the use efficiency of both indigenous and applied nutrient through chemical fertilizer
Physiological efficiency (PE) of applied N (kg yield increase per kg increase in N uptake from fertilizer)	PE = $(Y-Y_C)/(U-U_C)$	PE indicates the ability of a plant to transform nutrients acquired from fertilizer into grain yield; therefore, its low value suggests suboptimal growth may be due to nutrient deficiency, drought stress, heat stress, mineral toxicities, or pests
Apparent crop recovery efficiency (RE) of applied nutrient (kg increase in N uptake per kg N applied)	RE = $(U-U_C)/A$	RE depends on congruence between plant demand and nutrient release from fertilizer and is affected by nutrient application method, amount, timing, placement, and other factors (such as genotype, climate, plant density, abiotic/biotic stresses)
Internal utilization efficiency (IE) of a nutrient (kg yield per kg nutrient uptake)	IE = Y/U	IE indicates the ability of a plant to transform nutrients acquired from soil and fertilizer into grain yield; therefore, low IE reflects poor internal nutrient conversion due to stresses such as nutrient deficiencies, drought stress, heat stress, mineral toxicities, pests

Y crop grain (kg ha^{-1}) yield with applied nutrient, Y_C crop yield (kg ha^{-1}) in control treatment, *A* amount (kg ha^{-1}) of fertilizer nutrient applied, *U* Total plant nutrient uptake in aboveground biomass (kg ha^{-1}) at harvest (maturity) in a plot that received fertilizer, U_C Total plant nutrient uptake in aboveground biomass (kg ha^{-1}) at harvest (maturity) in a plot that received no fertilizer (control treatment)

AE_N and PE_N were also higher in maize and rice, compared with wheat grown under irrigated and rainfed conditions. The comparison of nutrient use efficiency under three N management strategies, viz., farmers practice (FP), SSNM, and RTNM in two different rice cultivars (Jinzao22 and Shanyou63), revealed a non-significant difference in RE_N, AE_N, and PE_N among SSNM and RTNM, although these indices were significantly lower in FP (Table 24.4). The relationship between fertilizer N rates and grain yield of rice, N uptake in aboveground dry matter, N harvest index, and nutrient use efficiencies in China is shown in Fig. 24.5 (Shengguo et al. 2015).

Nitrogen uptake by rice increases significantly with fertilizer N application rate (R^2 = 0.547) (Fig. 24.5), while PFP_N decreased significantly (R^2 = 0.7415). Peng et al. (2006) reported significantly higher AE_N, RE_N, and PFP_N with RTNM and FTNM, compared with FP of fertilizer N management in rice using SPAD meter (Fig. 24.6). However, AE_N and PFP_N in rice were significantly higher with RTNM,

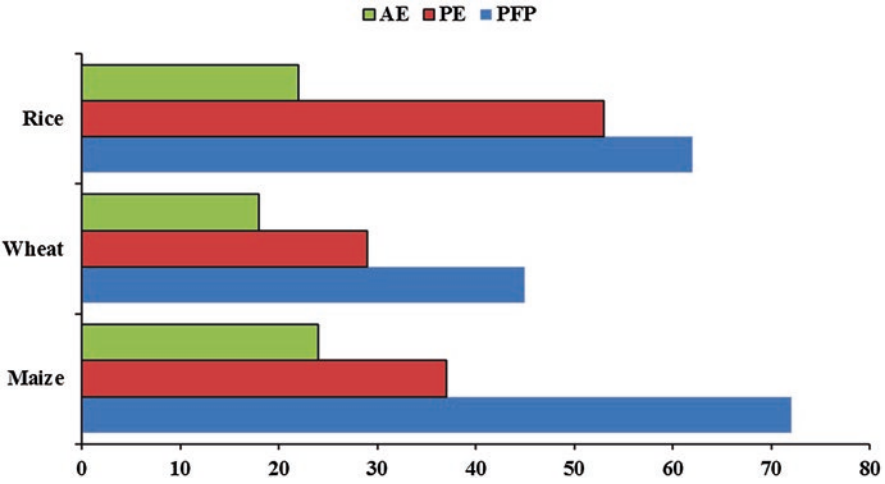

Fig. 24.3 Average nitrogen use efficiency (PFP, partial factor productivity; PE, physiological efficiency, and AE, agronomic efficiency) for cereals (rice, wheat, and maize; rice, irrigated ecosystem, and maize and wheat, both irrigated and rainfed ecosystems) in different regions of the world from the experiments conducted at research stations. (Source: Dobermann 2007)

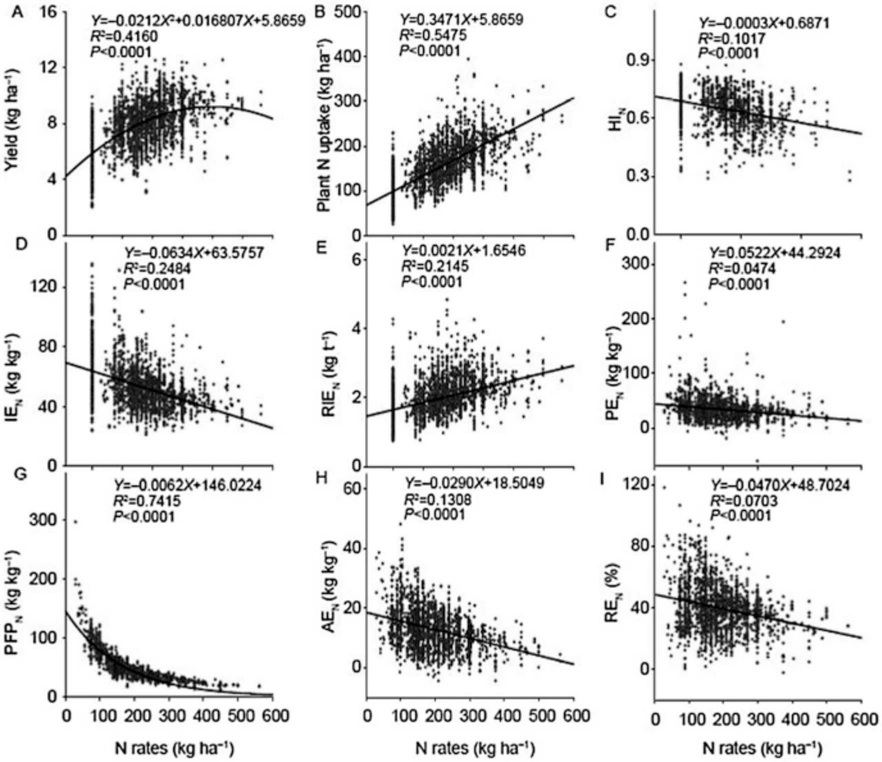

Fig. 24.4 Average nitrogen use efficiency (PFP, partial factor productivity; PE, physiological efficiency; and AE, agronomic efficiency) for cereals (rice, wheat, and maize; rice, irrigated ecosystem, and maize and wheat, both irrigated and rainfed ecosystems). (Source: Dobermann 2007)

Table 24.4 Comparison of nitrogen use efficiency under different fertilizer N management strategies: FP, farmers practice; SSNM, site-specific N management; RTNM, real-time N management in two rice cultivars in China

	Fertilizer N applied (kg N ha^{-1})		RE_N (%)		AE_N (kg kg^{-1})		PE_N (kg kg^{-1})	
N management strategy	Jinzao22	Shanyou63	Jinzao22	Shanyou63	Jinzao22	Shanyou63	Jinzao22	Shanyou63
FP	140	200	16a	26a	8.02a	3.40a	51a	13a
SSNM	120	110	23b	45b	13.6b	11.4b	60b	25b
RTNM	106	60	25b	40b	14.3b	18.4b	58b	46b

Source: Wen-xia et al. (2007)

Means followed by a different letter within a column are significantly different at $p < 0.05$

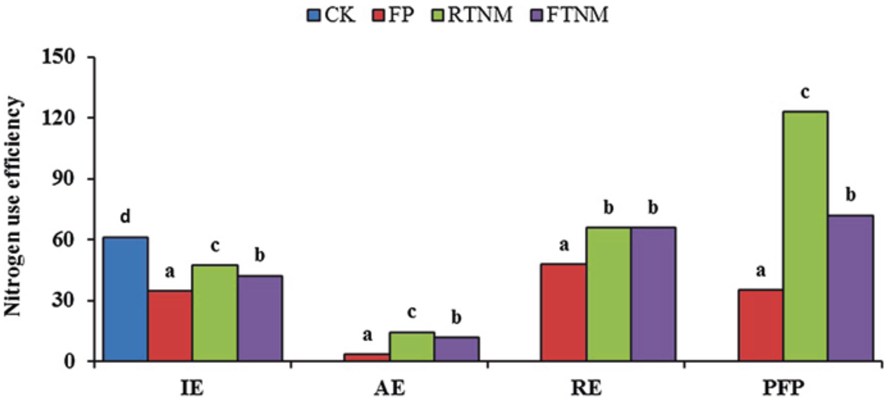

Fig. 24.5 Relationship between fertilizer N rates and grain yield of rice (**a**), N uptake in aboveground dry matter (**b**), N harvest index (**c**), internal N efficiency (**d**), reciprocal internal N use efficiency (**e**), physiological efficiency (**f**), partial factor productivity of applied fertilizer N (**g**), agronomic N use efficiency (**h**), recovery efficiency of applied fertilizer N (**i**) in China. (Source: Sheng-guo et al. 2015)

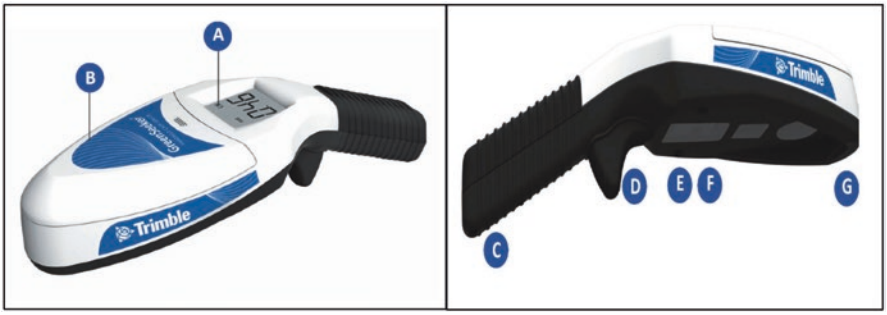

Fig. 24.6 Average (2 years and four locations) internal efficiency (IE, kg kg^{-1}), agronomic N use efficiency (AE, kg kg^{-1}), recovery efficiency of applied N (RE, %), and partial factor productivity (PFP, kg kg^{-1}) of N under different N management treatments (CK, control; FP, farmers' practice; RTNM, real-time N management using SPAD meter; FTNM, fixed time N management). Mean values for N use efficiency followed by different letters are significant at $p < 0.05$ by Tukey's multiple comparison test. (Source: Peng et al. 2006)

compared with FTNM. The IE of N, P, and K in rice, wheat, and maize (Table 24.5) showed a large variation depending upon the yield differences in different studies.

Wang et al. (2010) reported that to achieve potential productivity of wheat (6.9 Mg ha^{-1}) and maize (8.3 Mg ha^{-1}), wheat crop, on an average, requires 170 kg N ha^{-1}, 32 kg P ha^{-1}, and 130 kg K ha^{-1}, whereas maize requires 189 kg N ha^{-1}, 34 kg P ha^{-1}, and 212 kg K ha^{-1}. In another study, Hui-Min et al. (2011) reported that to achieve wheat productivity of 2–5 Mg ha^{-1}, 13–26 kg K ha^{-1} is required to produce 1.0 Mg wheat, whereas to achieve maize productivity of 3–6 Mg ha^{-1}, an application of 9–17 kg K ha^{-1} is required to produce 1.0 Mg maize. The reciprocal

Table 24.5 Internal use efficiency (IE) of fertilizer N, P, and K in cereal crops grown in different regions, estimated using quantitative evaluation of the fertility of tropical soils (QUEFTS) model at 60–70% of potential yield

Crop	IE_N (kg grains kg N^{-1})	IE_P (kg grains kg P^{-1})	IE_K (kg grains kg K^{-1})	References
Rice	42–96	206–622	36–115	Witt et al. (1999) and Witt and Dobermann (2004)
Rice	21–135 (53.9)	–	–	Sheng-guo et al. (2015)
Wheat	28.8–62.6 (43.9)	98.9–487.4 (227.0)	23.0–112.9 (52.7)	Chuan et al. (2013)
Wheat	40.1	269.1	43.1	Liu et al. (2006)
Spring maize	36–79 (59)	135–558 (287)	30–132 (65)	Xu et al. (2013)
Summer maize	31–70 (49)	108–435 (227)	32–110 (63)	Xu et al. (2013)
Maize	19.4–160.2 (54.3)	123.8–579.2 (251.5)	14.6–215.7 (78.2)	Jiang et al. (2017)

Values in the parentheses indicate mean

Table 24.6 Reciprocal internal use efficiency (RIE) of fertilizer N, P, and K in cereal crops grown in different regions, estimated using quantitative evaluation of the fertility of tropical soils (QUEFTS) model at 60–70% of potential yield

Region	Crop	RIE_N (kg N Mg^{-1})	RIE_P (kg P Mg^{-1})	RIE_K (kg K Mg^{-1})	Reference
China	Wheat	22.8	4.4	19.0	Chuan et al. (2013)
China	Wheat	25.8	3.7	23.3	Liu et al. (2006)
Southeast Asia	Maize	23.0	6.0	10.1	Setiyono et al. (2010)
China	Maize	20.3	4.4	15.9	Xu et al. (2013)
China	Maize	19.8	4.2	15.4	Jiang et al. (2017)
Asia	Rice	14.6	2.7	15.9	Buresh et al. (2010)
India	Rice	–	3.5	28.3	Pathak et al. (2003)

internal use efficiency (RIE) of fertilizer N, P, and K in cereal crops grown in different regions has been estimated by several researchers using quantitative evaluation of the fertility of tropical soils (QUEFTS) model at 60–70% of potential yield (Table 24.6). Buresh et al. (2010) predicted reciprocal internal efficiencies (RIEs) at 60–70% of yield potential corresponded to plant accumulation of 14.6 kg N, 2.7 kg P, and 15.9 kg K per tonne of rice grain yield using QUEFTS model (Table 24.5). Pathak et al. (2003), using a smaller data set from India, reported a higher RIE for K (28.5) and a comparable RIE for P (3.5), and Liu et al. (2006), using a data set from China, reported relatively comparable RIE for K (23.0) and P (3.7).

24.2.3.6 Soil Test-Based Fertilizer Application Approach

The general recommended dose (GRD) is suitable for the soils of medium fertility status and with no salt problem. But the soils differed widely with respect to their physical and chemical properties depending upon the fertilizer management by the individual farmer and the parent material from which they are originated. Further, the fertilizer application practices of farmers in any region are very diverse. Farmers not only apply either over or under fertilizer dose to the crops, but also the time and method of fertilizer application are very erratic. Even the uniform adoption of GRD does not always ensure the economy and efficiency of applied fertilizer, because the variation in the soil fertility status is not taken into account while recommending fertilizer dose. Therefore, the blanker fertilizer application regardless of the soil fertility status and other chemical/physical properties may end up with overuse of costly chemical fertilizers in high fertility soils and under use in low fertility soils. Such practice may lead to inefficient nutrient management, particularly in soils with contrasting fertilizer status or salt problems. At the same time, it may lead to the application of too much of the less required plant nutrient or too little of another nutrient which is the actual constraint in the optimum plant growth and hence the crop production.

Fertilizer application according to soil test results has been the most assessable option for the farmers since long to ensure balanced nutrition to the crops. Fertilizer recommendations based on soil test results are worked out by categorizing soils into low, medium, and high categories, considering GRD as a medium class. In general, for soils testing low or high, fertilizer recommendation for the crop is increased or decreased accordingly over GRD. Fertilizer recommendations based on soil test results are worked out by categorizing soils into low, medium, and high categories, considering GRD as medium class. In general, for soils testing low or high, fertilizer recommendation for the crop is increased or decreased by 25%, over GRD. Recommendation of nitrogenous fertilizers is given on the basis of the soil organic carbon (SOC) content, because SOC is known to govern nitrogen (N) availability in the soil system. In this contest, soils with SOC $<0.40\%$, 0.40–0.75%, and $> 0.75\%$ are rated as low, medium, and high N soils. Therefore, for soils testing low or high in SOC needs 25% more or less nitrogenous fertilizers, respectively, over GRD.

Soils with available $P < 5$, 5–9, 9–20, and > 20 mg kg^{-1} are rated as low, medium, high, and very high with respect to P supplying capacity to plants. Application of P fertilizer dose is recommended on the basis of P supplying capacity of soils. Fertilizer P recommendations to the crops are made not only on the basis of available P content, but the SOC content is also kept under consideration. Thus, if the SOC content is between 0.40% and 0.60%, the fertilizer P dose may be reduced by 25% of the recommended dose in medium P soil (5–9 kg P/acre) and by 50% in high P soils (>20 kg P/acre) with OC 0.40% (Table 24.7). Soils testing available $K < 55$ mg kg^{-1} and > 55 mg kg^{-1} are rated as low and sufficient K soils. In K-deficient soils, application of K fertilizers is recommended to meet its nutritional requirement. Soil test-based fertilizer application makes it possible to adjust (i) fertilizer application amounts and (ii) timing and methods of application based on soil

Table 24.7 Fertilizer P recommendations based on soil P test and soil organic carbon (SOC)

	Available P status (mg kg^{-1})			
SOC (%)	<5	5–9	9–20	>20
<0.40	Recommended	Recommended	Recommended	Recommended
0.40–0.60	Recommended	¾ recommended	½ recommended	0
>0.60	Recommended	½ recommended	0	0

Source: POP, Kharif-2018

test results, soil properties, and crops' response data from fertilizer trials. But, soil sampling and then its analysis are often time-consuming and laborious, and more often farmers do not get their soil test reports in time to ensure necessary changes in fertilizer application rates for the crop to be sown. Nonetheless, soil test results and soil test crop response correlation (STCRC) data are highly variable depending on the quality of sampling, analysis, and interpretation.

24.2.3.7 Fine-Tuning Fertilizer N Application Rates Using Leaf Color Chart (LCC)

One of the major factors for low nitrogen use efficiency is the fertilizer N application at uniform rates to spatially variable landscapes, despite of the fact that indigenous N supply, crop N uptake, and plants' response to applied fertilizer N are not the same spatially (Inman et al. 2005). Blanket recommendation of fertilizer application does not take into account the field-to-field variability and the dynamic changes in indigenous N availability within a growing season. Large field-to-field variability in soil N supply lowers the nitrogen use efficiency when blanket recommendations for fertilizer N application are followed. Recommendation of split fertilizer N applications at a specific growth stages did not result in a better match of the N supply from applied fertilizer with crop demand because of large variations in crop N requirements and soil N supply. Synchronizing the fertilizer N application to the crop N demand can result in high yield, reduced N losses, and more efficient utilization of applied fertilizer N. Therefore, improving nitrogen use efficiency requires greater synchrony between crop N demand and N supply from various sources throughout plant growing season (Cui et al. 2010; Zhang et al. 2012).

During the growing season, fertilizer N application is fine-tuned using portable diagnostic tools such as SPAD meter or with LCC. These are crop demand-driven, site-specific N applications gadgets that can enhance farmers' productivity and profits. Plant growth reflects the total N supply from all sources; therefore, a plant status could be a good indicator of N availability to a crop plants at a given time. It is an inexpensive alternative to SPAD meter that can quickly and reliably assess the N status of a crop based on leaf color and can be effectively used for need-based N management in crop. Farmers use leaf greenness as a visual and subjective indicator of the need for N fertilizer application and more often make fertilizer N application to crops based on leaf greenness (Wells and Turner 1984). LCC is standardized with the chlorophyll (SPAD) meter to assess the relative accuracy of LCC in measuring the greenness of plant leaves. In general, the difference between adjacent green color shades of the LCC is equal to 3–4 SPAD units. Therefore, LCC cannot indicate smaller differences in leaf greenness as the chlorophyll meter does. Using LCC shade 4 of greenness (LCC 4) as the threshold value for applying N to transplanted rice resulted in reduced application of fertilizer N and increased nitrogen use efficiency (Bijay-Singh et al. 2002). In Asia, research has shown that the same rice yield level could be achieved with about 20–30% less N fertilizer applied (Peng et al. 1996; Balasubramanian et al. 2000; Bijay-Singh et al. 2002).

24.2.3.8 Fine-Tuning Fertilizer N Application Rates Using SPAD Meter

A critical N level below which crop suffers from N deficiency and causing a yield reduction (known as threshold SPAD value) is obtained from the relationship between SPAD reading and leaf area-based N concentration. According to Peterson et al. (1993), SPAD threshold value is independent of the luxurious N consumption, because plants produce only as much chlorophyll as it needs, irrespective of how much N is in the plant. Leaf chlorophyll content could be estimated using chlorophyll meter (Takebe et al. 1990; Peng et al. 1996; Balasubramanian et al. 1999; Yang et al. 2003). A SPAD threshold of 35 for rice, which represents a leaf area-based N concentration (of 1.4 g N m^{-1} leaf area), is reported to achieve a potential grain yield (Kropff et al. 1994; Peng et al. 1996). In maize, Rostami et al. (2008) reported that SPAD meter is not a good technique for early prediction of N status, while the photosynthetic maturity is the best time for prediction of N status, because at this time chlorophyll reaches to its maximum. There are several factors which affect the SPAD reading such as environmental conditions, biotic and abiotic plant stress, supply of other nutrients (than N), and plant density and infect the crop variety (Peterson et al. 1993). Accurate prediction of plant N status using SPAD meter requires an individual calibration of the relationship between SPAD readings and N concentration for different cultivars grown under specific growth conditions and at a specified growth stage (Peng et al. 1995). Although SPAD meter provides a simple, rapid, and nondestructive method for estimating leaf chlorophyll content (Watanabe et al. 1980), due to relatively high cost of SPAD meters, this gadget seems to have limited acceptance by the farmers. LCC, on the other hand, is a simple, easy to use, and relatively inexpensive tool that could be used to determine field-specific N requirement of crops.

24.2.3.9 Fine-Tuning Fertilizer N Application Rates Using GreenSeeker

The “GreenSeeker” is a crop sensing system which effectively and precisely managed crop inputs especially application of N (nitrogen), urea, and NH_3. The GreenSeeker system uses optical sensors to measure and quantify the variability of the crop. It then creates a targeted prescription to treat the crop variability. Use GreenSeeker to apply N (nitrogen), urea, and NH_3 to improve crop yields and ultimately increase the profitability (Erdle et al. 2011). GreenSeeker can address field variability by applying the right amount of fertilizer, in the right place, at the right time (Quebrajo et al. 2015). The GreenSeeker ensures accurate and balanced nitrogen fertilizer applications, cutting farmers' costs, reducing nitrification and nitrogen runoff into groundwater and water systems, and raising crop yields (CIMMYT 2015). Using normalized difference vegetation index (NDVI) values from GreenSeeker, N Calculator automatically calculates the best nitrogen and urea rate.

However, among the GreenSeeker, the Trimble GreenSeeker (Fig. 24.7 and 24.8) handheld crop sensor is an affordable, easy-to-use measurement device that can be used to assess the heath or vigor of a crop in order to make better nutrient management decisions on your farm (Mohanty et al. 2015).

Typical applications for using this tool include sensing and agronomic research, biomass measurements and plant canopy variations, nutrient response, yield potential, and pest and disease impact. This allows to get real-time readings for grain crops, vegetables, turf, sugar cane, and many others. Hold the sensor over the crop

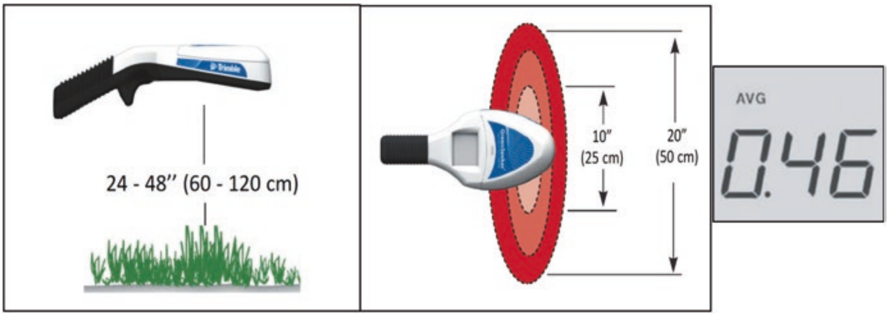

Fig. 24.7 A Trimble GreenSeeker with details: LCD display (**a**), battery access panel (**b**), wrist strap attachment loop (**c**), trigger (**d**), micro USB port for charging (**e**), remote switch connection (**f**), string attachment loop (**g**)

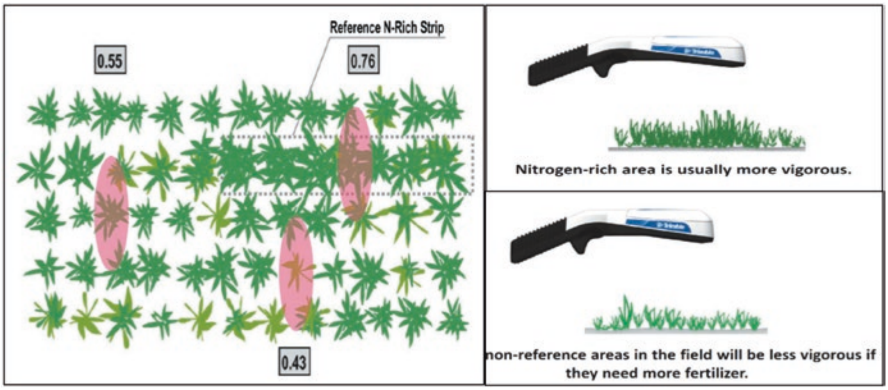

Fig. 24.8 How to work a Trimble GreenSeeker with details

canopy and then pull the trigger 24″–48″ above the crop (Fig. 24.8). Then, readings displayed on the display screen.

The sensor's field of view is an oval; its size increases with the height of the sensor (approximately 10″ wide at 24″ above the ground, 20″ wide at 48″ above the ground) (Fig. 24.8). To obtain a reading representing a larger area, walk with the sensor while keeping the trigger engaged, and maintain a consistent height above the target. The display updates continuously, but accumulates multiple readings and provides an average when the trigger is released. The maximum measurement interval is 60 seconds. It should pull the trigger to start a new measurement. The unit automatically turns off after completing the measurement; then pull the trigger to clear the screen, and begin a new measurement at any time (Fig. 24.8).

24.2.3.10 Using the Sensor to Estimate a Fertilizer Rate

A key use of this sensor is to estimate fertilizer application rates. Sensor measurements combined with agronomic information such as type of crop may be used to estimate a fertilizer rate. The steps that follow show one procedure to get readings for a field that includes a reference area. These values are then referenced on the chart and table to determine a rate per the example.

An N-rich strip is a small area within the field to which more than enough fertilizer has been applied at or before planting (Fig. 24.9). This area will be a gauge of the crop not limited in vigor due to insufficient fertilizer. Including a reference area or "N-rich strip" provides an accurate method to determine how much additional fertilizer is necessary to maximize the crop yield in a particular field. Use the peak value within the N-rich strip and a value typical of other areas of the field as two inputs to the Fertilizer Estimation Chart (Table 24.8) to determine an application rate. For example, row corresponding (see Table 24.7) 'winter wheat' and find the column that corresponds to maximum yield of crop and region at the top of the Table 24.8 (175 bu/ac). The value where the row and column intersect is your crop factor, for example, 439. For more information on the N-rich strip, practice is available (Trimble 2018).

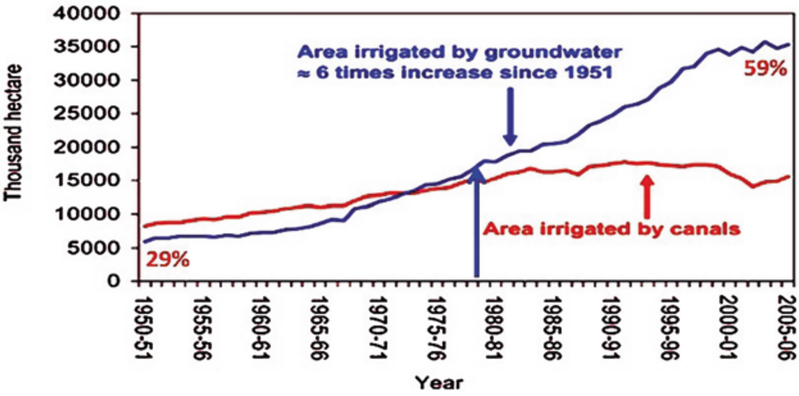

Fig. 24.9 Using the sensor to estimate a fertilizer rate

Table 24.8 Fertilizer Estimation Chart for estimation of crop specific fertilizers dose on the basis of GreenSeeker reading

			Maximum yield (bu/ac)											
Crop	%N	lb/bu	15	25	50	75	100	125	150	175	200	225	250	275
Spring wheat	2.45	60		66.8	134	200	267	334	401	468				
Winter wheat	2.30	60	37.6	62.7	125	188	251	314	376	**439**				
Dryland corn	1.30	56				99.3	132	165	199	232	265	298	331	
Irrigated corn	1.25	56					127	159	191	223	255	286	318	350
Barley	1.70	48	22.3	37.1	74.2	111	148	185	223	260				
Triticale	2.10	54	30.9	51.5	103	155	206	258	309	361				
Sorghum	1.34	56				102	136	171	205	239	273	307		
Canola	3.10	50	42.3	70.5	141	211	282							

Source: Trimble (2018)

24.2.4 Use of Resource Conservation Technology for Sustainable Crop Production

24.2.4.1 Promote Climate-Smart Agriculture (CSA)

Among the resource conservation technology, climate-smart agriculture (CSA) is a substitute approach to manage soil productivity and fertility sustainably (Lipper et al. 2014). The CSA concept has enlarged a considerable attention in developing countries, due to its potential to increase food security and farming system resilience, also for reducing the emissions of greenhouse gas (FAO 2010, 2013; Grainger-Jones 2011). In the year 2010, at the first Global Conference on Agriculture, Food Security and Climate Change at The Hague, the idea of CSA was first raised in researchers that came from different countries from all over the globe. It is composed on the three main pillars such as sustainably increasing agricultural productivity, familiarizing, and building resilience to climate change through sinking the emissions of greenhouse gas (FAO 2013; Lipper et al. 2014; Braimoh 2015; Mwongera et al. 2017).

The soil is the major component of CSA (Braimoh and Vlek 2008); therefore, one of the best examples of CSA in action is the use of so-called integrated soil fertility management (ASHC 2012). While soil organic matter plays a vital role for improving the soil fertility and productivity, the continuous use of crop residues, in combination with inclusion green manure, legumes, and organic manure, strongly influences soil productivity as well as nutrient status in the soil-plant system (Braimoh 2015; Hossain et al. 2016; Jahan et al. 2016). However, the goals of CSA cannot be encountered without plans and initiatives that encourage agricultural innovations and research, to establish the stronger connections between farmers, climate-smart supply chains, and markets (Braimoh 2015). Therefore, CSA needs to shift beyond development practitioners to involve government agencies more often.

24.2.4.2 Introduction of Conservation Agriculture (CA)

Conservation agriculture (CA) is an eco-friendly farming approach that fosters natural and ecological processes for improving agricultural productivity and sustainability by lessening soil disturbance, preserving permanent soil cover, and diversifying crop rotations (Dagar et al. 2016). CA can play a significant role in soil amelioration and crop production.

The permanent ground cover through residue management as well as inclusion of legumes is a fundamental aspect of CA, and it is important for several reasons, such as the presence of residue over the soil surface prevents aggregate breakdown by direct raindrop impacts as well as by rapid wetting and drying of soil (Le Bissonnais 1996), increases water-stable aggregates, enhances water-holding capacity and infiltration rate, ameliorates soil sodicity and salinity, lowers soil erosion through reducing runoff, increases root permeability in soil, and increases soil porosity that ultimately helps to increase the essential microbial activity including earthworms (Hamza and Anderson 2005; Hobbs and Govaerts 2010).

Considering CA-based zero-tillage cultivation, it was noticed that zero-tillage cultivation system with residues retention can save about 13–33% water use and

75% of fuel consumption (Hobbs and Gupta 2003; Naresh et al. 2013; Bhatt 2017), similarly bed planting also has the potential to save water use from 30–50% in wheat (Hobbs et al. 2008; Erenstein et al. 2008; Jat et al. 2009). Both the technologies have also been shown beneficial in terms of improving soil health, water use, crop productivity, and farmers' income (Gupta and Seth 2007). Under permanently raised bed planting with residue retentions, sodicity was reduced significantly, reducing Na concentration by 2.64 and 1.80 times in 0–5 cm and 5–20 cm layer, respectively, compared to conventional tilled raised beds (Govaerts et al. 2007a, b). As compared to conventional tillage, values of interchangeable Na, exchangeable fraction, and dispersal index were lower in an irrigated vertisol after 9 years of minimum tillage (Hulugalle and Entwistle 1997; Hulugalle et al. 1997).

24.2.5 Use of Nanotechnology for Sustainability of Crop Production System

A crop production system in general is a precision agricultural approach, where food and fiber produced are concurrently profitable; use on-farm affordable resources without hampering biodiversity; conserve quality of products, dynamic nature of soil, and systemic nutrient density of the available water; and support energetic rural community (Walters et al. 2016; Duhan et al. 2017).

This decent eco-friendly crop production system is further supported by the advanced application of nanotechnology-based approach (Parisi et al. 2015; Duhan et al. 2017). Currently, nano-based approaches have stigmatized the concept that something is impossible and beyond the reach of mankind. Present advancement made in the field of agriculture may majorly improve two basic aspects of agriculture that are soil and productivity apart from the universally required water.

Nanomaterials for the improvement and sustenance of soil and improvement of crop are generally either of organic (chitosan, polyacrylic acid, clay, zeolite, etc.), inorganic (Fe, Zn, SiO_2, TiO_2, etc.), or both hybrid origins (polymer-encapsulated carbon nanotubes, nanodiamonds, graphene, etc.) (DeRosa et al. 2010; Duhan et al. 2017; Morales-Díaz et al. 2017).

These nanomaterials are used for the preparation of various forms of nano-based agricultural tools in order to preserve soil dynamic nature of the soil as well as to improve crop productivity by nano-fertilizer and, additionally, to protect the crops from biotic stress by nano-pesticides and have seriously made an impeccable impact in the sustainable improvement of agricultural research (Chhipa 2017).

24.2.6 Slow-Release Fertilizers (SRF) to Improve Nutrient Use Efficiency

Matching nutrient supply with plant demand and maintaining nutrient availability are the two main pillars for increasing nutrient use efficiency (NUE) and mitigating the adverse consequences of global warming. Further, there is an interaction between rhizosphere, microorganisms, and soil pH which affects the ecosystem. Supply of a particular nutrient in soil higher than its demand will certainly lead to its losses either through leaching, runoff, volatilization (physical processes), nitrification, denitrification, immobilization (microbes) (e.g.,), exchange, fixation, precipitation, or hydrolysis (chemical reactions). Specific periods for higher nutrient demands are specified for each crop as macronutrient demand by seasonal crops is sigmoidal (Christianson and Schultz 1991; Shoji and Kanno 1994). Thus, keeping a balance between need and supply is the key to improve the NUE, where slow-release fertilizers, viz., neem-coated urea and polycoated urea, played a significant role in practicing sustainable and climate-smart agriculture. Further, there are different advantages, viz., environmental, economic, and physiological, which are associated with the slow-release fertilizers.

Under the environment benefits, it is very clear that slow release of the nutrient will certainly reduce their loss both to the underground and to the environment also as N_2O or CO_2 or CH_4 which on the long run will certainly mitigate the adverse effects of the global warming on one side while helps in practicing the CSA on the other side. As far as physiological benefits concerned, it is observed that slow-release fertilizers will improve germination and grain quality while reducing insect pest attack and disease infestation (Givol 1991; Trenkel 1997) as higher salt concentration in rhizosphere with common fertilizers (Trenkel 1997) will induce osmotic pressure and lodging (Goyal and Huffaker 1984). Furthermore, SRF will also improve the availability of the nutrients that generally got fixed, viz., P (Hagin and Harrison 1993), which further reported in plant edible parts such as P (Shaviv et al. 1995) and Fe (Mortvedt et al. 1992). Further, Givol (1991) delineated that SRF contained higher proportions of NH_4 which produced greater yields of millet and induced an increased accumulation of proteinaceous material in edible portion of the plants. As far as economic benefits are concerned, it is reported that SRF has potential to reduce nutrient losses (Shaviv and Mikkelsen 1993; Trenkel 1997). Further, CRFs reduce the demand for manual labor for applying split doses of the urea fertilizers in paddy season, such as for rice crop (Fujita et al. 1989, that is required during critical periods. CRF also cut down the total amount of fertilizer required to fulfill the crop need because of controlled release of the nutrients in the soil solution (Hauck 1985). Further, CRF could be classified into two types.

24.2.6.1 Slow (SRF) Vis-a-Vis Controlled Release (CRF) Fertilizers

While preparing CRF several factors viz. rate, pattern and duration of release (Shaviv 1996) which further decide its fate in improving the NUE. Under the SRF, the nutrients released slowly than the commercial available ones, but here rate, pattern, and duration of release are comparatively less controlled. According to Raban et al. (1997), SRF might be affected by factors, viz., storage and transportation, and with field conditions, viz., moisture content, etc. Microbially decomposable nitrogen products, such as urea-formaldehyde, could also be used as SRF. Generally, N fertilizers where ammonium is stabilized by inhibitors are classified as SRF which proves to improve NUE more particularly in medium to high CEC soils which have a good storage capacity of ammonium (Stangel et al. 1991; Landels 1994).

24.2.6.2 Systematic Classification

SRF or CRF could also be classified into three categories:

1. Low solubility organic N compounds which might be biologically decomposable compounds, viz., urea-formaldehyde, or chemically decomposable compounds, viz., isobutylidenediurea.
2. Hydrophobic polymers which restrict the dissolution of the fertilizers, viz., resins, etc., or hydrophilic polymers, viz., hydrogels.
3. Metal ammonium phosphate and partially acidulated phosphates rock (PAPR) are typical slow-release fertilizers of inorganic low solubility.

Further, Fan and Singh (1990) and Kumar et al. (2010) proposed the following four types according to the mode of release control: (i) diffusion, (ii) erosion or chemical reaction (decomposition), (iii) swelling, and (iv) osmosis. Further, SRF could be categorized into two types of fertilizers, viz., neem coated urea and poly-coated urea.

24.2.6.3 Neem-Coated Urea (NCU)

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are grown sequentially in an annual rotation constituting a rice-wheat (RW) cropping system which is a dominating system being practiced in ~85% of the cultivated area in Punjab. The nitrogen (N) requirement of these crops in the region is being met through urea (46% N), and through an extensive research, it has been substantiated that of the total quantity of applied N through urea, ~50–70% is subjected to leaching, ammonia volatilization, and denitrification losses. According to Singh and Singh (2003), N use/recovery efficiency in RW cropping system rarely exceeds 30–40%. The improvement in the N efficiency is, therefore, of prime importance, not only for achieving and sustaining high crop grain yield but also to protect the natural resources from degradation. The use of slow-release N fertilizers such as sulphur-coated urea (SCU) in rice has been reported to be a better option than ordinary urea (OU) in almost all types of soils (Singh and Katyal 1987). In India, the blended use of OU with neem cake was the traditional practice with the belief that when they are applied together, nitrogen use efficiency (NUE) in rice is enhanced (Agarwal et al. 1980; Singh and Singh 1986). Devakumar and Goswami (1992) reported that oil derived from neem seeds contain melicians of which epinimbin, deacetyl, salanin, and azadirachtin showed dose-dependent inhibition of nitrification. According to Singh and Singh (2003), oil forms a fine coating and protects the N due to denitrification losses, thereby ensuring regulated and continuous availability of N over a long period of time, as required by crops. Although it had been established long ago that neem products, when applied along with urea, can enhance NUE in crops (Singh and Singh 1986), the practice did not find large-scale application because a process to coat urea with neem products on a large scale was not available. The Indian Agricultural Research Institute (IARI) refined the technique of coating urea using neem oil emulsion @ 0.5–1.0 kg neem-oil tonne^{-1} of urea (Suri et al. 2004). Recently, National Fertilizer Limited (NFL) has also started the manufacturing of

NCU on commercial scale. Therefore, there was need to compare the efficiency of NCU in comparison to OU in RW cropping being practiced at farmers' field. Further, Bhatt's (2012) study in sandy loam soil of Kapurthala district of Punjab, India, revealed that there are no significant differences in agronomic efficiency of N (AEN) applied through different sources at equal applied level, while there was significantly higher AEN for 80% NCU/80% OU than 100% NCU/100%OU in both wheat and rice. The total energy productivity for wheat in 100% NCU/100%OU was 6.87% higher, with a decrease in energy productivity by 0.11 MJ ha^{-1} than 100% NCU/100%OU. However, in rice the total energy productivity was 14.9% higher in 100% NCU/100%OU with 0.16 MJ ha^{-1} over T1/T2 (Bhatt 2012).

24.2.6.4 Polycoated Urea (PCU)

The Association of American Plant Food Control Officials (AAPFCO) has adopted the term "enhanced efficiency fertilizers" (EEF) to characterize products that can minimize the potential of nutrient loss to the environment, as compared to conventional soluble sources, viz., urea (Hall 2005). Among EEF, two important groups of fertilizers, viz., slow- or controlled-release fertilizers, were being proposed (Trenkel 1997). One group is formed by condensation products of urea and urea aldehydes. The second group is comprised of coated or encapsulated fertilizers, such as S-coated urea (SCU) or polymer-coated urea (PCU), which reduce the transformation rate of fertilizer compounds, resulting in an extended time of availability in the soil even if applied with single dose.

SCU with 7-day dissolution rates in water of 10%, 20%, and 30% were used in most of the tests. Despite the favorable results often reported in field trials (Allen 1984), the SCU products required a 20–23% coating weight that resulted in a lower N content (35–37%) than uncoated urea (46% N) (Young 1974), which would increase transportation costs on top of the additional cost for S coating. Consequently, SCU has not been accepted by farmers, mainly because of its lower nitrogen content and higher price. PCU prepared by Gujarat State Fertilizer limited has around 42% nitrogen compared to 46% nitrogen present in conventional fertilizers (Singh et al. 2018).

However, as compared to the SCU, in PCU, the coatings are usually resins or thermoplastic materials, and their weight can be as low as <1% of the granule mass without significantly reducing the N content. Unlike SCU which releases urea through small pinholes that can result in a more difficult controlled-N release pattern, PCU releases N by diffusion of urea through the swelling polymer membrane. The release pattern is related to the coating composition and usually depends on soil moisture and temperature (Christianson 1988), although some products are reported to be affected little by soil moisture, soil microbial activity content, pH, and even temperature (Shaviv 2005). It is possible, by changing or combining coatings, to formulate fertilizers which release 80% of their nutrients in pre-established time intervals such as 80, 120, 180, or even 400 days (Shaviv 2005; Shoji et al. 2001). Hence, PCU were in more demand as compared to the SCU.

Fertilizer recovery with PCU was reported to be 70–75% compared with 50% with prilled urea (PU). The higher recovery of N from PCU products was related to

N release and subsequent N uptake by rice during the post-anthesis stage. A one-time application of PCU may have distinct advantages over prilled urea, not just in terms of labor saving but also because PCU may provide a more stable and sustained N release in rainfed crop systems where well-timed split N applications may not be feasible due to variability in rainfall and soil moisture (Singh et al. 1995). Thus, studying water-nutrient interactions also needs to be explored as PCU might be more effective under the stressed conditions, viz., rainfed areas.

Coated urea also performed better than conventional fertilizers by promoting increased grain yield and N uptake in rice in Spain (Carreres et al. 2003), winter wheat in China (Fan et al. 2004), peanuts in Japan (Wen et al. 2001), potatoes in the USA (Munoz et al. 2005), and maize in Japan (Shoji et al. 2001). Thus recognizing the need to increase the N-use efficiency and to mitigate the underground water pollution and global warming consequences, many countries have already started working in this direction, viz., China. Now preparing PCU at the lower costs is emerging as the new area of the research (Li et al. 2012).

But till now, as per our knowledge in India, the studies in this regard are missing in the literature though benefits of the PCU are well established throughout the world as many countries replaced the ordinary urea with PCU. Further, Singh et al. (2018) conducted PCU trials at Ballowal-Saunkheri and in Tarn Taran district of Punjab and result revealed that labour cut is therewhile Under unstressed (irrigated) and stressed (rainfed) conditions: In station trials as well as farmers' field trials 75% recommended N through polycoated urea (split doses) or 100% recommended dose of polycoated urea as basal dose gave better wheat grain yield, straw yield and yield attributing traits, which was statistically at par with treatments of 100% recommended dose of neem coated urea and 100% polycoated urea in split doses, and 50% N - polycoated urea and 50% N normal urea treatment, respectively. In maize, under unstressed (irrigated) and stressed (rainfed) conditions, 75% polycoated urea (split doses) treatments under irrigated and rainfed conditions gave higher grain and straw yield which was statistically at par with the other 100% polycoated urea treatments and significantly higher over 100% neem-coated urea treatment, while in rice under unstressed (irrigated) conditions, 100% polycoated urea (split doses) treatments gave higher grain and straw yield which was statistically at par with the other 100% polycoated urea as basal and 100% neem-coated urea treatment (split doses) (Singh et al. 2018).

24.2.7 Techniques to Improve Water Use Efficiency

Water is a must input for agriculture; it's timely and assured availability greatly affects the agricultural production. India is the largest groundwater user in the world (230 km^3 $yr.^{-1}$), more than a quarter of the global total water used (Tyagi et al. 2012). Indian subcontinent groundwater use has soared from 10–20 km^3 before 1950 to 240–260 km^3 by the turn of the century (Prihar et al. 2010). The small states of Punjab and Haryana often referred to as the "Food Bowl" of the country produce 50% of the national rice production (Dhillon et al. 2010). NASA's gravity mapping satellite "GRACE" tracks the local gravity filed of an area on the assumption that if we remove much of groundwater, there is a loss of mass which further resulted in the decrease of the gravity. Recent reports of the satellite showed that in North India about an area of 440,000 km^2 groundwater declined at an alarming rate of 1 ft. year^{-1} which further resulted in the loss of 4 cm loss of raw groundwater or 18 km^3 year^{-1} (Soni 2012). The status of water resources in Punjab state are presented in which shows annually we required 43 lakh ha-m of irrigation water and we have 30 lakh ha-m of water annually in our pocket, thus it mean we are already short of 13 lakh ha-m of water which we withdraw from the underground (Table 24.9) and water level in central parts of the state declining at an alarming rate (Fig. 24.1) where the significance of the different resource conservation technologies (RCTs) increased to manifold but again these RCTs are not universally applicable and are site specific.

Nationally, the area underground water irrigation has increased by six times over the last six decades (1950–1951/2005–2006) (Fig. 24.10) in contrast to declined share of water in agriculture because increased demand of nonagricultural sectors has increased from the last few decades (Tyagi et al. 2012).

Therefore, the comprehensive assessment of innovative resource conservation technologies (RCTs) for efficient water management in crop production should take stock of the costs, benefits, and impact on natural resources (Humphreys et al. 2010). The laser levelling, direct-seeded rice (DSR), bed planting, zero till (ZT) wheat with Happy Seeder and rice with mechanical transplanter, growing of

Table 24.9 Status of water resources in Punjab

Annual canal water available at head works	14.54 m ha-m
Annual canal water available at outlets	1.45 m ha-m
Annual groundwater available	1.68 m ha-m
Total annual available water resources	3.13 m ha-m
Annual water demand	4.40 m ha-m
Annual water deficit	1.27 m ha-m

Source: Jain and Kumar (2007)

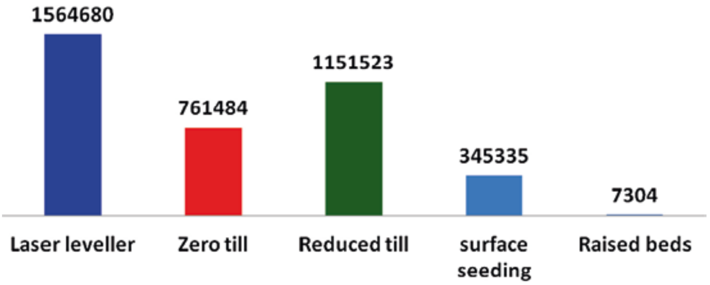

Fig. 24.10 Irrigation trend by canals and groundwater. (Tyagi et al. 2012)

short-duration cultivars, mulching, etc. are among the common RCTs being advocated in the region that had shown a promising potential for increasing the water productivity of the rice-wheat cropping system. We are going to discuss them as RCTs are cutting drainage losses and RCTs are cutting evaporation losses.

24.2.7.1 Laser Leveler and Its Impact on WP

Most of the times, uneven topography of land is considered as one of the factors responsible for lower land and water productivity for which laser land leveler already recommended in the region. Among various RCTs advocated for improving the water productivity, laser levelling is widely accepted and adopted in the region (Fig. 24.11). It was because of the fact that laser leveler levels all the dukes and dikes and causes uniform distribution of the water and caused distribution of irrigation water on a large area within shorter period of time. In uneven lands, many plants suffered from both excess and limited supply of the irrigation water. Further, more time taken up by low lying areas for filling and many a times, higher areas remained unirrigated where crop failure is not uncommon. In Indian Punjab, laser leveler was introduced on an experimental basis in the Sukhanand village of Moga district on an area of 150 acres, and around 300 farmers took part in these demonstrations. It was revealed that around 25–30% of irrigation water could be saved through this technique without having any adverse effect on the crop yield (Bhatt and Sharma 2009). Secondly, the irrigation water took comparatively lesser time for reaching the other corners of the field, and thereby in lesser time higher area could be irrigated which further results in higher land productivity.

Kahlown et al. (2006) and Jat et al. (2009) well documented the crop yield augmentation coupled with improved irrigation water productivity with land levelling. Further, Jat et al. (2011) shown higher irrigation water productivity in laser-leveled plots than traditionally leveled plots (Table 24.10) as compared to the controlled plots when fertilized at the same rate with different fertilizers.

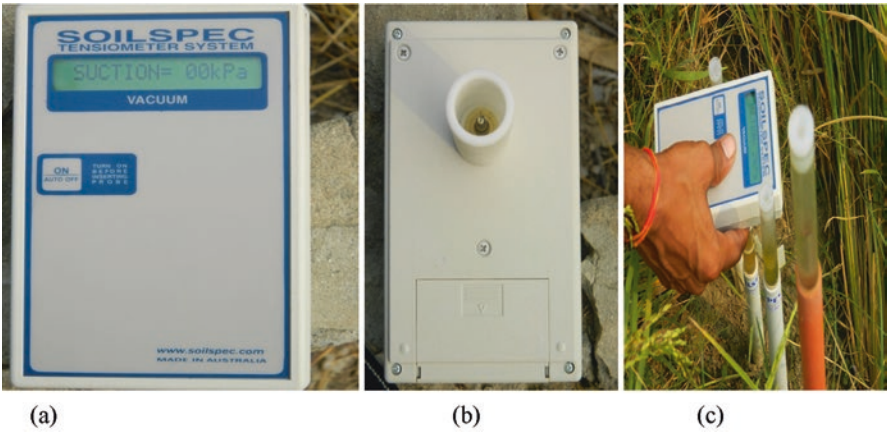

Fig. 24.11 Acreage (ha) of resource conservation technologies in South Asia. (Jat et al. 2009)

Table 24.10 Effect of laser land levelling and planting techniques on water productivity of wheat (mean of 2 years)

Treatment	Total number of irrigations applied	Irrigation water use (m^3 ha^{-1})	Irrigation water productivity (kg grain m^{-3} water)
Precision leveling ($N_{126}P_{26}K_{50}$ ha^{-1})	4.5	2847.5	1.80
Traditional leveling ($N_{126}P_{26}K_{50}$ ha^{-1})	4.5	3946.0	1.22
Traditional leveling ($N_0P_0K_0$ ha^{-1})	4.5	4789.5	0.560
SE±	–	13.88	0.043

Source: Jat et al. (2011)

24.2.7.2 Permanent Beds and Their Impact on Water Productivity

Permanent beds earlier proposed as resource conservation technique as it saved a subsequent amount of irrigation water but further in a due course of time contradictory studies reported by Kukal et al. (2010). According to them there is no saving in the amount of irrigation water under PTR and transplanted rice on permanent raised beds in a sandy loam soil, because of higher cracking of loam in permanent beds when a full-furrow depth of irrigation was applied, but on the contrary, higher water use efficiency (WUE) was observed in bed planted crops (Brar et al. 2011). With time, the irrigation water productivity on permanent beds decreased as side slopes of the permanent beds were compacted due to tractor tyre pressure during repeated reshaping and sowing of wheat and to natural aging of the beds (Kukal et al. 2008). Inquiring about water productivities under no-till, conventional till, and permanent beds, Jat et al. (2009) and Singh et al. (2010) found higher water productivity under permanent beds as compared to other two methods (Table 24.11 and 24.12). But Kukal et al. (2008) provide evidence that these beds were quite effective initially, but year after year, due to reshaping operation, the side slope of beds got compacted resulting in higher bulk density. Secondly, the surface area of these beds was about 25% higher, resulting in higher absorption of radiant energy which resulted in higher evaporation losses needing more water, and finally aged beds had lower water productivity. Thus, this RCT is still under contradiction as far as water and land productivities were concerned in subtropics of South Asia.

24.2.7.3 Short-Duration Crop Cultivars and Their Impact on Water Productivity

As Jalota et al. (2009) reported that in long duration cultivars (PR-118), irrigation water requirements decreased to 110 mm from 25 May to 10 June while 260 mm if transplanting time delayed to 25 June. Though they reported some yield loss there, ultimately water productivity increased because of greater saving of irrigation water. But in the short-duration cultivars (RH-257), grain yield also increased along with saving of irrigation water which increased the water productivity (Table 24.13).

Table 24.11 Irrigation water productivity (kg grain m^{-3}) of maize genotypes under different establishment methods

Maize genotype	No-till flat	Conventional tillage	Permanent beds
HQPM-1	2.1	2.1	2.9
Shaktiman-4	1.9	1.7	2.6
HM-5	1.5	1.3	1.9
ST-2324	2.1	2.2	3.1
Bio-9681	2.4	2.1	3.0
Mean	**2.0**	**1.9**	**2.7**

Source: Jat et al. (2009)

Table 24.12 Effect of different treatment on root density, soil water content, consumptive water use, and water use efficiency

Treatment	Root density (gm^{-3})	Consumptive water use (mm)	Water use efficiency (kg ha-mm^{-1})
Zero tillage	2358.9	468.0	9.34
Conventional tillage	2400.2	464.8	9.50
Bed planting	2716.9	460.8	*9.91*

Source: Singh et al. (2010)

Table 24.13 Effect of transplanting date and variety on yield and water requirements of rice

Transplanting date	Irrigation water (mm)	Grain yield (t ha^{-1})	Irrigation water (mm)	Grain yield (t ha^{-1})
	PR-118 (155–160 days)		RH-257 (110–120 days)	
25 may	2530	7.5	2350	6.8
10 June	2420	6.6	2310	7.3
25 June	2270	7.1	2120	7.5
Mean	2407	7.1	2260	7.2

Source: Jalota et al. (2009)

24.2.7.4 Soil Matric Potential-Based Irrigation and Their Effect on the Water Productivity

Generally, the farmers opted for flood irrigation in the fields which is responsible for wastage of a significant amount of irrigation water. Keeping this in view, Punjab Agricultural University, Ludhiana, has already recommended 2-day intermittent irrigation which means after flood irrigation, farmers have to wait for 2 days after the flooded water seeped into the ground. Further, one more good approach is to apply irrigation as per crop need depending upon the soil matric potential (Kukal et al. 2014) with the help of tensiometer. Tensiometer measured the soil matric potential and thus is a quite effective technique to decide when to irrigate a crop based on the soil suction behavior (Fig. 24.12). Kukal et al. (2005) and Bhatt and Sharma (2010) reported that soil matric tension-based irrigation scheduling helps in significant saving of irrigation water with almost similar/higher yields and thus

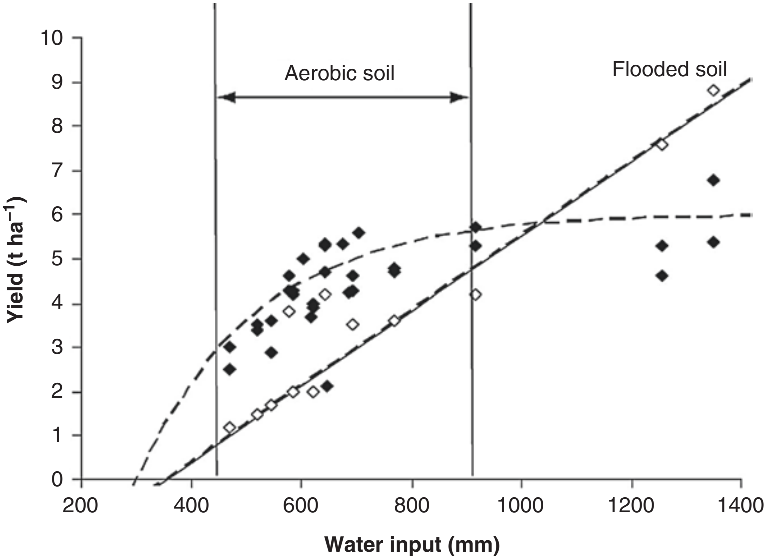

Fig. 24.12 Soil spec front view (**a**), rear view (**b**), and in action measuring soil water tension (**c**)

Table 24.14 Water productivity of puddle transplanted rice

Irrigation schedule	Irrigation water productivity (g kg^{-1})
Continuous flooding	0.28
Intermittent irrigation (2-day gap)	0.34
Tensiometer based	0.50

Source: Kukal et al. (2005)

Table 24.15 Soil matric potential-based irrigation scheduling results in farmers' fields in Kapurthala district

Year	Per cent irrigation water savings	Yield differences
2006	29.6–30.7	+0.5–1.5%
2007	25.0–27.2	At par
2008	18.0–27.8	At par
2009	16.6–20.8	+0.5–1.0%
2010	11.1–21.4	At par

Source: Bhatt and Sharma (2010)

helps in increasing the water productivity in the region as it dictates the farmers as when to irrigate (Table 24.14 and 24.15).

Thus in reality, it is an effective technique to save irrigation water particularly in rice in medium-textured soils, and KVKs of the PAU, Ludhiana, make every effort to make it popularize among the farmers of the state by organizing different camps, demonstrating in front of the farmers the worth of this technology by conducting on-farm trials, and with the result, farmers show their interest in this RCT and the department of agriculture and soil conservation department purchased and gave this to the farmers at subsidized rates for its use at their fields. But, tensiometers though are a sound technology for irrigating paddy fields, but not much welcomed by the farmers of the states. The following reasons might be claimed for its lesser adoption in the fields:

1. Due to complexity in saturating it with water overnight and secondly, fixing it in the ground and removing it 15 days prior to harvesting and cleaning it with sulphuric acid for the next season involve many technical issues.
2. Noting down reading or water level in strips on daily basis makes it difficult for the employed labor to use it.
3. Employed laborers are least concerned with declining underground water levels of the state, and many a times they are found irrigating fields even on rainy days as they are getting their wages for applying irrigation.
4. Many a times, farmers are not able to apply irrigation even when tensiometer dictates might be due to electricity cuts or lack of his turn.

24.2.7.5 Date of Transplanting (DOT) and Their Influence on the Water Productivity

DOT is a very important RCT for uplifting WP as early transplanted crop has highest evapotranspiration losses and lower water productivities associated with early transplanted/sown crops (Table 24.16). This is one of the most important RCTs which has a sound scientific base and which also guides the even politicians for saving the irrigation water. Earlier, farmers used to transplant the paddy nursery in May. During the month of May, the air is quite dry and thus lifts up water vapors to maintain vapor pressure gradient. As a result, farmers have to apply frequent irrigations to meet the crop demand which finally resulted in lower irrigation water productivity. Punjab government implemented the law to go for nursery sowing after 15 May and transplantation of nursery into the field only after 15 June. Any farmers violating this law are punished by disking his sown nursery back into the soil.

Getting extremely good response from this law, the Punjab government has now revised this rule where the date of nursery sowing and transplantation of this nursery into the field revised to 20th of May and 20th of June from this very year viz. 2018

Table 24.16 Effect of date of transplanting (DOT) and N levels (Kg ha^{-1}) on the crop water productivities (kg m^{-3})

Parameters	N_0	N_{240}	N_{300}	N_{360}	Mean
Transplanting rice on 5 June and wheat on 20 October	0.78	1.11	1.13	1.13	1.04
Transplanting rice on 20 June and wheat on 5 November	0.78	1.21	1.27	1.30	1.14
Transplanting rice on 5 July and wheat on 20 November	0.67	1.13	1.20	1.25	1.06
Mean	0.74	1.15	1.20	1.23	

Source: Jalota et al. (2011)

Table 24.17 Diversification for improving water productivity

Cropping systems	ET (mm)	E_b (mm)	Component crop yield (t ha^{-1})		Wheat equivalent yield (t ha^{-1})	Water productivities (Kg m^{-3}) based on	
			C_1	C_2		ET	NWL
Rice wheat	1030	210	6.0	4.5	9.7	0.94	0.78
Cotton wheat	980	901	2.0	3.5	8.6	0.88	0.80
Maize wheat	860	220	3.5	4.5	7.2	0.84	0.67

Source: Arora et al. (2008) and Jalota and Arora (2002)

and the experts are expecting good response and a hault in the decline of underground water as shorter the stay of a crop in the field, lesser evaporation and thus lesser required irrigation water and finally resulted in the higher WP Crop diversification played a pivotal role in decreasing.

Amount of irrigation water was required, and it was revealed that (Jalota and Arora 2002; Arora et al. 2008) particularly diversion from rice helped to increase the water productivity for the system as a whole. Evapotranspiration losses decrease if system diversified from rice-wheat rotation to cotton-wheat or to the maize-wheat rotation as cotton and maize had lesser water requirements to complete their life cycle as compared to the rice (Table 24.17).

In wheat, Timsina et al. (2008) reported that 10 November was the optimum time to increase the crop water and irrigation water productivity because of higher grain yield and lesser use of irrigation water; however late and earlier sowing decreases the water productivities because of lesser reported yields with the usage of higher irrigation water. Thus, up to mid-November is reported to be the best time to go for wheat sowing for having desired WP.

24.2.7.6 Direct-Seeded Rice (DSR) and Their Impact on WP

DSR avoid irrigation need for puddling operations and sow directly rice seeds into the soil using seed cum fertilizer drill. But yield often is somewhat lower due to severe iron deficiency and significantly higher weed pressure; therefore an integrated approach must be recommended to the farmers of the region for making success in DSR for marking an improvement in the land and water productivity (Bhatt and Kukal 2015). Further, it was delineated that DSR proves to be success in the heavy-textured soils while a failure in the light-textured soils.

In the DSR, it was observed that aerobic rice cultivars responded well than the lowland cultivars in terms of grain yield under the water stress conditions, viz., water-deficient areas; however under the submerged conditions, the lowland cultivars had an edge over the aerobic cultivars (Bouman et al. 2007; Fig. 24.13). DSR-AWD has resulted in higher irrigation water saving (33–53%) than puddle transplanted rice (PTR) (Fig. 24.14), albeit there was higher reduced seepage and runoff losses under DSR coupled with increased deep drainage (Sudhir-Yadav et al. 2011a) under clay-loam soil. They further reported that under the clay loam soils, DSR had higher water productivity than the PTR under 20 kPa suction, and this

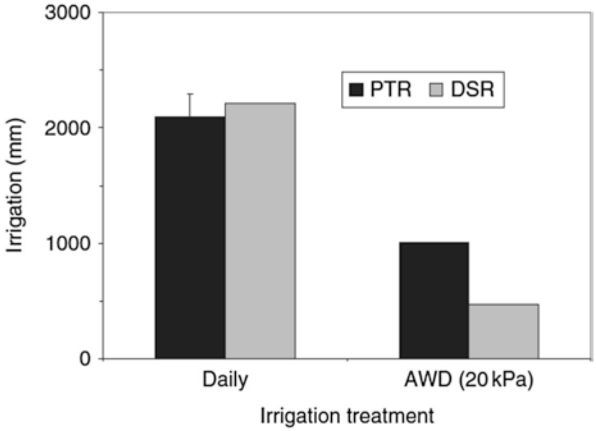

Fig. 24.13 Yield of aerobic rice varieties (black diamonds) and a lowland variety (open diamonds) under flooded and aerobic soil conditions. (Bouman et al. 2007)

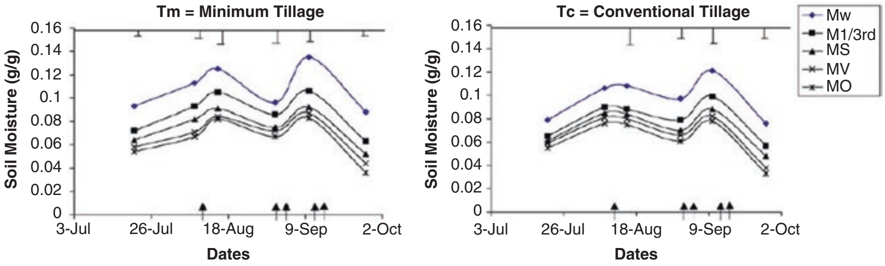

Fig. 24.14 Irrigation water use under PTR and DSR on clay loam soil. (Sudhir-Yadav et al. 2011b)

might be because of the higher number of micropores of clay loam soil, which retain water at a higher suction; however under the sandy loam soil, the trend might be different because of higher number of macropores of sandy loam soil which drain out quickly on slightly increasing the suction (Bhatt and Kukal 2015).

Owing to decreased average crop duration (Akhgari and Kaviani 2011; Table 24.18), a one-third to one-half saving of irrigation water in DSR than in PTR has been reported while maintaining the crop yield with similar irrigation schedule (Sudhir-Yadav et al. 2011b). Direct-seeded cultivars have a lower yield potential than the flooded cultivars but with 50% less consumption of water. Thus, they could be very well cultivated in the water-stressed regions which face scarcity of water but required rice for food security.

24.2.7.7 Underground Pipelines

Underground pipeline water distribution system is a unique water conveying system to different points in the farm which increased its water use efficiency. Further, area

Table 24.18 Effect of planting method on growth duration of rice cultivation

Variety	TPR D1	DSR D2	% Decrease in duration
Hassani	137	91	33.5
Ali Kazemi	134	98	26.8
Hashemi	134	98	26.8
Hybrid spring	144	108	25.0

Source: Akhgari and Kaviani (2011)

which earlier covered under water channels is freed now (up to 2–4%) (Michael 1978) which afterwards be used for growing of crops, thus expecting to have better land productivity with underground pipelines. Most of irrigation projects operate at low water use efficiency in the range of 30–40%, thereby losing 60–70% of irrigation water during conveyance and application. Though the application and use efficiencies of irrigation water can be improved by using underground pipeline system, it is recommended in the region. Furthermore, this technology is being popularized among farmers by providing them subsidies by the state government. Generally, farmers have to invest Rs 20,000–30,000 for underground pipelines for an area of 1 acre to improve the water use efficiency well water productivity. But till date this system is still adopted by very less number of tops the farmers in the region. Reasons might be ignorance, unawareness, and unwillingness to divert from old open channels (where the water actually seen) and the complex operation of earthing-up while fitting pipes in the field. Further, to help the farmer about the selection of most appropriate diameter of underground pipeline, a decision support system is to be designed (Ahuja et al. 2017).

24.2.7.8 Drip and Sprinkler for Orchards and Vegetables

Both drip and sprinkler systems of irrigation are quite efficient in improving the water use efficiency as they cut off water wastage to a significant level by applying irrigation water as per need. Disease spreading from one plant mainly in orchards to another also cut off. The Department of Soil and Water Conservation, Government of Punjab, India, is also offering subsidy up to 75% on these technologies along with a tube-well connection on priority basis. A drip irrigation system irrigates the plants at the rhizosphere. It would drip water slowly into the soil at a low rate. A drip irrigation system provided fertilizer to the water through a network of valves, pipes, tubing, and emitters which further improves the nutrient use efficiency. It was done through narrow tubes that deliver water directly to the base of the plant. Due to water hole was very small, so often clogged easily. Installation of this system must take into account a good filtration system. This watering system was prepared specifically for water-stressed regions. A drip irrigation system uses less space. It would enable farmers to grow crops on household consumption throughout the year.

Sprinkler irrigation system irrigating the field crops by sprinkling the water at rate lesser than infiltration rate of the soil for having maximum water as wells nutrient use efficiency. The drip irrigation system reduces the total irrigation water requirements to 50% by significantly cutting off conveyance losses. Effectiveness of irrigation system depends on several factors like soil texture, environmental factors, measured plant height, stem size of plants and weight of plants, etc. Comparison of the advantages and disadvantages between the drip irrigation system and the sprinkler irrigation system found that the drip irrigation system has high efficiency and uses less water pressure and high yield, saving water, labor, and time in watering. It provides higher land productivity when compared to the sprinkler irrigation system to the same of planting areas and quantity of water. Plants received regularly water on specific at roots. The drip irrigation system is available with a variety of plants and soil to all areas which showed the rate of water used for planting in the vertical space with sprinkler irrigation and drip irrigation, respectively. The drip irrigation system could provide better performance than the sprinkler irrigation system (Keeratiurai 2013).

24.2.7.9 Mulching and Its Impact on WP

The effect of spreading crop residues on the soil surface (mulching) in improving of water productivity has been ascribed to restricted evaporative losses because of decrease in radiant energy reaching to soil to cause phase change from liquid water to gaseous phase, decrease of vapor pressure difference within soil and ambient air, and finally decrease in vapor lifting capacity of the air, thereby causing yield augmentation (Bhatt and Khera 2006; Bhatt et al. 2004).

As far as dealing with crop residues is concerned, almost every option had a limitation that if we burn the crop residue, then it causes air pollution and allows the fixed carbon to go back in air which is not desired at all. Second option is the incorporation of the residues back into the soil, but this option causes N-immobilization and causes a yield loss in the next crop. So finally what should be done? The answer to this very question is Happy Seeder as with this technique, there is no need for pre-sowing irrigation which finally causes around 30% saving in irrigation water (Singh et al. 2008). Happy Seeder allowed sowing of wheat crop in the standing paddy stubbles, and with this there is no need to remove the rice stubbles outside the field, and secondly rice residues act like mulch which decreases the evaporation losses and decreases the amount of water used per irrigation (Table 24.19). The mulch load is also capable of changing the fate of even RCT like zero tillage which becomes even inferior to conventional tillage in the absence of mulch loads during the wheat season (Bhatt and Singh 2018).

24.2.8 Real Water-Saving Technologies

Sustainable use of groundwater is an important interdisciplinary challenge, and it can be concluded that most of the RCTs, viz., laser levelling, bed planting, underground pipelines, soil matric potential-based irrigation, direct-seeded rice (DSR), etc., lead to substantial reduction in irrigation water input by cutting off the drainage losses, which are not desirable in the areas especially where the GW is declining at an alarming rate, as is true for the central districts of Punjab, India. These technologies might be termed as “energy-saving technologies” as energy used to withdraw

Table 24.19 Water saving in wheat with ZT (Happy Seeder) over CT in Punjab

Irrigation	CT wheat (cm irrigation^{-1})	ZT wheat (cm irrigation^{-1})	Water saving with ZT over CT method
Pre-sowing irrigation	10	0	100%
First irrigation	7.5	6.38	15%
Second irrigation	7.5	6.75	10%
Third irrigation	7.5	7.5	0
Fourth irrigation	7.5	7.5	0
Total	40.0	28.1	30%

Source: Singh et al. (2008)

underground water could be saved now and these could have a promising role in southwestern districts of Punjab which are already suffering from the problem of waterlogging and where drainage is not required at all (Humphreys et al. 2010).

Similarly, mulch loads partition greater fraction of ET (evapotranspiration) losses to the T(transpiration) component by diverting it from E (evaporation) component which further helps in improving both land and water productivities as higher in low of water certainly improves the inflow of nutrients. Real water-saving technologies are those which divert higher fraction of water into that sink from where it can be reused. Among all the recommended technology, only two viz. short duration cultivars as and time of transplanting may be considered as real watersaving technologies as they divert greater fraction of ET water (used to meet evaporation +transpiration requirements) to T component without cutting off drainage losses which further improves intake of nutrients along with water which further results in higher both land and waterproductivity. Thus, for the water-stressed regions as in case of Central Punjab, RCTs, viz., growing of short-duration cultivars and delaying transplanting/sowing of the crops particularly rice (which cuts off the evaporation but not the transpiration) to coincide with the less evaporative demand periods are the real water-saving techniques which further help to uplift the declining of both land and water productivities in South Asia.

24.2.9 Research and Policy Implication for Improving Overall Livelihoods of Farmers

Scientists across the globe are experimenting for developing technologies which improved the livelihood of the farmers of the region. In their attempt, a number of technologies have been developed by them which are known as resource conservation technologies (RCTs) which on one hand help them to improve their both land and water productivities while on other also helped them for practicing climate-smart agriculture. Climate-smart agriculture helped the farmers to mitigate the adverse effects of the global warming on to their agriculture by one or other or by integration of some techniques. Some of these technologies are fertilization based on the soil test reports, laser levelling, adoption of the short- or medium-duration cultivars, direct-seeded rice, zero tillage, Happy Seeder for sowing of wheat seeds into the standing rice stubbles, irrigation based on the soil matric potential through tensiometer, double zero tillage, mulching and drip and sprinkler irrigation, underground pipeline system, etc. for improving both land and water productivities along with practicing climate-smart agriculture. Already details of these technologies are being discussed here in this chapter. Further, the government must be very much aware to frame new policies or laws which will reduce burden on the natural resources.

An ordinance was issued in 2008 which made it mandatory for farmers to not to seed rice nursery before 10 May and its transplanting rice only after 10 June. Later ordinance converted to water-saving regulation: “The Punjab Preservation of Sub-soil Water Act” in 2009. Effective implementation of this act, fall in water table can be checked by about 60–65% of long term falling rate (Singh 2009). Now from this very year, viz., 2018, the date of transplanting legally shifted to 20 June 2018, and the favorable results are being expected. Reason being in early transplanted/sowed crop faces dry air and higher temperature, higher vapour pressure gradient and thus finally higher moisture/vapour losses, thus we have to give frequent irrigations for having the similar productivity, while transplanting/sowing at appropriate time in mid-June, rains are there which moist the air, vapour pressure gradient decreased, lesser evapotranspiration losses and thus finally higher water productivity of the concerned crop as ET losses remains almost same and by decreasing evaporation losses, transpiration losses could be increased which further subsequently improves the inflow of the nutrients within the plants to improve the both land and water productivity. In wheat, Timsina et al. (2008) reported that 10 November 10 was the optimum time to increase land and water productivity because of higher grain yield and lesser use of irrigation water; however late and earlier sowing decreases the water productivities because of lesser reported yields with the usage of higher irrigation water. Therefore, timely transplanting of rice and wheat really helps in saving the irrigation water required to meet the crop needs without affecting the grain yields and thereby improving land as well as water productivity of the rice-wheat system as a whole. The success of different land and water management programs entirely depends upon the participatory approach and has shown the ability of low-cost interventions at enhancing resilience to climate change for sustainable agriculture. Some of the efforts which might be made by government through framing different policies will certainly help to practice climate-smart agriculture in the region which further helps to improve the declining land and water productivity in the region.

(a) Climate-smart land and water management programs should be situation and location specific as national and state programs importantly, Primthan to just allocate the money to run these programs. Some survey performs could also be frame Minister *Krishi Sinchai Yojana* (PMKSY), National Mission for Sustainable Agriculture (NMSA), National Water Mission and Mahatma

Gandhi National Rural Employment Guarantee Act (MGNREGA). Furthermore, there is a need to delineate the effect of these programs rather which further help to rectify the problem of the local and poor farmers of the region.

(b) Custom hiring centers should be there at village level which further played a significant role in providing costly agricultural machinery, viz., tractors, seed drills, Happy Seeder, etc., at cheapest rates to the farmers on turn basis one by one. This practice certainly helps the poor farmers to improve their water and land productivity.

(c) Some sort of training programs, viz., beekeeping and animal husbandry, must be provided to the local poor farmers of the targeted area even through Krishi Vigyan Kendra or some local centers which create the employment for the farmers which help them to make them busy not only during the rest periods in between rice-wheat crops but also during the intervening period.

(d) Water availability during the stressed period must be assured even through village level agriculture planning and depending upon the water availability and supply and demand relationships.

24.3 Conclusions and Future Plans

Excessive pumping of underground to grow different agricultural crops needs to be checked as it declined at a faster rate more particularly in the water-stressed regions. Both intensive tillage operations and declining water table pose a threat to the profitability and sustainability of the rice-wheat cropping sequence of South Asia. Water consumption quantity of the rice is exceptionally higher than the other cereals as around 3000–5000 L of water to produce 1 kg of grain, thereby resulting in lower water productivity. Further, repeated puddling operation deteriorates the soil structure and forms the “plough pan” at about 5–15 cm which further poses threat to the aerobic wheat crop’s root growth. Intensive tillage operations used to prepare the seedbeds open up the soil aggregates which further expose the hidden organic matter to the microorganisms which oxidizes it in the form of CO_2 which when escaped in the atmosphere causes global warming. Global warming is a serious threat in front of the sustainable agriculture. Evidences show that the improvement in the water productivity at the research trials is much higher than what observed at the farmer’s fields. Thus, there is an obvious assignment for the soil scientists, agronomists, and the plant breeders to work out some sort of action plan for improving both land and water productivities by testing and advocating some integrated approach by considering site-specific problems of the farmers which is also socially acceptable to them. Soil evaporation, deep drainage, and runoff losses must be minimized to decrease the gap in the seasonal supply of the irrigation water which further depends upon the water resources situations, viz., rainfall patterns, irrigation system, and scheduling, and other features of the cropping system. A number of technologies termed as resource conservation technologies (RCTs), viz., laser land levelling, alternate wetting and drying (AWD), irrigation system in rice on fixed day interval or soil matric potential (SMP)-based scheduling, mechanical transplanting, zero-tilled wheat and transplanted rice, direct-seeded rice, rice and wheat on raised beds, and mulching, have been recommended by the scientists across the region to improve the declining land and water productivities in the region. But the performance of these RCTs is site and situation specific, and their performance also depends on the soil texture as DSR is extremely profitable in heavy-textured soils but proves to be a failure in the areas having light-textured soils due to observed severe iron deficiency and observed significantly higher weeds. Diversification is also one of the main thrust areas which need to be adopted by the local farmers. Rainfed farmers could also improve their WP by using straw mulches and tillage to retain more rainfall and decrease evaporation from the soil, rainfall harvesting and recycling, and optimum fertilizer use. For preparing/implementing some effective future plans, attempts being made here to identify some knowledge gaps and future plans/strategies must be used for improving the declining of both land and water productivities in the region so as to practice the climate-smart agriculture for overall, improving the livelihoods of the farmers of South Asia.

1. Drip irrigation, alternate furrow irrigation, irrigation based on soil matric potential, DSR, straw mulching, etc. are the techniques based on actual water supply and demand for irrigation, but there is an obvious need to standardize micro-irrigation techniques for increasing WUE in wheat-based cropping systems of SA.
2. If rainfall patterns predicted well in advance, then by counting water requirement of our crop, one could efficiently plan his/her crop calendar as well as rotation.
3. New crop cultivars must be developed by recognizing genes more particularly of higher water requiring crops, viz., rice which further helps to reduce water feeding to this crop which ultimately results in higher water productivity.
4. Farmers must diversify their crop rotation with low water requiring crops. The government will also provide must incentives in this regard to encourage the farmers.
5. Site-specific performance of advance irrigation systems, viz., drip, and sprinkler systems, must be delineated for each cropping rotation under texturally divergent soils for their adoption for the location-specific areas.
6. Residual effect of recommended different resource conservation technologies not only on proceeding or succeeding crops but also during intervening period will be delineated well in advance for making the farmers to adopt one as per their conditions.
7. Proper information regarding effective and judicious use of poor-quality irrigation waters must be there for the farmers having poor-quality underground water for irrigation. Moreover, stress tolerant cultivars will also be developed.
8. Techniques portioning higher fraction of evapotranspiration (ET) water from E (evaporation) to T (transpiration) must be developed and demonstrated to the farmers as greater the transpiration proportionately higher will be the nutrient inflow in plants through their roots which further improve the land productivity.

9. Some target areas for the new research will be to increase groundwater storage, recharge, and get rid of constraints to accomplish the probable in rainwater harvesting.
10. All the proposed resource conservation technologies to improve land and water productivity are site and location specific therefore technologies will be well recognized for the area to area for the convenience of the farmers so that he will integrate different techniques which will be suitable to his area without considering other techniques which has nothing to do with his area.

If by anyhow an increase in water productivity of just 0.1 kg of grain m^{-3} is possible, then we will be in a position to save a significant proportion of the water by feeding the people, which might be used in other allied sector as per need. Perfect adoption of different RCTs is still not possible up to now in spite of every effort made by scientists, extension workers, policy makers, etc. Government policies (planned in proper way) will certainly help us to meet goals of higher productivity well in advance. Moreover, there is a need to identify a set of resource conservation technologies which is both site and location specific and which will really help the farmers to improve their livelihoods under their soil textural class and agroclimatic conditions. Therefore, refinement of such integrated approaches comprising of one or more number of RCTs which are location/area/soil textural class/agroclimatic condition specific needs to be identified which will not confuse them but rather help them to pick up one as per their need.

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Adaptation Strategies to Mitigate the Evapotranspiration for Sustainable Crop Production: A Perspective of Rice-Wheat Cropping System

25

Rajan Bhatt, Akbar Hossain, and Mirza Hasanuzzaman

Abstract

Both land and water productivities are declining day by day because of depleting underground water table and unscientific conventional practices used to establish the different crops, more particularly rice and wheat cropping system in South Asia. Climate change further complicated the situations, where unpredictable rain both in terms of amount and frequency, high-temperature regimes, frequent floods, and drought adversely affected the yields in total. Evapotranspiration (ET), comprised of evaporation (nonproductive component) and transpiration (productive component), and their management are important in improving both land and water productivities. Crop water requirements during vegetative phase varied mostly due to the variation of crop canopy cover and microclimatic conditions. Efforts are being made through resource conservation technologies (RCTs) to improve the land productivity as it is closely linked with livelihood standards under the decreased or will be decreased water availability depending upon the geological conditions. RCTs partition the water/moisture from the share of an unproductive portion (E) to produce one (T) from where it could be reused for encouraging water and hence nutrient intake. Transpiration led to an increasing flow of water in plants through roots, and along with water, the inflow of the nutrients also increased, which further led to higher grain weights and grain yields. Therefore, partitioning water from E to T is the only way to improve the

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land productivity and hence livelihoods even at a global level with special reference to the developing countries. Set goals could be achieved only through short-duration crop cultivars, timely paddy transplantation, underground pipelines, sprinkler and drip irrigation, and zero tillage with mulch at the soil surface. Present chapter delineates the importance of ET for planning and management of water resources with RCTs with innovative strategies to manage crop ET for improving agricultural land and water productivity under changing climate at the global level.

Keywords
Climate change · Evapotranspiration · Mitigation strategies

25.1 Introduction

Agriculture around the globe has been and is likely to remain the major consumer of water, but the share of water allocated to irrigation is likely to decrease due to changing climate in the next two decades (Meier et al. 2018) due to demand of higher fraction of water share by its other allied sectors (Bhatt et al. 2016). Irrigation is the largest direct human water use, including large amounts of green and blue water required on agricultural sector (Rost et al. 2008; Döll et al. 2012). Rice-wheat cropping system (RWCS) – a dominating production system – occupies 24 million hectares (M ha) throughout India and China alone. The Indo-Gangetic Plains (IGP) have RWCS, covering around 12.3 M ha area in India, 2.2 M ha in Pakistan, 0.8 M ha in Bangladesh, and 0.5 M ha in Nepal (Ladha et al. 2003; Timsina and Connor 2001; Singh et al. 2005). Almost 45% of the region's food grains and nearly 42% of staple grains are provided to 1.3 billion populations in South Asia (Jat et al. 2005). In India, Punjab and Haryana often referred to as the "Food Bowl" of the country produce 50% of the national rice production (Dhillon et al. 2010). Further, intensive cultivation of rice-wheat cropping sequence has resulted in a number of sustainability issues, viz., declining water table, deteriorating soil health (because of repeated puddlings), arising micronutrient deficiencies, decreased land and water productivity, etc. The increase in depth to the groundwater in North-West India has three major negative effects (Hira 2009): (1) higher energy requirement and cost of pumping groundwater; (2) increasing tube-well infrastructure costs; and (3) deteriorating groundwater quality, which will ultimately be to the degree that the groundwater becomes unusable because of upwelling of salts from the deeper native groundwater (Kamara et al. 2002) and because of saline groundwater intrusion into fresh groundwater (as a result of reversal of groundwater flows due to the lowering of groundwater levels in fresh groundwater regions below levels in areas with saline groundwater).

For rice, we have to provide the submergence conditions, and according to one estimate for producing 1 kg of rice, around 4000 liters of irrigation water is required which is not required as inhabitants of this region not are fond of it. For this reason, produced paddy grains products are sold to foreign countries at their decided rates with a feeling of proud without including the cost of water, energy used to cultivate it (Humphreys et al. 2010; Bhatt et al. 2016). Further, productivity, profitability, and sustainability of rice-based systems are threatened because of the inefficient use of inputs; increasing scarcity of resources especially water, land and labor; emerging energy crisis; and rising fuel prices (Bhatt et al. 2016). The global water scarcity analysis has shown that up to two-thirds of the world population will be affected by water scarcity over the next several decades (Wallace and Gregory 2002); therefore the conventional practices must be replaced with advanced, farmer-friendly, and climate-smart technologies.

Climate is changing because of natural forces and mainly due to anthropogenic desired factors of getting more and more and better and better which ultimately results in the emergence of climate change (Gadgil 1996). Carbon dioxide (CO_2) concentration in the atmosphere increased from 280 ppm (preindustrial phase) to 315 ppm in 1967 and 356 ppm by 1993 (Schimel et al. 1995) which further jumped to 38% up to now than the preindustrial era) and expected to reach 450–550 ppm in 2050 and 700 ppm by the end of the twenty-first century if some alternate steps not recommended by the scientists are used by the farmers. Accelerated production of higher concentrations of CO_2 with methane (CH_4), N_2O (nitrous oxide), ozone (O_3), and chlorofluorocarbons (CF_3Cl_3) resulted in the rise of global temperature by 0.74 °C ± 0.18 °C (average figure) from the last century (Trenberth and Jones 2007), and this figure reported to be 0.6 °C (Meehl and Stocker 2007), as depicted in the Intergovernmental Panel on Climate Change (IPCC) 4th assessment report. Further reported consequences of global warming include that unusually hot summer experienced in the Northern Hemisphere, Japan has declared its record temperatures a natural disaster, Europe is baking under prolonged heat, with destructive wildfires in Greece, and in the Western United States, drought-fuelled wildfires are spreading (Schiermeier 2018). Climatic parameters such as atmospheric CO_2 concentration, temperature, rainfall (RF), humidity, sunshine hours, and soil fertility status are important factors to delineate the crop growth and abrupt variation in any of factor which limit both land and water productivity universally. Generally, crop yields are enhanced with increased CO_2 levels (Kimball and Idso 1983; Kimball et al. 2002) while decreased with increased temperature (Tao et al. 2008), and under the effect of global warming, both are increasing, and thus their balance accordingly will decide the land productivity of a particular region. Under the changed climatic conditions, synchronization between crop phenology and optimum temperature is disturbed and may require a shift in planting date.

Further, due to the changing climate and also the increase use of underground water for intensive rice cultivation in the rice-wheat system in South Asia including India, Pakistan, Bangladesh, Sri Lanka, and Nepal, the water table is declining at a sharp rate. Researchers in these regions are making the best of its efforts to develop some situation-specific integrated approaches with a set of RCTs which helps the farmers of the region to improve their livelihoods (Pathak and Wassmann 2009).

In order to take care of declining groundwater and improving land and water productivity under the climate change scenario, different RCTs, viz., zero-tilled wheat with residues at surface, mulching, underground pipelines, sprinkler and drip irrigation, short-duration crop cultivars and timely transplantation of paddy, etc., are being advocated for increasing the productivity, sustainability, and profitability of this system by reducing the unnecessary evaporation losses and portioning higher fraction of ET water to which further improved water and nutrient intake and finally land productivity and hence livelihoods. Detailed descriptions of adaptation strategies to mitigate the ET for sustainable crop production in the era of climate change are described in the following subheading:

25.2 Adaptation Strategies to Manage Evapotranspiration in Agriculture

Following are some of the important adaptation strategies which were being tested in agricultural systems at research farms and recommended to the farmers of the globe for managing the ET water for overall improvement in the land and water productivity, and thus finally in the livelihoods of the farmers more particularly of the developing countries.

25.2.1 Date of Transplanting (DOT) and Their Influence on Evaporation

Date of transplanting is very important RCT for managing ET water as the early transplanted crop has the highest evaporation losses which further associated with lower water/land productivities and finally resulted in lower livelihoods (Table 25.1).

This is one of the most important RCT which has a sound scientific base and which also guide the even politicians for saving the irrigation water. Earlier, farmers used to transplant the paddy nursery in May. During May, the air is quite dry and thus lifts up water vapors to maintain vapor pressure gradient, results in higher evaporation losses. As a result, farmers have to apply frequent irrigations to meet the crop demand which finally resulted in lower irrigation water productivity while transplanting nursery in the month of June as encountered with rains which moist the air, and moist air has lesser evaporation demands, the share of extra

Table 25.1 Effect of date of transplanting (DOT) and N-levels (Kg ha^{-1}) on the crop water productivities (kg m^{-3})

Parameters	N_0	N_{240}	N_{300}	N_{360}	Mean
Transplanting rice on 5 June and wheat on 20 Oct	0.78	1.11	1.13	1.13	1.04
Transplanting rice on 20 June and wheat on 5 Nov	0.78	1.21	1.27	1.30	1.14
Transplanting rice on 5 July and wheat on 20 Nov	0.67	1.13	1.20	1.25	1.06
Mean	0.74	1.15	1.20	1.23	

Source: Jalota et al. (2011)

evaporation partitioned toward transpiration which further improves the grain yields and livelihoods of the farmers. The government of Punjab implemented the law to go for nursery sowing after 20 May and transplantation of nursery into the field only after 20 June from this very year, viz., 2018, and the farmers were forced to follow this practice by a law.

Further, crop diversification helped in diverting water from uneconomical head to the economic one. It was revealed that (Jalota and Arora 2002; Arora et al. 2008) particularly diversion from rice helped to increase the water productivity for the system as a whole. ET losses decrease if system diversified from rice-wheat rotation to cotton-wheat or the maize-wheat rotation as cotton and maize had lesser water requirements to complete their life cycle as compared to the rice (Table 25.2). In wheat, Timsina et al. (2008) reported that November 10 was an optimum time to increase the crop water and irrigation water productivity because of higher grain yield and lesser use of irrigation water; however late and earlier sowing decreases the water productivities because of lesser reported yields with the use of higher irrigation water. Therefore, the best time to go for wheat sowing for having desired water productivity is up to mid-November.

25.2.2 Underground Pipelines for Avoiding Evaporation Losses

The underground pipeline water distribution system is a unique water conveying system to different points in the farm which increased its water use efficiency. Further, an area which earlier covered underwater channels is freed now (up to 2–4%) (Michael 1978) which afterward be used for growing of crops, thus expecting to have better land productivity with underground pipelines. Most of the irrigation projects operate at low water use efficiency in the range 30–40%, thereby losing 60–70% of irrigation water during conveyance and application. Though the application and use efficiencies of irrigation water can be improved by using the underground pipeline's system, it is recommended in the region. Furthermore, this technology is being popularized among farmers by providing them subsidies by the state government. Generally, farmers have to invest 290–430 US$ for underground pipelines for an area of one acre to improve the water use efficiency as well as water productivity. But till date this system is still adopted by significantly lesser number

Table 25.2 Diversification for improving water productivity

Cropping systems	ET (mm)	E_b (mm)	Component crop yield (t ha^{-1})		Wheat equivalent yield (t ha^{-1})	Water productivities (Kg m^{-3}) based on	
			C_1	C_2		ET	NWL
Rice-wheat	1030	210	6.0	4.5	9.7	0.94	0.78
Cotton-wheat	980	901	2.0	3.5	8.6	0.88	0.80
Maize-wheat	860	220	3.5	4.5	7.2		

Source: Arora et al. (2008) and Jalota and Arora (2002) of farmers) the farmers in the region. Reasons might be ignorance, unawareness, and unwillingness to divert from old open channels (where the water seen) to the complex operation of earthing up while fitting pipes in the field. Further, to help the farmer about the selection of the most appropriate diameter of underground pipeline, a decision support system is to be designed (Ahuja et al. 2017).

25.2.3 Drip and Sprinkler for Orchards and Vegetables

Both drip and sprinkler systems of irrigation are quite efficient in improving the water use efficiency as they cut off water wastage to a significant level by applying irrigation water as per need. Secondly, disease spreading from one plant mainly in orchards to others also is cut off. The Department of Soil and Water conservation, Government of Punjab, India, is also offering subsidy up to 75% on these technologies along with a tube-well connection on a priority basis. A drip irrigation system irrigates the plants at the rhizosphere. It would drip water slowly into the soil at a low rate. A drip irrigation system provided fertilizer to the water through a network of valves, pipes, tubing, and emitters which further improve the nutrient use efficiency, and the irrigation system uses less space. It was done through narrow tubes that deliver water directly to the base of the plant. Installation of this system was found to be a good filtration system as the waterhole of the system was very small, so often clogged easily. This watering system was highly effective dry regions, and farmers can grow crops on domestic consumption throughout the year.

The sprinkler irrigation system is irrigating the field crops by sprinkling the water at a rate lesser than infiltration rate of the soil for having maximum water as well as nutrient use efficiency. The drip irrigation system reduces the total irrigation water requirements to 50% by significantly cutting of conveyance losses. The effectiveness of an irrigation system depends on several factors like soil texture, environmental factors, measured plant height, stem size of plants and weight of plants, etc. The drip irrigation system is highly effective, water-saving, and less laborious time in the watering than the sprinkler irrigation. The drip irrigation system is available with a variety of plants, and soil to all areas showed the rate of water using for planting in the vertical space with sprinkler irrigation and drip irrigation, respectively. The drip irrigation system could provide better performance than the sprinkler irrigation system (Keeratiurai 2013).

25.2.4 Mulching and Its Impact on Water Productivity

The effect of spreading crop residues on the soil surface (mulching) for improving the water productivity and to restrict evaporative losses through decreasing the solar radiation reaching to the soil (Fig. 25.1; Bhatt and Khera 2006; Bhatt et al. 2004). As far dealing with crop residues is concerned, almost every option had a limitation as if we burn the crop residue then it causes the air pollution and secondly allow the fixed carbon to go back in the air which is not desired. The second option is the

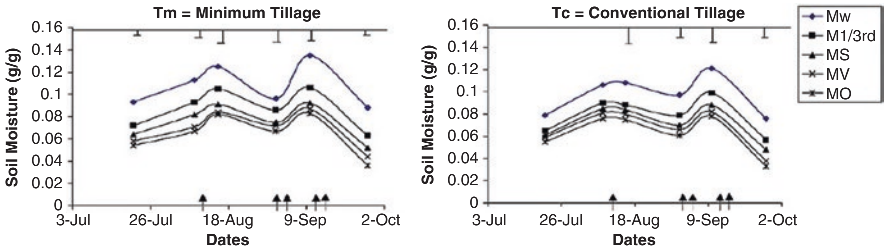

Fig. 25.1 Soil moisture content of surface soil as affected by tillage and different modes of mulch application. (Adapted from Bhatt and Khera 2006)

Table 25.3 Water saving in wheat with ZT (Happy Seeder) over CT in Punjab

Irrigation	CT wheat (cm irrigation^{-1})	ZT wheat (cm irrigation^{-1})	Water saving with ZT over CT method
Pre-sowing irrigation	10	0	100%
First irrigation	7.5	6.38	15%
Second irrigation	7.5	6.75	10%
Third irrigation	7.5	7.5	0
Fourth irrigation	7.5	7.5	0
Total	40.0	28.1	30%

Source: Singh et al. (2008)

incorporation of the residues back into the soil, but this option causes N-immobilization and causes a yield loss in the next crop. So finally what should be done? The answer to this very question is Happy Seeder, as with this technique, there is no need for pre-sowing irrigation which finally causes around 30% savings in irrigation water (Singh et al. 2008).

Happy Seeder allowed sowing of the wheat crop in the standing paddy stubbles, and with this there is no need to remove the rice stubbles outside the field, and secondly rice residues act like mulch which decreases the evaporation losses and decrease the amount of water used per irrigation (Table 25.3). The mulch load is also capable of changing the fate of even RCT like zero tillage which becomes even inferior to conventional tillage in the absence of mulch loads during the wheat season (Bhatt and Singh 2018).

25.2.5 Short-Duration Crop Cultivars and Their Impact on Water Productivity

Jalota et al. (2009) reported that in long-duration cultivars (PR-118), irrigation water requirements decreased to 110 mm from 25 May to 10 June while to 260 mm if transplanting time was delayed to 25 June. Though they reported some yield

Table 25.4 Effect of transplanting date and variety on yield and water requirements of rice

Transplanting date	Irrigation water (mm)	Grain yield (t ha^{-1})	Irrigation water (mm)	Grain yield (t ha^{-1})
	PR-118 (155–160 days)		RH-257 (110–120 days)	
25 May	2530	7.5	2350	6.8
10 June	2420	6.6	2310	7.3
25 June	2270	7.1	2120	7.5
Mean	2407	7.1		

Source: Jalota et al. (2009)

loss there, ultimately water productivity increased because of greater saving of irrigation water. But in the short-duration cultivars (RH-257), grain yield also increased along with the saving of irrigation water which increased the water productivity (Table 25.4).

25.2.6 Zero-Till Wheat in Standing Rice Stubbles

Crop residue management on or off the field is the major challenge more particularly of paddy not only for the farmers but also for the scientists. Majority of the rice and wheat in Punjab is combine-harvested, leaving 0.3–0.6 m high-anchored straw and loose straw in windows. Management of the rice stubble (more than 7 t ha^{-1}) is a major problem as the timely sowing of wheat is the priority for the farmers. Incorporation is both time and energy consuming (Gajri et al. 2002). Incorporation of the rice straw delays wheat sowing beyond the optimum date (before November 15) for maximum yield beyond which the wheat yields start decreasing. Thus the farmers opt for burning of crop residues which results in air pollution and loss of nutrients at 35 kg N ha^{-1}, 21 kg K ha^{-1}, and 3 kg ha^{-1} each of P and S (Yadvinder-Singh et al. 2008), coupled with degrading soil physical and biological health (Yadvinder-Singh et al. 2005). Burning of rice residues responsible for the production of the greenhouse gases, viz., CO_2, CH_4, NO_2, and N_2O, and particulate matter (Gupta et al. 2004) further deteriorates the whole ecological conditions. Thus, the technologies that enable retention of rice residues over the soil surface as mulch would reduce the evaporation losses and improve declining land and water productivity. Retaining the rice residues as mulch also offers the potential benefits of reduced water loss due to the suppression of soil evaporation (E_s), which further improves the inflow of water in the plant roots along with nutrient against the transpiration pull (Al-Darby et al. 1989;Yadvinder-Singh et al. 2005; Balwinder Singh et al. 2011a, b, 2014). Zero tillage (ZT) on long run improves the soil physical environment (Bhaduri and Purakayastha 2014; Gómez-Paccard et al. 2015) and lowers soil compaction (Palese et al. 2014; Bhaduri and Purakayastha 2014; Zheng et al. 2015), while conventional tillage breaks down the macroaggregates into microaggregates which expose the once hidden organic matter to the organisms which oxidize it to CO_2 (Roper et al. 2013; Das et al. 2014; Kuotsu et al. 2014), further increasing the soil surface area which further absorbs higher sunlight and which further increased the evaporation losses. The contradictory results related to zero tillage effects on soil and crops are reported in the literature (Chopra and Chopra 2010; Singh et al. 2015), and poor performance was claimed only because of the significantly observed higher weed pressure.

The recent development of a residue/trash handling zero tillage sowing implement, the "Happy Seeder" (Sidhu et al. 2007, 2008), provides the capability of direct drilling of wheat seeds in standing rice stubbles. Happy Seeder simultaneously cuts and removes the straw in the way of the sowing tynes and spreads the straw on the surface as mulch behind the tynes. Therefore, direct drilling of wheat seeds into the soil is a viable option to put wheat seeds into the soil, and secondly, the loose straw acts as mulches reduces soil evaporation (Es) and partitions greater fraction of water toward transpiration component (Balwinder Singh et al. 2011a, b). The direct drilling of wheat in standing rice stubble is an important resource conservation technique being propagated in the rice-wheat regions of South Asia (Beff et al. 2013; Balwinder Singh et al. 2014) for improving the overall grain yields, soil health, and livelihoods of the farmers.

The positive benefits of zero tillage on crop production (Gomez-Paccard et al. 2015), water use efficiency (Guan et al. 2015), carbon sequestration (Zhangliu et al. 2015), avoidance of terminal heat stress in wheat (Erenstein and Luxmi 2008; Jat et al. 2009; Chakraborty et al. 2010; Gupta et al. 2010), and economic performance by cutting field preparation cost (Tripathi et al. 2013) are well recognized. Retaining the residues as a mulch also offers the potential benefits of reduced water loss due to the suppression of soil evaporation, suppression of weeds, increased soil organic C, and improved soil structure which finally improves the grain yields (Yadvinder-Singh et al. 2005); however, contradictory results are reported in the literature (Chopra and Chopra 2010; Tahir et al. 2008; Singh et al. 2015), which were because of the higher weed pressure in ZT plots (Balwinder Singh et al. 2014; Bhatt and Kukal 2015a; Balwinder Singh et al. 2014) and because of lesser herbicides efficacy in ZT plots as compared to CT plots (Singh et al. 2015).

A positive yield effect of ZT is often associated with the more timely wheat establishment (Hobbs and Gupta 2003; Laxmi et al. 2007), which further reported to increase the grain yields in the region struggling for higher yields because of late planting effects. While in late sown sites, no significant yield difference was reported between ZT and conventional tillage planted wheat (Aslam et al. 1989). Similarly, Farooq et al. (2007) reported that the lack of a significant yield effect has undermined widespread in ZT system in Punjab. Thus, there is a need to delineate the residual effect of zero tillage in wheat on the next rice crop including the intervening period in between two crops (Bhatt and Kukal 2015b).

25.2.7 Real Water-Saving Techniques for Improving Water Productivity

Around 70–80% of available freshwater is currently used in agriculture in many regions in the world (Hoekstra and Chapagain 2007). However, it is estimated that a larger fraction of available water will be required for nonagricultural purposes, due to urbanization and industrialization in the future (Boserup 2017). At the same time, climate change has already noticed the limited water resources for many regions of the world (Bandyopadhayay et al. 2009), which has negative feedback to future sustainability agricultural production (Gheysari et al. 2015). However, in arid and semiarid regions of the world, water availability is the major factor that limits crop yield (Er-Raki et al. 2007). Scientists already proposed several effective irrigation strategies to optimize water use efficiency, thereby cost effective and environmental friendly for sustainable crop production for these regions (Geerts and Raes 2009; Delirhasannia et al. 2010; Sadeghi et al. 2015). However, there is little evidence that farmers have accepted these water-saving technologies (Lohmar et al. 2003), and the efficacy of these technologies has a debate (Deng et al. 2004). On the other hand, there has been a little research conducted to extend and adopt these technologies for the welfare of farmers in rural level. A detailed description of these recommended water-saving technologies is described as follows:

25.2.7.1 Traditional Technologies

Traditional technologies include border and furrow irrigation and field leveling. These are widely adopted technologies because the majority of farmers around the world have been using these techniques as well. These irrigation methods have relatively low fixed costs and are separable in the sense that one farm household can adopt the practice independent of the action of its neighbors (Blanke et al. 2007). One of the most fundamental traditional technologies is developing channels or bunds in the field in order to direct the flow of the water to the crops without letting the water flow freely across the plots. Border irrigation is an irrigation technique in which a single plot is separated into zones. Each zone is on a slightly different level so that water flows from one to the other, rather than flooding the field all at once. This technology increases the control a farmer has over irrigation application on each section of his plot, which may result in reduced applied irrigation (Blanke et al. 2007).

Closely related, furrow irrigation is an irrigation system in which crops are planted on raised ridges between furrows. Once applied, irrigation water flows through these furrows. Wang et al. (2004) reported that the furrow irrigation system increased water productivity in winter wheat as compared with traditional flood irrigation.

A third traditional technology is targeted at the entire field plot. In the case, the field should be well-leveled to allow water to spread across the plot more evenly without designing bunds or channels to direct the water flow. The irrigation system enhances water infiltration and reduces soil erosion and also increases the yield of growing crops (Deng et al. 2004).

A fourth level traditional technology is a surface level plastic irrigation pipe that refers to a coil of hosepipe (soft, flexible plastic pipe), which is used to transport irrigation water to farmers' fields. Zuo (1997) found that surface water piping techniques, including low-pressure pipes, can save up to 30% of water in addition to small amounts of land.

25.2.7.2 Household-Based Water-Saving Technology

Household-based technologies include plastic sheeting, drought-resistant varieties, retain stubble/low till, and surface level plastic irrigation pipe. These technologies are normally popular and quickly adopted by households than traditional technologies, due to relatively low fixed costs and are highly divisible. Typically, the adoption of these technologies is more recent.

Plastic sheeting is a production technology rather than an irrigation technique. The plastic film is used to cover soil during or before the crop growing season. This term is an umbrella term for a number of more specific techniques that involve the use of plastic film to trap moisture between the ground and the sheeting. For example, Abdulai et al. (2005) reported that ground cover rice production system (GCRPS) could save 50–90% of applied irrigation under experimental field. In addition, it increases soil temperature by allowing earlier planting and harvesting. Plastic sheeting is also found to increase soil temperatures under experimental field conditions as reported by Li et al. (2003). In another research, Li et al. (2004) found that using plastic mulch in combination with pre-sowing irrigation increased both yields and water use efficiency and also increases soil temperature, but that plastic mulch by itself did not increase yields.

Scientists already noticed that due to the climate change, water resources in many regions of the world have already noticed the limit (Bandyopadhayay et al. 2009), which has negative feedback to future sustainability of agricultural production (Gheysari et al. 2015). However, there are two ways to mitigate the problem either by developing and using drought-tolerant cultivars or by practicing improved water management practices. Therefore, scientists around the globe are trying to develop drought-resistant crop varieties for the efficient use of water or grow under water deficit condition (Hossain and Teixeira da Silva 2013).

Retain stubble/low till is a technique in which the stubble from one crop is left on the field after this crop is harvested. Field studies of mulching using crop residue in Northern China show that it can improve water use efficiency by reducing soil evaporation and increase yields in comparison to traditional techniques including furrow (Zuo 1997; Pereira et al. 2003; Deng et al. 2004).

25.2.7.3 Community-Based Technologies

Community-based technologies are well adopted by a community or a group of families/farmers than an individual household. These technologies' setups are with underground pipes, which are linked with a water body such as rivers, seas, or canals. For example, sprinkler irrigation systems are one type of community-based irrigation technologies, since which have a huge fixed cost. These irrigation systems require substantial water pressure to operate. To attain sufficient pressure, communities or a group of households need to construct water towers/tank and elaborate piping networks. Therefore without collective coordination of multiple households, it is difficult to operate. Regardless of sprinkler systems' increase in water use efficiency and given fixed plot areas and crop choice (e.g., Peterson and Ding 2005), sprinkler and drip systems save labor in addition to water but have relatively high costs (Zuo 1997).

In the case of underground pipe, systems include any system of underground pipe (cement, metal, or plastic) used to transport water for irrigation. Typically, underground piping systems have above ground access fittings every 50–100 meters. Zuo (1997) noted that these techniques save water (up to 30%) in addition to a small fraction of land area, compared to unlined canal systems.

Lined canals are irrigation canals lined with cement or any other relatively impermeable material. The irrigation system reduces the percent of water that seeps through the canal into the surrounding soil during conveyance from the water source (surface system or well) to the field, which can increase the percent of water in the canal available for irrigation (Zuo 1997; Cai et al. 2003).

25.2.7.4 Some Improved Water-Saving Modern Technology

25.2.7.4.1 Alternate Wetting and Drying Farrow Irrigation

Suitable irrigation methods such as sprinkler, drip-fertigation, sub-surface and sustainable available ground, and surface water resources management are still lacking in most of the countries around world. Therefore, improved irrigation method is essential for avoiding soil water and nutrient leaching as well as groundwater pollution (Lincoln et al. 2009) and attaining preferred crops yield (Pawar et al. 2013). Two water-saving strategies could be considered: deficit irrigation (DI) and partial root-zone drying (PRD) or alternate furrow irrigation (AFI) technique. Partial root-zone drying (PRD) technique or alternate furrow irrigation (AFI) is an ideal improvement of DI, which is relatively easy to apply in the field conditions, and it is essential in the areas where water resources are limited and ET is very high (Sepaskah and Ahmadi 2010). In DI system, a percentage of ET or a part of field capacity is applied to the entire root-zone to sustain desirable crop yields and substantively increase water use efficiency (WUE). Although, DI systems have a harmful effect on field crops' yield, it is suitable to fruit garden to increase fruit quality and also increase WUE (Pulupol et al. 1996). PRD or AFI is an idyllic upgrading of DI, which is relatively easy to apply in the field crops, and it is essential in the areas where water resources are limited (Sepaskah and Ahmadi 2010). The concept of PRD or AFI irrigation system was first introduced by Grimes et al. (1968). After that Sepaskah et al. (1976), Liu et al. (2003), Zegbe et al. (2004), and Abd El-Halim (2013) conducted numerous extensive studies on cotton, grape, potato, maize, and tomato through PRD or AFI systems. Sarker et al. (2016) found that the technique of alternate wetting and drying furrow irrigation (AWDFI) (Fig. 25.2) saves water by 35–38% substantially higher than traditional furrow irrigation method (TFI) in field conditions, while AWDFI improved water use efficiency (WUE) by 37–40% without significant reduction in yields when irrigation water was applied up to 80% field capacity. They also found that plant biomass and fruit yield of tomato did not obtain a significant difference between the treatments of AWDFI and TFI when irrigating with 100% field capacity. Therefore, AWDFI technique had the potential to increase WUE and quality of fruits, which may provide a useful approach to apply a practicable method in the field of tomato production at areas where irrigation water resource is limited and ET was high (Sarker et al. 2016).

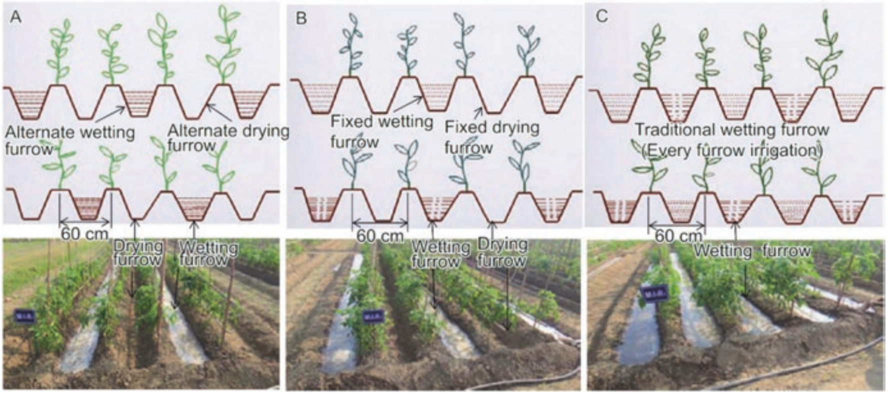

Fig. 25.2 (**a**) Alternate wetting and drying furrow irrigation (AWDFI), (**b**) fixed wetting and drying furrow irrigation (FWDFI), (**c**) traditional furrow irrigation method (TFI). (Adapted from Sarker et al. 2016)

25.2.7.4.2 Conjunctive Use of Saline and Freshwater Increases the Productivity of Crops in Saline Coastal

The insufficiency of agriculture water around the globe is rising not only for the sources of water bodies are reducing but also the quality of water is deteriorating (Parsons et al. 2010; Qadir et al. 2010; Elliott et al. 2014). Among the intimidations that are worsening the quality of irrigation water, soil salinization is the vital one. The severity of such menace is higher in the coastal regions in most of the affected countries (Connor et al. 2012; Daliakopoulos et al. 2016; McFarlane et al. 2016; Murad et al. 2018). Soil salinity, caused by a high concentration of salts in the soil, is one of the most severe environmental factors that limits the productivity of crops. The FAO and the UN Environment Programme already have been estimated that globally around 4 million km^2 of land are salinized, of which nearly 20% of arable land and 50% of cropland are affected by salinity (Ravindran et al. 2007; Rozena and Flowers 2008). Therefore, soil salinity in around the world is a great threat for sustainable crop production to meet the food security of the increasing population. The best strategy for increasing intensification is through using saline water for irrigation wherever and/or whenever it is possible.

Based on the results of the 2 years study, Murad et al. (2018) revealed that the conjunctive use of fresh groundwater and moderate saline canal water could benefit to sustain maize productivity. They also suggested that an early irrigation with freshwater followed by two irrigations with saline water – first at vegetative with freshwater and second at tasseling and third at grain filling each with saline canal water – is the best for improving the productivity of field crops where soils are saline. However, location-specific appropriate irrigation scheduling methods and criteria need to be developed for the saline affected zones for popular crops to minimize yield reductions and to optimize sustainable use of limited fresh groundwater and abundant saline water.

25.2.7.4.3 Resource Conservation Technologies (RCTs)

Sustainable use of groundwater is an important interdisciplinary challenge, and it can be concluded that most of the RCTs, viz., laser leveling, bed planting, underground pipelines, soil matric potential-based irrigation, direct seeded rice (DSR), etc., lead to substantial reduction in irrigation water input by cutting off the drainage losses, which are not desirable in the areas especially where the GW is declining at an alarming rate, as is true for the central districts of Punjab, India. These technologies might be termed as "energy-saving technologies" as energy used to withdraw underground water could be saved now, and these could have a promising role in Southwestern districts of Punjab which are already suffering from the problem of waterlogging and where drainage is not required at all (Humphreys et al. 2010; Bhatt and Kukal 2014).

Similarly, mulch loads partition greater fraction of ET losses to the T (transpiration) component by diverting it from E (evaporation) component which further helps in improving both land and water productivity as high and low of water certainly improve the inflow of nutrients. "Real water-saving technologies" are those which divert a higher fraction of water into that sink from where it can be reused. Among all the recommended technology, only two, viz., short-duration cultivars and time of transplanting may be considered as real water-saving technologies as they divert greater fraction of ET water (used to meet evaporation + transpiration requirements) to T component without cutting off drainage losses which further improves intake of nutrients along with water which further results in higher both land and water productivity. Thus, for the water-stressed regions as in case of central Punjab, RCTs, viz., growing short-duration cultivars and delaying transplanting/sowing of the crops particularly rice (which cuts off the evaporation but not the transpiration) to coincide with the less evaporative demand periods, are the real water-saving techniques which further help to uplift the declining of both water and productivity in the South Asia.

There are many other management decisions that can optimize the cost of return and contribute toward a sustainable crop production in the future. Among them improved crop management practices, development of high yield, and stress-tolerant crop cultivars are most important for sustainable crop production under future changing climate (Hatfield et al. 2001; Liu et al. 2010). Furthermore, the collaborating effects among all these growing proprieties and other managing activities can provide real meaningful gains, they do so often on the regional-to-local scale, and their efficacy is based on prior conditions, edaphic controls, water, and fertility management (Gheysari et al. 2015).

25.3 Research and Policy Implication for Improving Overall Livelihoods of Farmers

Scientists' attention in different scientific program across the globe is to improve the livelihood of the farmers. In this regard, a number of technologies already have been developed and recommended to the farmers for improving both land

and water productivities and also suggested them for practicing climate-smart agriculture to mitigate the adverse effects of the future global warming. Some of these technologies are laser leveling, adoption of the short- or medium-duration cultivars, direct seeded rice (DSR), zero tillage, Happy Seeder for sowing of wheat seeds into the standing rice stubbles, irrigation based on the soil matric potential through tensiometer, double zero tillage, mulching and drip and sprinkler irrigation, underground pipeline system, etc., which work in fields but again their performance is situational and site-specific, and their performance could not be compared. For example, DSR is efficient in heavy textured soils but not suitable for light textured soils, due to high weed pressure and specific nutrients deficiency such as potassium (K), iron (Fe), and boron (B). Thus, DSR should be recommended in heavy textured soils, further same is the case with other technologies. Furthermore, the government should be very much aware to frame new policies or laws which will reduce the burden on the natural resources and also should provide with some incentives for the farmers for adopting RCTs as to get benefits from RCTs 3–5 years required to become effective. In the case of RCTs technology, initially, there is a yield loss, due to initial residue incorporation led to N-immobilization resulted in a yield loss. Therefore, the loss of the farmer must be compensated by the government to attract more farmers to the RCTs technology, otherwise, no one will be interested to divert from the conventional practices. The government may pass some laws to implement some RCTs, e.g., an ordinance was issued in 2008 which made it mandatory for farmers to not to seed rice nursery before 10 May and its transplanting rice only after 10 June. Later ordinance was converted to water-saving regulation, for example, “The Punjab Preservation of Sub-soil Water Act in 2009.” Effective implementation of this act fall in water table can be checked by about 60–65% of long-term falling rate (Singh 2018). Now from this very year, viz., 2018, the date of transplanting legally shifted to 20 June 2018, and the favorable results are being expected. Reason being in early transplanted/sowed crop faces dry air and higher temperature, higher vapor pressure gradient, and thus finally higher moisture/vapor losses, thus we have to give frequent irrigations for having the similar productivity. While transplanting/sowing at appropriate time in mid-June, rains are there which moist the air, vapor pressure gradient decreased, and lesser ET losses, and thus finally higher water productivity of the concerned crop as ET losses remains almost the same, and by decreasing evaporation losses, transpiration losses could be increased which further subsequently improves the inflow the nutrients within the plants to improve both land and water productivities. Therefore, timely transplanting of rice and sowing of wheat really helps in saving the irrigation water required to meet the crop needs without affecting the grain yields and thus thereby improving land as well as water productivity of the rice-wheat system as a whole. The success of different land and water management program entirely depends upon the participatory approach that has shown the ability of low-cost interventions at enhancing resilience to climate change for sustainable agriculture.

In conclusions, the following points come out from the above discussion:

(a) Timely allotment and evaluation of the farmer's friendly program is an important part of any allotted project for an area-specific program; therefore after the project, its effect on the farmer's livelihood must be delineated.

(b) Custom hiring is the best practice which also enjoyed the reach of even poor farmers as most farmers are willing to adopt RCTs, but higher mechanization cost proves to be a great hurdle. Therefore, at the village level, different cooperative societies must be there which offer different machines, viz., Happy Seeder on custom hiring.

(c) Employment-generated training program pertaining to beekeeping, vegetable production, dairy, animal husbandry, etc. must be provided to the farmers through different training institutes set up by the government or public center employment for the farmers which helps to make them busy during not only the rest periods in between rice-wheat crops but also during the intervening period.

(d) Water availability during the stressed period must be assured as life-saving irrigation even through village-level agriculture planning and depending upon the water availability and supply and demand relationships.

25.4 Conclusions and Future Plans

Unjudicious and flood irrigations must be avoided, and different techniques must be adopted by the farmer for need-based irrigation. Excessive underground water pumping from the lower strata must be checked, and some price money is to be imposed on the farmers same as that of electricity. Presently, in Punjab, India, electricity is provided free of cost to the farmers. Further, intensive tillage operations must be discouraged, and emphasis must be set on the zero tillage but with residue retention onto the surface for enjoying the benefit of mulching and improving the profitability and sustainability of the rice-wheat cropping sequence of the South Asia. Irrigation requirement of paddy is exceptionally higher which reduces its irrigation water productivity. Further, repeated puddling operation deteriorates the soil structure and forms the "plough pan" at about 5–15 cm which further poses a threat to the aerobic wheat crop's roots growth. Intensive tillage exposes the once hidden organic matter to the microorganisms which oxidize it in the form of CO_2 which is ultimately responsible for global warming which proves to be a serious threat in front of the sustainable agriculture. Evidence shows that the improvement in the water productivity at the research trials is much higher than that observed at the farmer's fields. Thus, there is an obvious assignment for the soil scientists and agronomists to work out some sort of action plan for improving both land and water productivity, which is also socially acceptable to them. Performance of recommended RCTs is both site- and situation-specific, and their performance also depends on the soil texture and agroclimatic conditions. Further, rainfed farmers could also improve their WP by using straw mulches and tillage to retain more rainfall and decrease evaporation from the soil, rainfall harvesting and recycling, and optimum fertilizer use. For adopting climate-smart agriculture for overall improvement in the livelihoods of the farmers at the global level, following points must be considered while finalizing any future plans for improving both land and water productivity, hence livelihoods of the farmers.

1. Need-based irrigations must be applied using techniques such as drip irrigation, alternate furrow irrigation, irrigation based on soil matric potential, DSR, straw mulching, etc., but there is an obvious need to standardize micro-irrigation techniques for increasing WUE in wheat-based cropping systems.
2. Agro-meteorological services must be well equipped with the latest equipment for predicting any extremes well in time so one could efficiently plan his/her crop calendar as well as rotation.
3. Water and stress-tolerant crop cultivars must be developed by recognizing genes responsible for ultimate results in higher water productivity even in salt-affected soils.
4. The government must provide some incentives for the farmers practicing CSA techniques as initially yields declined for 3–5 years, and then afterward CSA plots have same or even higher land productivity without putting any adverse effect on the soil or water resource base.
5. Drip and sprinkler systems must be delineated for each cropping rotation under texturally divergent soils for their adoption for the location-specific areas.
6. Intervening period will not be neglected as generally the case is and soil moisture dynamics must be delineated as under the effect of the RCTs being practiced for establishing previous crop.
7. Extension services or lab to land program must be strengthened enough to educate and aware the farmers and compensate them where it is as and when required.
8. A higher fraction of ET water must be portioned from E to T component for improving water and nutrients along with water and thereby yield potentials of different cultivars.
9. Increased groundwater storage, recharging, poly-coated urea performance, and getting rid of constraints to accomplish the probable in rainwater harvesting are the new researchable areas.
10. Different RCTs are site- and location-specific, and therefore a set of package pertaining to technologies will be well recognized to the area for the convenience of the farmers.

Till now, the perfect adoption of different RCTs is not possible in spite of every effort made by scientists, extension workers, policy makers, etc. Government policies (planned in the proper way) will certainly help us to meet the goals of higher productivity well in advance. Moreover, an incentive must be provided to the farmer practicing the climate-smart agriculture for attracting more farmers because of an expected yield loss experienced by them as a set period of 3–5 years is required for RCTs to become effective. There is a need to identify a set of resource conservation technologies which is both site- and location-specific and which will really help the farmers to improve their livelihoods under their soil textural class and agroclimatic conditions. Therefore, a set of an integrated package with different RCTs needs to be identified which will not confuse them rather help them to pick up one as per their need.

Conflicts of Interest The authors declare no conflicts of interest.

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Tools and Techniques of Postharvest Processing of Food Grains and Seeds

26

Irfan Afzal, Sania Zahid, and Saira Mubeen

Abstract

Poor storage and lack of technical efficiency can result into 50–60% losses in cereal grains. In the past 30 years, most of the research investment has been made to increase the production of food crops, while only 5% research was directed toward reducing postharvest losses. Increased production of agricultural crops is necessary to ensure food security, but this will also exhaust the natural resources and is facing severe challenges of climate change and scarcity of land and water resources. Another approach is reduction of postharvest losses of cereal grains and seeds, which are mainly due to poor storage conditions as global annual food losses are amounting to 1.3 billion metric tons or enough food to feed 2 billion people. Postharvest losses reduce the quantity of agronomic crops as well as quality of seeds, which ultimately affects the economical and market value. Seed composition, moisture content, storage temperature, and relative humidity are related to seed longevity reduction during storage. However, recent studies have suggested high seed moisture content as the most important factor involved in seed deterioration, hastening insect, and fungal infestation. New technologies whicch contribute in overcoming these losses can help in enhancing seed shelf life and its quality. This chapter will provide a thorough understanding of postharvest losses in agronomic crops of developing countries and their reasons and status of storage losses and also provide new inventions for proper handling and storage of economically important seeds. It also gives detailed information about improved technology and its efficiency and various other technical inventions of effective storage especially on agronomic crops.

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Seed supply chain · Hermetic storage · Drying beads · Heated air drying

Abbreviations

SMC	Seed moisture contents
PHL	Postharvest losses
RH	Relative humidity
PEG	Polyethylene glycol
US	United States
UNEP	United Nations Environment Programme
FAO	Food and Agricultural Organization
PICS	Purdue Improved Cowpea Storage

26.1 Introduction

Climate change and burgeoning population are major risks for food security. The world's population will increase up to 9.1 billion (34% higher than today) in 2050 (FAO 2009). Almost this increase in population will happen in developing countries. About 70% more cereals are needed to feed this increased population. Thus, demand for cereal grains projected to 3 billion tons in 2050, which means that the grain production would be increased up to 50% in 2050 to feed the increasing population. However, 25% grain production would be enough if we control the postharvest losses between harvest and human consumption. No doubt, increase in yield is very important to feed the increasing population; however, postharvest management is a more resource-efficient way of increasing food availability without use of agricultural inputs than increasing grain production. According to an estimate, 1 billion people can be fed by reducing loss and waste of food (Kummu et al. 2012).

Postharvest losses in food grains range up to 25% in developing world, only due to mishandling, spoilage, and pest infestation. According to this estimation, one quarter of food produced never reaches the consumer's end, wasting the effort and money used for producing that. This figure is quite large and alarming, especially for those countries where people are already facing food insecurity (Guru and Mishra 2017). In the last few decades, most of the countries have focused on improving their agricultural production, land use, and population control as their policies to cope with this increasing food demand. Increased production without minimizing the postharvest losses is not profitable as one third of total production is lost at this stage (Bradford et al. 2018). Maintaining seed quality and quantity during postharvest management didn't receive more attention as it should be. In food supply chain, magnitude of losses varies with crops, postharvest operations, areas of storage, and economical conditions. Commonly these losses result in weight reduction, nutritional value, and seed viability and quality (Boxall 2001).

Crops are generally grown seasonally in the world and stored for short or long term for food reserves or seed for the next season. About 50–60% losses in cereals have been observed in storage, only due to technical inefficiency. In developing countries, produces are stored carelessly in traditional storage structures made up of without any scientific design. The resource-poor farmers in developing countries have no alternatives but to meet more than 75–90% of their seed needs through poorly stored and low-quality seed (Afzal et al. 2016). This type of poor storage triggers deterioration process and unable to protect seeds or grains against pest's attack which accounts for more than 40% physical and nutritional losses in food grains (Chomchalow 2003; Kumar and Kalita 2017). Lack of adequate storage facilities results in millions of tons of food grains spoiled annually due to exposure to high humidity and rain (World news 2009). Estimated losses for maize in traditional storage structure range up to 59.48% only after 90 days (Kumar and Kalita 2017). These losses can be greater, especially in regions where high temperature and relative humidity persist from maturation to storage (Kumar and Kalita 2017). In South Asia, 40–50% losses in cereal production have been reported due to improper postharvest practices (Bari 2015). Cereals are on the top in calorie basis among all other agriculture commodities with 53% losses (Kumar and Kalita 2017). Reduction in losses of cereals is one of the most important steps in food security and sustainable agriculture. If attention is not given to these cases, situation will go up to 80% loss in cereals (Fox 2013). These losses critically play with the life of smallholder farmers as they utilized their lands, energy, and water to produce that food which undergoes the losses procedure. Drying and storage are the key components that should be handled carefully to minimize food grain losses. The viable approach is the drying of seeds and grains whether through natural or artificial means after harvest followed by hermetic packaging to make the product dry and keep it dry until used in the value chain.

This chapter will enlighten the practical and effective interventions for reducing the postharvest losses in agronomic crops during supply chain and improving food security. Application of improved drying methods at both small and large scales can effectively reduce grain moisture to safe level required for storage and thus discourage growth of mold and insect if properly packed in hermetically sealed bags during the season.

26.2 Seed Supply Chain of Agronomic Crops

Seed supply chain is based on numerous operations, i.e., harvesting, threshing, cleaning, drying, processing, and storage, and finally transported to the market for end consumers. Postharvest losses usually occur during these operations when care is not taken and seeds are exposed to various improper and inefficient practices. For reducing postharvest losses, it is very necessary to understand the supply chain and its factors which directly affect the losses and seed quality (Fig. 26.1).

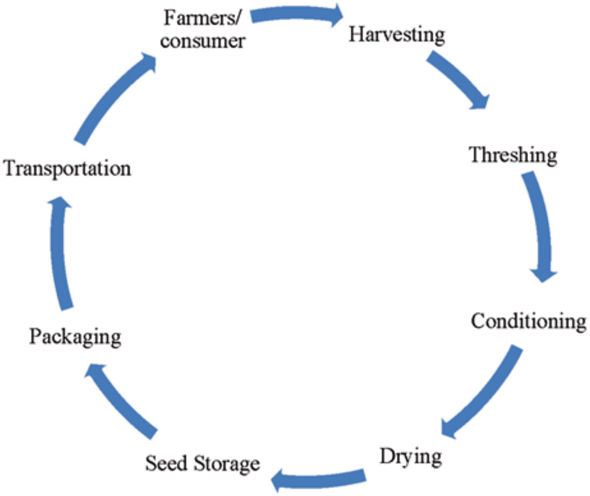

Fig. 26.1 Basic steps in seed supply chain

26.2.1 Harvesting and Threshing

Crop harvesting at a proper time with proper moisture determines its quality and fate for storage. Both early and late harvesting affect the crop yield and its quality. Harvesting in developed countries is done by combine harvesters, while developing countries still rely on manual methods through cutters, knives, and sickles. At early harvesting higher moisture contents present in crops, increasing efficacy and drying cost (Khan 2010), while late harvesting invites rodents, birds, animal attacks, and natural damage, i.e., shattering (Baloch 2010). In developing countries, late harvesting of crops is a common problem due to shortage of labor in harvesting season which brought severe shattering and more than 50% postharvest losses (Grover and Singh 2013). After harvesting, crops remained in the field till threshing, a time where if moisture is high in seeds, this can cause mold and fungus attack. Crop is directly exposed to open environment, rodents, and birds, which causes quantitative loss. Like harvesting, threshing is also done using manpower for agronomic crops in developing countries. But now, for wheat and rice, small threshers are also used.

Leguminous crops like mung bean and mash bean are still now threshed manually (trampling and beating) or through using animal power. During threshing, seeds are detached from the panicles through rubbing, stripping, or collision or their combinations. Lack of threshing equipment is the main cause of seed quality loss. Breakage of grain, cracks in seed coat, incomplete threshing, abrasions, and other mechanical damages increased the chances of microbial attack (Shah 2013).

Combine harvesters are used in developed countries, which performed both functions of harvesting and threshing of seeds along with cleaning of seeds from straws, and chaffs are also done through it. But it is best in large crop area; for small area, other harvesters or manual harvesting of crops is preferred by farmers. Some crops like cotton and pigeon pea required handpicking (usually two or more than two). Farmers pick the balls from each plant manually and place them in basket, later crop is cut and harvested for next crop.

26.2.2 Conditioning and Drying

Cleaning of seed is a process to separate the sound seed from damage and broken grains along with weed seeds and from other external materials, i.e., chaff, stones, straw, and sands. Cleaning of seed is done soon after harvesting to increase the efficiency of drying in dryer. The best way to clean the seed is through the winnowing process, in which seeds are cleaned by using air pressure. It is a common method in developing countries, while cleaning machines are used in developed countries to decrease the labor cost while increasing efficiency. On the other hand, screening or sifting is also helpful in seed cleaning. Broken or damage seeds are the main target of fungi, molds, and other microbes which further cause infestation and infection during processing and storage. During winnowing, seed losses occur up to 4% (Sarkar et al. 2013). For cleaning different equipment are used which are widely adopted in developing countries as follows:

(i) Scalper (rough cleaning of large trash).
(ii) Huller scarifier (scarification of seeds).
(iii) Air screen machine (scalping, aspirating, and grading).
(iv) Stoner (modified form of gravity separator).

These equipment are used in separating the seeds from other unwanted materials. But sometimes seeds of different sizes, colors, and lengths should be separated from the others for their best quality. This process is called upgrading and done through different mechanical operators. There are numerous upgrading machines that help in separating seeds of good quality on the basis of weight, size, color, texture, etc. (Gregg and Billups 2016).

After cleaning, seeds should be dried to safe moisture for long-term storage. It improves seed quality during storage and transportation and handling. Most of the agronomic crops can be safe with moisture contents below 13% for excessive storage. Seed drying is mostly done by two common methods, i.e., natural drying and force drying. Insufficient drying is the cause of mold growth and quality in storage and ultimately milling of different agronomic crops. Natural drying of crop is done through solar heat. The crop is left in the field in the form of stacks after harvesting to reduce the maximum moisture and then threshed. It is commonly adopted by developing countries but highly dependent upon weather condition and relative humidity and laborious. Unexpected rain and high relative humidity lower the quality of crop, and also get it contaminated by stone straws and other materials. In sun drying about 3–4% losses of total production are reported (Abas et al. 2014). Developed countries are modernized with mechanical drying where whole seed lot is dried using high temperature containing air which absorbs most of the moisture from crop and dries them at safe point. It is more advantageous than sun drying in preserving seed quality and reduced handling losses. Its maintenance cost is too high, so farmers of developing countries avoid using it (Alavi et al. 2012).

26.2.3 Storage and Packaging

Storage of seeds is the major supply chain unit and key process in sustainable agriculture. Thus storage should be highly controllable which can maintain good environment for safe storage. Most of the damage occurs in the storage condition when temperature and humidity are uncontrollable (Bala et al. 2010). Seeds can be stored by traditional or modern methods. In traditional method, usually Pusa bin, reinforced cement concrete bin, circular steel bin, plastic bin, aluminum bin, and prefabricated steel bin are common. On the other hand, modern methods included conditioned storage, cryogenic storage, containerized storage, and hermetic storage. Seeds are grown and stored for a short period after harvesting for the next sowing, but poor conditions in storage highly damage the seeds (Aulakh et al. 2013). Warehouse infrastructure and storehouses should be in proper conditions and with proper materials, which can prevent insect pest and rodent attack. But many countries have no ideal storage houses with proper design and materials, which prevents rodents and severe envirnments.

Temperature fluctuations, seed moisture contents, and relative humidity in storehouse are major factors, which are highly responsible for the seed losses (Majumder et al. 2016). For proper control of fungal growth, less than 14% moisture contents in cereals while 8–9% moisture in oilseeds along with 65–70% RH are recommendable. Moisture contents due to ambient relative humidity also determined the insect population in seeds during storage. Chemical fumigations are also done before seeds are stored to prevent infestation and infection of insects, pests, their larvae, and other organisms (Upadhyay and Ahmad 2011). Proper ventilation in the storehouse avoids product overheating.

Storage materials also influenced the seed quality in storehouse. For long term storage, packaging material should be air tight and cannot exchange the gaseous ions which are helpful in oxidation and reduction process of metabolic events and cause seed ageing during storage. Storage of seeds in cloth, paper and jute bags and sacks are preferred which are good source of insects and pest attack even in low temperature containing low RH (Afzal et al. 2017). Therefore, storage materials should be sealed so that seeds can survive even for a long-term period. In modern era, hermetic storage is preferred by developed countries to store seed. This technology is now highly adapted by developing countries where high humidity and erratic rains are common (Bradford et al. 2018).

26.2.4 Transportation

Transportation of seeds is the last step in seed supply chain where seeds are sent to the market and finally consumers buy them for the next production. Transportation would be easier if roads and paves are well constructed. In contrast, if roads and infrastructure were of poor quality, seeds and other food products would be damaged. In developed countries, losses due to transportation are very low as compared to developing countries. Their loading and unloading facilities and engineered services are helpful in reducing postharvest losses. In Central and South Asia, crops are transported in animal carts, bullocks, open trucks, and small vehicles. Poor condition of roads and infrastructure highly contaminated the crops, which affect the quality. About 2–9% losses occur due to poor transportation (Alavi et al. 2012). Seeds packed in conventional bags or low-quality bags highly reduced the seed vigor and germination when expose to various types of environments during transportation. In developing countries seeds are moved multiples times and loaded and unloaded several times which increase the damage rate and result in spoilage.

26.3 Factors Responsible for Postharvest Losses during Storage

Seed deterioration is the main problem in storage of seeds especially in those areas where humidity and temperature are higher at the time of maturity and storage. Safe storage is necessary for maintenance of grain quality characteristics that can be expressed in terms of germination, baking quality, oil composition, and color and malting quality. Due to deterioration, greater economic loss occurs every year by the consequences of mechanical damage and microorganism activities, which enhanced this mechanism during production, storage, and shipping of seeds and grains. Moisture contents of storage environment, grain temperature, initial seed quality, and storage gasses are the interrelated factors that play a role in seed losses (Befikadu 2014). The kind of the seed being stored, genotypic factors, initial seed viability, and several environmental factors like temperature, moisture, oxygen, and carbon dioxide affect the deteriorative changes in seeds during storage (Farhadi et al. 2012).

26.3.1 Genetic Factor

Genetic factor is also responsible for the shelf life of seed during storage. Chemical composition of seeds and seed coat and genetic diversity also influence seed longevity (Copeland and Mcdonald 2005). Some seeds are short lived like some vegetable seeds (onion, parsnip, and lettuce) and few agronomic crops (like rye); they can only survive few months, while cereals can survive up to several years with high germination rate. Alsike, *Albizia*, *Trifolium*, and *Goodia* on the other hand have excellent longevity and germinability. Seeds having more oil contents in their compositions are more prone to lose their viability in high relative humidity and high temperature. Oilseeds and cereals can’t be stored in the same storage environment (Shelar et al. 2008).

26.3.2 Temperature

Temperature is a critical factor that triggers biochemical processes and hastens the rate of seed deterioration in storage (Shelar et al. 2008). Storage temperature is mostly affected by sun, heat generated by respiration of seed, and microorganism. With few exceptions, temperature in the range of 10–60 °C is best for microorganism growth. At 25–30 °C with 80% RH, most of the crops lose their vigor and viability. But these crops can be maintained at >50% RH and 5 °C temperature up to many years. Directly managing the store environment is economically not feasible, so other measures especially managing the moisture contents in safe range are necessary (Befikadu 2014). Harrignton said as a regard the interactive effect of temperature and moisture with respect to seed vaibility, "Sum of % RH and temperature (F) shouldn't exceed 100 for storage of seed with great vaibility" (McDonald 2007). It was reported that for long-term storage, RH should not exceed more than 50% at 5–10 °C for safe storage of seeds. Sensitivity of seed in storage is dependent on interracial effect of temperature and water contents of seed. High temperature in combination with higher seed moisture contents can produce favorable conditions for the multiplication of microflora. Moreover, slight increase in moisture and temperature induces positive effect on fungal growth. In conclusion, low temperature of store rooms help in reducing the fungal and microbial attack on seed commodities.

26.3.3 Moisture Contents

At the time of harvesting, high moisture content and high relative humidity can influence the seeds' physical and physiological maturity and quality for storage (Copeland and McDonald 2002). Seeds stored at more than 14% MC can accelerate the seed respiration and other metabolic activities, which lead toward seed aging. In store, moisture above 20% can produce heat through seed respiration process, which kills the seed or may cause fire. All biological and biochemical activities of seeds occur only in the presence of moisture contents. In general perception, the higher the moisture contents of the grain, the more the chances of mold and insect attack along with seed deterioration. According to an overview, below 13% MC fungi cannot grow in starchy seeds while 7–8% for oilseeds (Bewely et al. 2013). In storage, insects and fungi are the principal agents of deterioration, and development is particularly associated with temperature and moisture contents. Some insects, i.e. granary weevil, lay their eggs internally in the seed and feed on the endosperm of the embryo, while in some crop seeds eggs are mostly laid on the seed surface, and their larvae bore into the seed (Desai 2004). Biodeterioration of grains is due to its own metabolic activities and insect, mite, and mold attack, while these all are the consequences of higher moisture contents. All such problems have influence on seed trading standard and seed storability (Suma et al. 2013).

Seed hygroscopic nature makes it susceptible for moisture change according to moisture variations in the surrounding environment. Environmental temperature and relative humidity are also considered important for controlling the seed moisture contents (SMC). Fluctuations in these factors cause variation in %SMC.

According to Harrington, the first rule of thumb (each one percent reduction in seed moisture will double the life of seed) is only applicable for seeds stored at SMC less than 14% (McDonald 2007), the first rule of thumb (each one percent reduction in seed moisture will double the life of seed) is only applicable for seeds stored at SMC less than 14%, while the second rule of thumb (each 5 °C reduction in seed temperature will increase the seed life two times) is for those seeds stored down to at least a temperature of 32 °F (0 °C) (Copeland and Mcdonald 2005). But care should be taken with less moisture about >5%, as it can disrupt the membrane structure and enhance seed aging.

26.3.4 Oxygen

The presence of air around the seed has a remarkable effect on seed storage. Cereals which have less than 10% SMC survive best if the surrounding air comprises of more carbon dioxide and less oxygen (as in hermetic storage), while the reverse case is beneficial at moisture greater than 14%. Moisture content has the tendency for increasing carbon dioxide and lowering the oxygen around the seed. With decreasing oxygen level, mold growth, grain damage, and respiration rate are gradually decreased (Kulkarni 2004). According to estimation, reduction in oxygen during seed storage slows the seed aging processes and also prolongs the shelf life of seed (Groot and Surki 2011 and Table 26.1).

Table 26.1 Safest moisture limits for different crops stored up to 1 year

Crops	Moisture contents (%)
Corn	13–15
Sorghum	13–15
Soybean	12–14
Wheat	10–12
Oat	10–13
Barley	10–13
Rice	10–12
Sunflower	8–10

26.4 Recent Approaches to Reduce Postharvest Losses

Complementary approach to attain food security is to reduce postharvest losses during supply chain of crops. Almost one third of the food items are subjected to spoilage before the final consumption due to mishandling (Rockefeller Foundation 2013). Postharvest losses are a problem of great concern especially for developing countries in which postharvest losses major fraction is contributed by the losses during storage. The major reason behind this loss is the use of traditional storage structures which are insufficient to avoid insect infestation and mold growth. Technology interventions and use of improved storage structure are the best options to minimize these losses. Hermetic storage creates an oxygen-depleted environment for insects' growth and automated modified atmosphere for increased carbon dioxide. These hermetic structures also make transfer of change of moisture impossible. According to a study, approximately 98% reduction in storage losses has been observed in this type of packaging material (Kumar and Kalita 2017).

26.4.1 Dry Chain Technology

In developing countries, usually agricultural commodities, when harvested, are stored in cloth and porous bags even without losing their moisture, which make them more susceptible to environmental fluctuations (high relative humidity, rain, temperature, etc.). Improper drying and unavailability of proper storage house lead to more losses in rainy and high humidity areas. So the possible solution is dry chain technology, where products are sufficient dried and then stored in hermetically sealed containers at ambient temperature (Bradford et al. 2018). The basic principle behind this is to reduce seed moisture contents to a safe level and then store the product in high temperature with sealed storage. This technology is developed by the researchers of UC Davis, with the slogan "Make it Dry-Keep it Dry." That means, for minimum postharvest losses, moisture and temperature should be controlled without having more energy to maintain temperature. However, a poor approach is to store wet seed under high temperature after harvest that results in quick decline of seed viability. The good approach is to dry seeds at safe level and pack them in hermetically sealed containers without energy costs. The maintenance of this dryness throughout supply chain contributes to the higher quality of seeds (Afzal et al. 2017). Subcontinent has both dry and wet climatic zones where two cropping seasons are practiced, i.e., Rabi (October/November to April/May) and Kharif (June/July to November/December). Seeds harvested in either season go through summer monsoon rains (Fig. 26.2) where they lose quality mainly due to the combination of high MC and high temperature. In spring, air drying may be sufficient to achieve low dryness levels (wheat 10% SMC); however, without packaging, this dryness was lost during monsoon. Improving storage of dry products has been the focus of several researchers and organizations in Pakistan (USAID 2009; Dawn News 2010).

Seed is hygroscopic in nature and warmer at the time of harvesting and thus can gain moisture from the atmosphere. Cereals and legumes could be stored in high

Fig. 26.2 Effect of RH on seed moisture contents of crops during spring and autumn seasons

Fig. 26.3 Use of desiccant beads for drying and preservation of seeds in closed containers

temperature with low moisture contents, while other products that cannot be dried up to safe level should be stored in low temperature (cold storage). In temperate regions, temperature and relative humidity are mainly controlled by precise ventilation of the storage house, while in warm and humid areas, ventilation with the outside air may be harmful because air is already enriched with moisture content. In the case when seeds or plant produced is stored for the long-term durations, e.g., in seed banks, both the reduction in moisture contents and temperature may be mandatory for the best storage (Bradford et al. 2018).

26.4.2 Seed Drying Strategies

Worldwide, improved food quality with good nutritional is of major concern. According to estimation 80 million tons of food grains are lost by damage from the molds and insects due to poor postharvest management. Seed storage at elevated RH and moisture leads to fungal and insect growth along with aflatoxin production. In this situation dry chain technology is a major solution in solving all the above problems (Bradford et al. 2018). This technology involves the drying of seeds and other commodities (cereals, pulses, and nuts) after harvest as soon as possible. After drying to suitable moisture level, seeds are stored in hermetic sealed packaging material to preserve this commodity at initial moisture level until used. No large infrastructure or energy investment is required for the maintenance of this dry chain as compared to cold chain technology in which continuous refrigeration in warehouse, trucks, and markets is required. Implementation of dry chain is good option for improving food security, nutritional value, and health in both human and animals (Afzal et al. 2016 and Fig. 26.3).

26.4.2.1 Seed Drying Principle

All seed drying methods are based on the principle of establishment of moisture gradient from seed to the air. So, it's necessary that relative humidity of air used for drying should be below than the moisture in seed. Rapid seed drying causes moisture loss from outer surface of the seed quickly without removing moisture from internal seed structure. This rapid moisture loss develops a physical stress, and resultant is the cracks in seed structure (i.e., rice) and ultimately loss in viability and vigor (McDonald and Copeland 1997).

26.4.3 Drying Methods

26.4.3.1 Natural or Sun Drying

Natural or sun drying technique is still commonly used for drying commodities. In natural drying system, seeds are usually spread on the floors or on large pieces of synthetic fibers or cloth. This system also permits the drying in field before harvesting and in shallow layers. Seeds can be stirred periodically to facilitate uniform and rapid drying. This process relies on the heat generated by sun, relative humidity from the air, and wind velocity for removing moisture. But where large quantities of drying are desired, this practice is laborious and makes the drying process very difficult (McDonald and Copeland 1997). Due to uncontrolled weather conditions, sun drying is a risky option. Solar drying is a recent approach to improve the sun drying process. Solar is still the heat source, but a foil surface inside the dehydrator helps to increase the temperature, and ventilating process decreases drying time. Shorter drying time provides edge for reducing food/grain spoilage and mold growth (Ahmed et al. 2013).

26.4.3.2 Heated Air Drying

In comparison to traditional sun drying, heated air drying or mechanical air drying provides a better option. This system is beneficial in terms of reducing the labor cost and allowing drying any time of day or night. In case of recirculating dryers, recirculation of grains allows uniform drying, and automatic air drying system also controls the drying rate by prohibiting overdrying or overheating of grains (Rice knowledge website). Heated air drying is more beneficial in high humidity areas where natural drying is difficult. Seed quantity in seed bin, airflow rate, and desired moisture of commodity will affect the time required for drying (McDonald and Copeland 1997).

Among different dryers used in the seed industry, batch dryers are the simplest dryers consisting of storage bin having perorated floor and blower for air movement. Recirculating batch dryers are also common in developing countries that have advantages over batch dryers as they allow continuous mixing of grains resulting less variation in moisture contents in similar lot. Continuous flow dryers are more efficient that allows gentle, uniform, and energy-efficient drying system. Size capacity and power in this type of dryers are modifiable by adjusting the number of drying cells and grain bins. Drying cells allows the grain drying without risk of overdrying or underdrying.

26.4.3.3 Desiccant-Based Dryers

Use of desiccants is another approach used in drying. Desiccants are substances that attract water molecules from air through adsorption or absorption process. In this type of drying system, desiccants are kept mostly in airtight metal box, and seeds are kept on desiccant in open jars or bags. Silica gel granules coated with cobalt chloride are commonly used as desiccant, as it is nontoxic, inexpensive, and efficient. Micro-capillary surface of these desiccants allows the adsorption of water molecules from the seed, grain, or any other commodities as much as 40% of their dry weight. Silica gel changes their color from blue to pink above relative humidity of 45%. By using this approach, seeds can be kept at equilibrium moisture contents for several years. These beads are suitable for preservation of germplasm and expensive seed of less quantity, however, it is difficult to use these beads at large scale (McDonald and Copeland 1997; Hay and Probert 2013).

Drying beads specifically adsorb and hold water molecules in their microscopic pores due to their modified ceramic material (aluminum silicates or zeolites) (Hay and Probert 2013). Generally these beads have the capacity of absorbing 20–25% moisture of their initial weight. Main Advantage of these is the regeneration capacity and can be regenerated at a temperature of greater 200 °C for 3–4 h. Their benefit compared to silica gel is that even after regeneration, they have no loss in their water holding capacity and can be reused 10,000 times without losing their original capacity (Bradford et al. 2018).

26.4.4 Hermetic Seed Storage Technology

For better storage and transit of seeds in bulk form, a new approach has been made known as “hermetic storage.” Mostly this technology is now used in those countries (Asia, Africa, and Latin America) where humidity and temperature highly influenced the seed quality in storage and transportation. It is a modified atmosphere type of storage, which fully restricts the exchange of gasses and thus protects the agriculture products from insects and other stored grain pests. This technique is very useful in cereals, especially in legumes and oilseed crops. Hermetic storage is also called “hermetic silo storage” or “airtight storage” or “sealed storage,” because in this storage, modified atmosphere is created maybe through microbial respiration or through other commodities to generate CO_2 and use already-existing O_2 in the bags. Studies revealed that hermetic bags could store seeds safely up to many months; moreover, this technique also reported best for less postharvest losses (<1%) during intercontinental shipments (Navarro 2006 and Table 26.2).

Although seed longevity is maintaind through this process, seed vigor remains to be decreasing due to other seed chemical and biochemical reactions. Application of fumigants for seed storage is still continued in developing countries, although

Table 26.2 Application of hermetic storage technology for different crops

Crop name	Storage material and capacity	Storage moisture (%)	Storage period	Preserved quality traits
Wheat	Hermetic bunkers 10,000–20.000 tons	>12.5	Up to 2 years	Significant reduction in seed degradation and maintenance of baking qualities (Varnava and Mouskos 1997)
Barley	Hermetic bunkers		Up to 3 years	0.66–0.98% losses in total weight and preservation of germination up to 88% (Varnava and Mouskos 1997)
Shelled maize	Cocoons	26%	96 days	59 ppb of aflatoxins, increased up to 90 ppb after 1 week of storage and constant after 90 days. Can be stored for an extended period of time without significant increase in aflatoxins and changes in starch (Weinberg et al. 2008)
Coffee beans	Super grain bags		9 months	Can be stored without refrigeration
Cocoa beans	Hermetically sealed containers			Oxygen depletion of less than 15% was observed with increased carbon dioxide concentration of 23% within 6 days, at relative humidity of 73% and 26 °C temperature (Aronson et al. 2005)
	Hermetic sealed container	7.3%		Decrease in oxygen concentration up to 0.3% within 5.5 days. No insect survive in this oxygen-depleted environment (Navarro et al. 2007)

methyl bromide is terminated for its contribution in ozone depletion (UNEP 2002), phosphine pellets are still in use. However, some pest and insect larvae modify their immune system toward phosphine in some countries (Savvidou et al. 2003). Both oxygen and temperature prevailed storage problems and affect the seed quality, which results in high amount of free fatty acid, rancidity and ultimately cause mycotoxins. This issue can be handled by application of hermetic storage, which further ceased all activities of living organisms as well as cell metabolism.

26.4.4.1 Principle

Hermetic storage can be operated by a farmer to store his seeds for long-term storage without using any insecticide or pesticide. The principle behind hermetic storage technique is to develop an oxygen-depleted, CO_2-enriched environment which prevents further insect and pest development and is lethal for them to survive in sealed bags (Mutungi et al. 2014). It also saves agriculture commodities from rodents, mold, and outer high relative humidity. It is an environmentally safe and friendly technique in contrast to chemical treatment, fumigation, and climatic issues. In this way, seeds maintain their germination rate, vigor, and quality (Villers et al. 2006). Previous research and recent studies accelerate the demand of hermetic storage and its installation on commercial basis. It is easy to install and relocate with favorable cost.

Hermetic storage becomes popular in Asia because of its safe principle. Cereals, legumes, and other oilseed crops, which are tending to be deteriorating in high humidity and cause infestation, are safe under hermetic storage. In the 1980s, the Department of Agriculture, Israel, started research on alternative method to application of chemicals and fumigations, and as a result, they developed hermetic storage.

26.4.4.2 Types of Hermetic Storage

There are different types and forms of hermetic storage depending on transportation and storage, respectively. Three main forms of hermetic storage are organic, vacuum, and gas hermetic fumigation. It is a name of hermetic storage type based upon the activity of metabolism and respiration of insects, pest, and other microflora, which generate a modified atmosphere containing less oxygen and high CO_2 and thus ceased further metabolism and other process which requires oxygen for completion (Jonfia-Essien et al. 2010). During vacuum hermetic fumigation, lower the pressure in container by vacuum which caused suffocation and thus disinfestations of the commodities are done and store up to several months. Lastly, for gas hermetic fumigation, an external source of gas is used during shipment of crushable commodities. All these methods generate low-oxygen atmosphere for microorganism, and they can't continue their respiration and metabolic activities to survive, and ultimately death occurs. It will take few days to cause death of microflora and also prevents the commodities from ochratoxin A and aflatoxins (hazardous to human health). Due to low permeable material of hermetic bags, further absorption of moisture is restricted to move in or move out of the material, and thus seed is also safe from exterior moisture in hot humidity areas.

Organic hermetic storage is most commonly and extensively used in many countries. This is commercially available for conventional bags with 5–300 tons capacity for storage ranging from few months to several years. This system is now used on farmer's farms and villages and also on district level for seed storage. In this, seeds of various values can be stored, i.e., rice, wheat, barley, hybrids of maize, coffee, cocoa, pulses, vegetable seeds, and sorghum. Super Grain Bags are recently introduced which are transportable form of hermetic storage. Super bag is made up of multilayers of polyethylene having a less permeable barrier layer to prevent exchange of moisture and air and has very low vapor transmission rate, i.e., $<10\ \mathrm{gm}^{-2}\ \mathrm{day}^{-1}$ (http://grainpro.com).

PICS stands for "Purdue Improved Cowpea Storage" bags that are triple layer bags made up of high-density polyethylene and polypropylene material. The inner two bags are of polyethylene material (80 microns), while the outer covering bag is of polypropylene texture. These bags were made under the project of USAID for the protection of cowpea from *Callosobruchus maculatus* (F.). These bags are the best example of dry chain technology as they inhibit insect and pest growth by limiting oxygen and controlling the penetrating relative humidity, so that commodities can be saved for a long time. PICS bags are nontoxic and chemical-free technology with easy handling for the farming community. Recently many studies have been done for the storage of seeds in PICS bags for the determination of seed viability and longevity. Maize, cowpeas, wheat, peanut, sorghum, and common beans have been stored in PICS bags in developing countries to prevent insect and pest infestation (Williams et al. 2014; Afzal et al. 2017). Maximum germination, vigor, and longevity were obtained from those samples which were stored in PICS bags. Other than PICS bags, super bags can also be used; it contains all features of hermetic storage.

26.4.4.3 Application of Hermetic Storage

There are many reasons for which hermetic storage is effective and thus quickly adapted by more than 32 countries. These are: Long term storage of staple food, maintaining germination % and preserves the quality of hihg vale seeds. Despite these, new applications in hermetic storage are under process to store more valuable different products, i.e., high moisture maize, milled and brown rice, basmati rice and rice bran, ochratoxin-free coffee, and other oil commodities. In 2004 the International Rice Research Institute used hermetic storage for rice seeds; after 10 years of storage, storage of rice seed is well understood and applied by different other countries. During 2007–2013, about 3 million hermetic bags are sold in Central and West Africa (Kumar and Kalita 2017). Grain pro bags were used in Afghanistan for the storage of wheat while in Guatemala and Zambia for corn and coffee seeds (Grain Pro 2010). These bags were also used for rice in Vietnam (Ben et al. 2009). PICS bags were tested for the quality preservation and aflatoxin contamination in maize seeds. Maize stored in PICS bags showed 3% losses in weight with no aflatoxin contamination as compared to those stored in polypropylene bags with 35% losses on weight basis and higher contamination (Afzal et al. 2017).

26.5 Seed Treatment and Chemical Fumigation

Seed treatment is a process in which seeds are disinfested and disinfected from numerous diseases (seed-borne and soilborne) and insect pest attack in store houses. It's a process in which various chemicals are applied to keep seed safe from inner or surface pathogenic organisms and keep them for long-term storage. It is considered a sound practice for agronomic crops and garden crops. Nowadays, treating seeds with chemical is a more important and standard practice before storage and planting. Due to many reseons, seed treatment is considered best i.e. injured seed (good site for fungal attack), seed-borne diseases or maybe soilborne diseases, unfavorable conditions for germination, and chemicals for better germination and growth. There are three main methods of seed treatment, which help in the protection of seeds from fungal and bacterial spores named as mechanical, physical, and chemical methods (Desai 2004).

In the mechanical method, seeds are free from pathogenic materials, and this needs mechanical power to clean the seeds. But in this method, pathogen attached to seed surface is not removed, and further cleaning is necessary. In the physical method, seeds are treated with various treatments like hot water, water soaking, use of x-rays and gamma rays, and also magnetic field which are helpful in controlling most of the fungi and enhance seed germination performances. Hot water treatment was used before the 1950s, but in modern era, soaking of seeds (priming) is under attention by many researches. Seeds are soaked for 2–8 h depending on the crop and in different types of solution and dried again which enhanced their inner capability to stand even under harsh climate and different soil types (drought, salinity) (Taylor et al. 1998). Some crop seeds showed imbibitional injury that can be reduced by using 1% salt solution and polyethylene glycol (PEG) (Afzal et al. 2009).

Use of x-rays and gamma rays is also helpful in ionizing the microorganism and other seed components, which helps in germination (Melki and Salami 2008). But this method can cause mutation in DNA and is also harmful for the seeds' composition. Magnetic field is now under consideration, as specific magnetic flux with specific time for seed treatment can enhance the seed performance in field. But this method is far from common farmer range.

26.5.1 Seed Priming

Priming of seeds is a pre-sowing treatment for the enhancement of crop performance. It contains partial imbibition and then drying. Different chemicals could be used as priming agents, i.e., water, PEG, matric priming, chemicals, salts, etc. Seeds are soaked for a specific time that the III germination phase (radicle protrusion) doesn't start and seeds are again dried on their initial moisture. This phenomenon leads the seeds to complete all their metabolic processes required for germination, and therefore at the time of sowing, it reduced the mean germination time in field. Through this seeds exhibit high rate of germination and uniformity both in optimal and adverse environments. Performance of soybean, pepper, spinach, wheat, and maize was also reported by using different priming techniques. A study revealed the seeds' performance even in drought and salt stress conditions (Bruce et al. 2007; Afzal et al. 2016).

26.5.2 Seed Coating

Seed treatment with chemicals started in the 1920s with the semesan and ceresan compounds. But in the 1950s, chemicals were properly used for seeds by a botanist who introduced the copper sulfate treatments (Copeland and McDonald 2005). The ideal chemical should be highly effective toward pathogen, be nontoxic to seeds as well as human health, have higher stability, and be easily applied and commercially competitive. But present chemicals don't meet these conditions.

Chemical method is most common in developing countries as it is easy to handle and more efficient in less time. Both organic and inorganic fungicides are used in the form of dust, suspensions, and liquid. Dosage of chemicals depends upon crop, storage time, and application method. Dust, liquids, and suspensions are different forms of application. Wet treatment coating and pelleting of seeds are new methods of applying chemicals which protect the seed from seed-borne diseases as well as soilborne pathogens. Wet treatment is also used for the application of fungicide; seeds are soaked for a specific time period in the water having fungicide and then dried and used. Although this technique is laborious for large cultivation, it also needs space for drying and is time-consuming. Coating is like this, but the amount of water is less than 1%, and fungicide attaches to the surface of seed with a sticky material. Many inert and active ingredients are used like binders, carriers, wet agents, sticking materials, dyes, emulsifiers, and suspending agents. These ingredients are able to enhance germination, attractive appearance, dusting of and increase adherence. This technique has been found accurate and useful for uniform application of fungicides on seeds. It doesn't change the shape of seed and is a safe method. In contrary, pelleting obscures the seed shape and increases the seed size with weight. Seed pellets are made; usually small seeds are treated through this application. Treatment of seeds increased seed germination, vigor, crop yield, storage capacity, and resistance against seed-borne and soilborne pathogens. This also controls insect pest attack in the storehouse.

Many countries still used synthetic chemicals for the control of storage pests and insects. Among them, tablets of phosphine and methyl bromide are common (Kumar and Kalita 2017). With less than 13% moisture in maize crops, Phostoxin can be used in grains. This is available in Actellic and permethrin form, and only licensed technician can sell those. In Africa, for storage of shelled grains in polypropylene bags, Actellic super was used (Groote et al. 2013). More than 93% farmers used this method as a cheap source for the protection of grain from storage pest in Tanzania (Kimenju and Groote 2010). However, synthetic chemicals are effective, but they are expensive and hazardous to human health and cause genetic resistance in related pest along with reduction in seed viability (Mutungi et al. 2014). Some countries reported that phosphine tablets developed genetic resistance in insects for chemical fumigation (Savvidou et al. 2003; Villers et al. 2010). Accurate timing of fungicide application along with correct dose will decrease the postharvest losses and increase efficacy.

26.5.3 Chemical Fumigation

Chemical fumigation is a common practice to control storage insect and pest infestation. In chemcial fumigation, fumes are produced in ware-/ storehouse which penetrate into body during respiration, reach to trachea and attach to hemolymph which then cause death of organism. Different chemicals have been used for fumigation like ethyl formate, sulfuryl fluoride, ethanedinitrile, and carbonyl sulfite. These were used for cockroach and termite infestation. Carbon tetrachloride and ethylene dichloride are used for eggs, larvae, and adults of storage insect and pest. Cyanogen is also toxic for the insect and pest. Common fumigants like sulfur dioxide, trichloroacetonitrate, ethylene dichloride, methyl formate, methyl bromide, etc. also have been used. Tablets of aluminum phosphide are effective and the safest fumigant for storehouses. For cereals and legumes, tablets of phosphide and methyl bromide are widely used. Some organic insecticides are also available named fenitrothion, pirimiphos-methyl, and azamethiphos which are toxic for *lipscelid psocid*. Silica dust solution of 0.1% (hydrophobic amorphous) can control *callosobruchus chinensis* after 48 hours of applicationand same result was obtained by applying wood ash of burnt wood of trees. Many farmers use sand and quartz instead of silica dust to kill the larvae of insects. For grain borer, ground surface of storehouse is treated with diatomaceous spray. All these chemicals are effective when the storehouse is fully sealed and temperature is less than 50 °F. For stored grain beetle, allyl acetate is effective, and terpenes are used for the cotton bollworms (Upadhyay and Ahmad 2011).

26.6 Conclusion and Future Prospects

Postharvest losses are major problems among developing countries. In agriculture commodities maximum fraction falls for the cereal losses on calorie basis and highly affects the livelihood of farmers. Traditional storage and inadequate conditions of storage resulted in higher physical and quality losses. Proper handling and better storage help to overcome this proportion and increase the rate of available products and revenue. These suggestions help in reducing postharvest losses in agronomic crops:

- Development and acknowledgement of improved storage structures and modern interventions to small farmer communities, so that crop should be safe from field level to consumer level.
- Use of hermetic bags in high humidity area can reduce the losses due to moisture and insect attacks. They are more helpful in maintaining high germination, vigor, and quality.
- Various low-cost postharvest technologies can be used by farmers so that their revenue will increase by removing poverty. This will help in sustainable agriculture with low input cost.
- Cost-effective technologies should be used collectively or by the collaboration of public-private sector partnership.
- Researchers should introduce convenient but efficient methods to checked relative humidity and temperature from field to market. New methods of drying the agriculture commodities in high humidity areas and waterproof bags and containers also help in maintaining quality of food.

Modern postharvest technologies help in food security through various modes. It provides benefits in terms of earning and food to poor people with low price. Adoption of new modern technologies can reduce the postharvest losses up to 30%, and food will be available to community for maximum consumption. It will also reduce the energy and inputs which are used by farmer for production of new crops.

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27

Nanotechnology and Its Role in Agronomic Crops

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Abstract

With the rapid advancement in the field of nanotechnology, the application of nanoparticles, with a particle size less than 100 nm, designed for sustainable crop production, reduces nutrient losses, suppresses disease, and enhances the yields. Nanoparticles influence on the key life events of plants that include seed germination, seedling vigor, growth, and photosynthesis to flowering. Furthermore, suitable strategies adopted by plants in the presence of nanoparticles under stressed environments are also being presented. This review systematically summarizes the role of nanotechnology in agronomy of plants.

Keywords

Nanotechnology · Nanoparticles · Plant growth · Soil

Abbreviations

Al_2O_3	Aluminum oxide
cc	Cubic centimeter
CeO_2	Cerium oxide
cm	Centimeter
CO_2	Carbon dioxide
dia	Diameter
DNA	Deoxyribonucleic acid

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Fe_2O_3	Ferric oxide
H_2O_2	Hydrogen peroxide
IAA	Indole-3-acetic acid
mm	Millimeter
mM	Millimolar
NiO	Nickel oxide
nm	Nanometer
ppm	Parts per million
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
UV	Ultraviolet
ZnO	Zinc oxide
μg/ml-	microgram/milliliter

27.1 Introduction

Nanotechnology is recognized by the European Commission as one of its six "Key Enabling Technologies" that contributes to sustainable competitiveness and growth in several fields of industrial application. Presently, nanoparticles are being extensively used in medicine, biotechnology, electronics, material science, and energy sectors and have great potential in agriculture and food sectors. Agriculture is facing a wide spectrum of challenges in crop production system such as crop yield stagnation, low nutrient use efficiency, declining organic matter, multi-nutrient deficiencies, climate change, shrinking arable land and water availability, resistance to GMOs, and shortage of labor besides exodus of people from farming. These problems are further intensified by an alarming increase in food demand that will be needed to feed an estimated population of nine billion by 2050. At present to ensure the food security from limited availability of land and water resources, we need 4% annual growth rate in agriculture.

Nanotechnology is emerging as the sixth revolutionary technology in the present scenario after the Industrial Revolution of the mid-seventeenth century, Nuclear Energy Revolution in the 1940s, Green Revolution in the 1960s, Information Technology Revolution in the 1980s, and Biotechnology Revolution in the 1990s. Nanotechnology has great potential for transforming the agriculture through efficient management of soil nutrients; however, there are considerable uncertainties with regard to human health and environment that need to be taken care of.

Nanotechnology is a new growing and fascinating field of science which permits advanced research in many areas such as physics, chemistry, biology, material science, electronics, medicine, energy, environment, and health sectors (Manimaran 2015) and involves designing, development, and application of materials and devices at the molecular level in nanometer scale, i.e., at least one dimension ranges in size from 1 to 100 nanometer (Fakruddin et al. 2012). Initially, it was primarily being used in medicine, material science, and electronics, but there is a great scope of nanomaterials in agriculture as fertilizer and pesticides, in seed science, and in food to establish and conserve the human health and environment. Nanotechnology offers exciting ways for averting the herbicide overuse and also a safe and effectual delivery. The usage of nanostructure systems in agriculture has increased tremendously in the current era for the controlled release of agrochemicals as well as for plant nutrients (Gonzalez et al. 2014). Nanobiotechnology can improve our understanding of the biology of various crops and thus can potentially enhance yields or nutritional values, as well as develop improved systems for monitoring environmental conditions and enhancing the ability of plants to absorb nutrients or pesticides.

Nanoparticles are spherical or faceted metal particles typically <100 nm in size. These particles are having high surface area (30–50 m^2/g), high activity, better catalytic surface, and rapid chemical reaction, are rapidly dispersible, and absorb abundant water, so nano-fertilizer may increase the efficiency of nutrient uptake, enhance yield and nutrient content in the edible parts, and minimize its accumulation in the soil. Nanoparticles have unique physicochemical properties and the potential to boost plant metabolism (Giraldo et al. 2014). According to Galbraith (2007) and Torney et al. (2007), engineered nanoparticles are able to inter into plant cells and leaves and also can transport DNA and chemicals into plant cells.

27.2 Effect of Nanotechnology in Soil

Fertilizers are integral part of agriculture that assist growth and development of plants. Compared to regular fertilizers, nano-fertilizers have been proven to be more efficient. Smaller size of nanoparticles (NPs) provides additional surface area, which enhances the availability and facilitates more absorption of fertilizers by the plants and thus reduces losses of fertilizers due to leaching, emissions, and long-term incorporation by soil microorganisms (Liu et al. 2006). Nano-fertilizers are released at slower rates which help in maintaining soil fertility by decreasing the toxic effects associated with over-application of traditional chemical fertilizers (Suman et al. 2010). Singh and Lee (2016) studied the potential of nano-TiO_2 in phytoremediation of soil. Use of nano-TiO_2 in soybean plant increases the uptake of Cd from 128.5 to 507.6 $\mu g/plant^{-1}$ with an increase in the nano-TiO_2 concentration from 100 to 300 mg kg^{-1} in the soil.

27.3 Effect of Nanotechnology in Plants

Nanoparticles interact with plants causing many morphological and physiological changes, depending upon properties, concentration and size of nanoparticles (Table 27.1).

Table 27.1 Summary of the effect nanoparticles in different crop species

Type of crops	NP	Concentration	Crop	Mechanism	References
Cereals	Au	50	Pearl millet (*Pennisetum glaucum*)	Improved seed germination and growth of seedling	Parveen et al. (2016)
	CuO	10	Maize (*Zea mays*)	51% plant growth	Adhikari et al. (2016)
		500	Wheat (*Triticum aestivum*)	Biomass increased	Dimkpa et al. (2012)
	Fe/SiO_2	0–25	Barley (*Hordeum vulgare*) and Maize (*Zea mays*)	Improved mean germination time	Najafi Disfani et al. (2017)
	FeO	2 g/l	Wheat (*Triticum aestivum*)	Increased chlorophyll content, antioxidant enzyme activities, protein and carbohydrate content	Ghafari and Razmjoo (2013)
	Nano-(Fe_2O_3 + ZnO)	2 g/l	Wheat (*Triticum aestivum*)		
	SiO_2	15 Kg/ha	Maize (*Zea mays*)	Affected growth parameters	Yuvakkumar et al. (2011) and Supiyaprabhaet al. (2012)
	Mn	0.05–1	Rice (*Oryza sativa*)	Improved Zn uptake 5.66 mg/hill	Yuvaraj and Subramanian (2015)
	ZnO	10	Maize (*Zea mays*)	Improved plant height and dry weight	Adhikari et al. (2015)
	TiO_2	1000	Canola (*Brassica napus*)	Increase chlorophyll content	Mahmoodzadeh et al. (2013)
	CeO_2	500 mg/kg	Barley	Increased plant biomass but inhibited grain formation	Rico et al. (2015)
	CeO_2	62.5 and 125 mg	Rice (*Oryza sativa*)	Significantly reduced the H_2O_2 generation in both shoots and roots	Rico et al. (2013)
Pulses	Ag	60	*Phaseolus vulgaris*	Increased shoot and root length and dry matter	Salama (2012)

	Ag	100 µM	Mung bean (*Vigna radiata*)	Antagonize inhibition by 2,4-D at 500 µM of plant growth	Karuppanapandian et al. (2011)
	FeO	30-60	Soybean (*Glycine max*)	Chlorophyll increased	Ghafariyan et al. (2013)
	FeO	0.50 g/l	Soybean	Increased 48% of yield	Sheykhbaglou et al. (2010)
	FeO	250–500	Pea (*Pisum sativum*)	Seed weight and chlorophyll increased	Delfani et al. (2014)
	Nano Fe chelates	2 g /l	Chickpea	Increased the seed/pod, pod/plant,1000-seed weight and yield as compared to control up to 17, 48, 13, and 65%, respectively	Valadkhan et al. (2015)
	Nano Fe chelate	6 g/l	Faba bean (*Vicia faba* L.)	Increased grain yield, protein percent, and chlorophyll content	Nadi et al. (2013)
		50	Mung bean (*Vigna radiata*	Biomass	Dhoke et al. (2013)
	P	100	Soybean (Glycine max)	Increased the growth rate and seed yield by 32.6% and 20.4%	Liu and Lal (2014)
	Mg	2.5	Cowpeas (*Vigna unguiculata*)	Increment in stem Mg content, plasma membrane stability, and chlorophyll content	Delfani et al. (2014)
	Mn	0.05–1	Mung bean (*Vigna radiata*)	Shoot length, chlorophyll content and the photosynthesis rate increased	Pradhan et al. (2013)
	ZnO	01–2000	Mung bean (*Vigna radiata*) and Chickpea (*Cicer arietinum*)	Plant growth increased at 20 ppm in mung bean and in chickpea at 1 ppm	Mahajan et al. (2011)
		1000	Groundnut (*Arachis hypogea*)	Improved germination	Prasad et al. (2012)
		1.5	Chickpea (*Cicer arietinum*)	Improved shoot dry weight and antioxidant activity	Burman et al. (2013)
		20	Mung bean (*Vigna radiata*)	Biomass increased	Dhoke et al. (2013)

(continued)

Table 27.1 (continued)

Type of crops	NP	Concentration	Crop	Mechanism	References
		500, 1000, 2000, 4000	Mung bean (*Vigna radiata*)	Dry weight	Patra et al. (2013)
	Mo	8	Chickpea (*Cicer arietinum*)	Plant mass and number of nodules increased	Taran et al. (2014)
	S	500, 1000, 2000, 4000	Mung bean (*Vigna radiata*)	Dry weight	Patra et al. (2013)
	TiO_2	10	Mung bean (*Vigna radiata*)	Improvement in plant growth and nutrient content	Zheng et al. (2005)
	$CaCO_3$	+ Humus acid	Peanut	Increase the absorbability of nutrients (N, P, K, Ca) by plants	Liu et al. (2005)
		125 cc/Ha	Cowpea (*Vigna unguiculata*)	Cowpea yield up to 26–51%	Owolade and Ogunleti (2008)
Fiber	ZnO	25–200 mg/L	Cotton	Growth and total biomass by 130.6% and 131%	Venkatachalam et al. (2017)
	Nano-P	0.5–1 g/l	Cotton	Increased nutrient uptake under water stress condition	Hussien et al. (2015)

Oilseeds	Fe	2 g/l	Sunflower (*Carthamus tinctorius* L.)	Increased biomass	Torabian et al. (2017)
	SiO_2	20 mM	Safflower (*Carthamus tinctorius* L.)	17% more capitulum in branch than control	Janmohammadi et al. (2016)
	SiO_2	20 mM	Cress (*Lepidium sativum* L.)	Increased peroxidase enzyme activity and oil essence	Salarpour et al. (2013)
	Nano-Fe + nano-Mn	1/1000 + 1.5/1000.	Canola (*Brassica napus* L.)	Increased canola grain yield under water deficit condition	Pourjafar et al. (2016)
	CeO_2	200 and 1000 mg kg^{-1}	Canola (*Brassica napus* L.)	Inhibited plant uptake of salt, increase plant biomass under saline condition	Rossi et al. (2016)
	CeO_2	800 mg kg^{-1}	Sunflower (*Helianthus annuus* L.)	Reduced boron's (B) nutritional status of sunflower in original soil and the B phytotoxicity in B-spiked soil	Tassi et al. (2017)
	ZnO	0.5 g/l	*Sesamum indicum* L.	Increased shoot and root length, dry and fresh weight of shoot and root	Narendhran et al. (2016)

27.3.1 Seed Germination

Seed germination and seedling establishment are the crucial phases that determine plant yield. Successful execution of seed germination depends upon the mobilization of stored food by the enzymes amylase and protease for the survival of young plant until it is capable of making its food by photosynthesis (Khan et al. 2017). Srinivasan and Saraswathi (2010) observed that nanoparticles facilitate seed germination by serving as new pores in thick seed coat so that water and substrate can easily penetrate into the seed. Khodakovskaya et al. (2009) reported that carbon nanotube (CNT) improves the germination of tomato. Prasad et al. (2012) found that treatment of nanoscaled ZnO (25 nm mean particle size) at 1000 ppm concentration promoted both seed germination and seedling vigor of peanut, resulting in early establishment in soil marked by early flowering and higher leaf chlorophyll content. Single-walled carbon nanohorn (SWCNH) nanomaterials accelerate seed germination of some crops studied and enhance the growth of different organs of corn, tomato, rice, and soybean (Lahiani et al. 2015). Rengel and Graham (1995) reported from pot culture experiments on wheat plants that increasing seed zinc content from 0.25 μg seed^{-1} to 0.70 μg seed^{-1} significantly improved root and shoot growth under Zn deficiency. Tripathi et al. (2015) have studied that silica nanoparticle was able to alleviate chromium (VI) phytotoxicity in *Pisum sativum* L. seedlings. Si NPs protect pea seedlings against Cr(VI) phytotoxicity by reducing Cr accumulation and oxidative stress and upregulating antioxidant defense system and nutrient elements. Suriyaprabha et al. (2012a, b) studied that nano-SiO_2 (20–40 mm) gave higher seed germination (95.5%) due to more absorption of Si (18.2%) than the bulk silica-treated seeds. According to Thuesombat et al. (2014), jasmine rice that had been treated with different sizes and concentrations of silver nanoparticles (AgNPs) showed phytotoxic effect on the rice seedling and affect establishment. Fathia et al. (2017) found that foliar spray of nano-Fe_2O_3 and ZnO at 2 g L^{-1}in wheat grown in saline soil promoted plant height, shoot dry weight, leaf area and Fe and Zn concentration, and declined Na concentration means nanoparticles have the capacity to protect plants from salinity stress.

27.3.2 Photosynthesis

Photosynthesis is the process of conversion of light energy to chemical energy, which determines productivity of green plants. In plants nanoparticles enter into the cellular system via roots and stomata, affecting transpiration, plant respiration, and photosynthesis, and interfere with translocation of food material. Hong et al. (2004) studied that 0.25% nano-TiO_2 (rutile) promoted photosynthesis by activation of photochemical reaction such as the absorption of light energy, transforming light energy into electron energy, electron transport rate, oxygen evolution rate, and photophosphorylation efficiency in chloroplasts of spinach. Cu NP improved photosynthesis in *Elodea desaplanch* by 35% at low concentration inactivation of ribulose bisphosphate (RuBP) carboxylase, a key enzyme in photosynthetic CO_2 fixation, due to copper interaction with SH groups. This enzyme in *Elodea* can account for up to 15% of total soluble protein (Nekrasova et al. 2011) and seeding growth up to 40% in lettuce (Shah and Belozerova 2009). Liu et al. (2005) showed that nano-iron oxide compared to other treatments such as organic materials and iron citrate increases the rate of photosynthesis and iron transferring to the leaves of peanut (Karimia et al. 2014) compared with iron chelated fertilizer and nano-iron chelated fertilizer in different concentrations on some physiological and biochemical responses of mung bean (*Vigna radiata*) and detected that nano-iron chelate (10 ppm) gave higher catalase enzyme activity and higher peroxidase enzyme activity, resulting in higher photosynthetic activity. Accordingly, Prasad et al. (2012) reported that seeds treatment of peanut with NP ZnO (25 nm) at 1000 ppm enhanced the chlorophyll content of leaves rather than chelated bulk zinc sulfate ($ZnSO_4$) suspensions. Nanosilica-treated plants under drought condition showed higher photosynthesis rate and stomatal conductance but lower transpiration rate similar to the non-treated plants (Ashkavand et al. 2015).

27.4 History

Nanotechnology was first coined by Norio Taniguchi at the International Conference on Industrial Production in Tokyo in 1974. He illustrated the concept of processing, separation, and consolidation of material in nanometer size. Richard Feynman placed ideas of nanotechnological strategy for the first time in his lecture delivered in 1959 at the session of the American Physical Society which was later elaborated by Eric Drexler in 1986. In the early 1980s, the concept of nanotechnology flourished with two major developments: the introduction of cluster science and development of the scanning tunneling microscope (STM) in 1981. These technologies helped in the discovery of fullerenes in 1985 and carbon nanotubes in 1991.

Many inventions took place during the 1990s, which helped further development of nanotechnology. Since 2000, a significant number of scientific and technical research developments have been taking place all over the world especially in countries like Japan, Germany, England, France, China, and South Korea and recently in the CIS countries. It can be said that the period up to the 1950s may be considered as prehistory of nanotechnology, while nanotechnology paradigm was formed in the 1960s, and the development of the concept of nanotechnology took place between the 1980s and 1990s. In the twenty-first century, nanotechnology is emerging as a major factor for commercial success.

Nanotechnology has the capacity to transform the society because of its wide application in the medicine, industry, and agriculture sector. In the second half of the 1980s and early 1990s, a number of important discoveries were made; this created an essential impact on the further development of nanotechnology. In December 2002 the importance of nanotechnology has been recognized internationally, and the US Department of Agriculture (USDA) drafted the world's first "roadmap" for applying nanotechnology to agriculture and food to resolve the technological and environmental challenges. The 90% of nano-based products and patents are produced by seven countries, namely, the USA, China, Germany, France, Japan, Switzerland, and South Korea, while India's contribution is far from surfacing. The Indian government has setup a nano-research project during the Eleventh Five-Year Plan at an outlay Rs.100 crore Khan and Rizvi (2014).

27.5 Types of Nanomaterial

On the basis of size, nanoparticles are classified into several different classes:

1. Nanoclusters – semicrystalline nanostructures with dimensions within 1–10 nm.
2. Nanopowders – formed by aggregation of nanocrystalline nanomaterials with dimensions between 10 and 100 nm.
3. Nanocrystals – single crystalline nanomaterials with dimensions between 100 and 1000 nm.

Depending on the origin, there are three types of NSPs:

(a) *Natural* – Natural nanoparticles have existed from the beginning of the earth's history, and they have been generated by a number of natural processes including weathering, erosion, volcanic eruption, hydrolysis, and biological activities.
(b) *Incidental* – Incidental nanoparticles, also defined as waste or anthropogenic particles, take place as the result of man-made industrial processes (diesel exhaust, coal combustion, welding fumes, etc.).
(c) *Engineered* – Engineered nanomaterials can be grouped into various types.

1. Carbon nanotubes – Carbon tubes have elongated shapes with 1–2 nm in diameter. They are light and chemically stable and have high strength, high length compared to a small diameter, and remarkable optical properties (Hou et al. 2002; Tersoff and Ruoff 1994) so that they developed into idyllic material for many applications. Carbon tubes may be single-walled carbon nanotubes (SWCNT) or multi-walled carbon nanotubes (MWCN). SWCNT are cylindrically prepared from one sheet of graphite (Iijima and Ichihashi 1993), while multi-walled carbon nanotubes (MWCN) can be formed by folding more than one sheet of graphite (Iijima 1991).
2. Inorganic nanoparticles:
   - Metal-based materials (TiO_2, ZnO, Al_2O_3, Fe_3O_4, Fe_2O_3, NiO, CoO, CeO_2, etc.)
   - Quantum dots(cadmium sulfide and cadmium selenide).

I. Dendrimers that are nano-sized polymers built from branched units, capable of being mold to perform specific chemical function.
II. Nanoparticles used in insecticide, herbicide, and other pesticide for efficient delivery system.

III. Nanosensors – for plant health and soil health monitoring, pest detection.
IV. Nano magnet – for removal of soil contaminate.
V. Nanocapsules – for delivery of vaccines into plants.
VI. In genetic engineering of plants, delivery of desired DNA into the plants using nanoparticle-engineered nanomaterials has received a particular attention for their positive impact in improving many sectors of economy, including consumer products, pharmaceutics, cosmetics, transportation, energy and agriculture, etc. and are being increasingly produced for a wide range of applications within the industry (Nowack and Bucheli 2007; Roco 2003).

27.6 Application of Nanotechnology in Agriculture

27.6.1 Nano-fertilizers for Balanced Crop Nutrition

Chemical fertilizers have aided farmers in increasing crop production since the 1930s. Fertilizers have great role in sustaining modern agriculture, but injudicious use of chemical fertilizer causes soil compaction, decreased fertility, contamination of air and water, and release of greenhouse gases and strengthens pesticides, destroying the soil structure and also affecting the genetic diversity. So there is need to evolve a nano-based fertilizer in order to address issues of low fertilizer use efficiency, imbalanced fertilization, multi-nutrient deficiencies, and decline of soil organic matter. 40–70% of nitrogen, 80–90% of phosphorus, and 50–70% of potassium of the applied normal fertilizers are lost to environment and cannot be absorbed by plants, causing not only substantial economic and resource losses but also very serious environment pollution (Trankel 1997; Saigusa 2000).

27.6.2 Impacts of Nanoparticles on Plant Growth and Development and Toxic Responses

27.6.2.1 Carbon Nanotubes

Liang et al. (2013) examined the effect of carbon nanoparticles (CNPs) on flue-cured tobacco which increased plant height, leaf area, dry matter accumulation, chlorophyll, soluble protein, and N and K in plant organs. Meanwhile, Wang et al. (2012) found that the optimum dose of oxidized multi-walled carbon nanotubes for enhancement of and faster root growth and vegetative biomass in wheat seedlings is 80 ppm after conducting in vitro studies on wheat, usually ranging from 10 to 160 ppm of oxidized multi-walled carbon nanotubes. Yan et al. (2013) studied that SWCNT triggered overexpression of various biotic stress-related genes, such as subtilisin-like endoprotease, *Meloidogyne*-induced giant cell protein, and threonine deaminase in maize, which cause stimulatory effect on early seedling growth. Similarly, Srivastava and Rao (2014) reported water-soluble MWCNT (dia, $10 - 20$ nm; length, $10 - 30$ μm) enhanced the germination of wheat and maize. Lin and Xing (2007) found that exposure to 2000 mgL^{-1}significantly increases ryegrass

(*Lolium perenne*) seed germination and root length (17%). Similarly, Khodakovskaya et al. (2009) observed that multi-walled carbon nanotubes (10 − 40 μgmL^{-1}) are able to penetrate into the tomato seed coat, boosting the germination rate by getting higher water uptake and increasing the seed germination up to 90% (compared to 71% in control) in 20 days and also increasing plant's biomass. Tripathi and Sarkar (2015) studied the effect of water-soluble carbon nanodots (wsCND) at 150 μg which can easily enter the vascular bundle of the plant to carry forward more nutrients and water to enhance the growth of wheat plant in both light and dark conditions.

Tan et al. (2009) demonstrated the use of MWCNT with rice cell suspension to increase reactive oxygen species (ROS) and decrease the cell viability of rice plant, but the result is reversed after addition of ascorbic acid which gave a hypersensitive response of rice cell with MWCNT which was sufficient to prevent microbial pathogens from completing their life cycle. Mondal et al. (2011) studied the effect of oxidized MWCNT (dia – 20 nm) on mustard (*Brassica juncea*) at exposures of 2.3–46.0 mgL^{-1} which enhanced germination (99% in 22 days) and increased root and shoot growth. However, the rate of germination began to decrease at higher MWCNT exposure levels. Conversely, Tripathi et al. (2011) investigated the 10-day exposure of citrate-coated water-soluble CNTs (ws-CNTs) at concentration of 6.0 mgmL^{-1} in gram (*Cicer arietinum*) and hypothesized that ws-CNTs formed an "aligned network" inside the vascular tissue that increased water uptake efficiency and enhanced plant growth. However, effects of water-soluble CNPs (ws-CNPs) extracted from biochar in wheat and detected that soil application of ws-CNPs at concentration of 50 mg/L increases threefold the root and shoot growth as compared to untreated controls (Saxena et al. 2014).

27.6.2.2 Si-Based Nanoparticles

Silicon (Si) is the second most abundant element in the earth's crust after oxygen (Ma 2004). In silicon dioxide nanoparticles, silicon (Si)-deficient plants show abnormal growth because of weaker structure and are more susceptible to biotic and abiotic stresses compared with Si-rich plants (Rafi et al. 1997). Si is acknowledged as a beneficial element for plant (Wainwright 1997) that facilitates growth and development by increasing accumulation of proline, free amino acids, nutrient content, antioxidant enzyme activity, and gas exchange and improving efficiency of photosynthetic apparatus (Kalteh et al. 2014). Nano-SiO_2 enhances plant growth and development by increasing photosynthetic rate, transpiration rate, stomatal conductance, PS-II potential activity, effective and actual photochemical efficiency, electron transport, and photochemical quench (Xie et al. 2012; Siddiqui et al. 2014). Exogenous application of nano-SiO_2 and nano-titanium dioxide (nano TiO_2) improves seed germination of soybean due to increase of nitrate reductase (Lu et al. 2002).

Yuvakkumar et al. (2011) showed that soil application of nanosilica increases seed germination (2–11%), water usage efficiency (up to 53%), and total chlorophyll content (13–17%) of maize crop. Suriyaprabha et al. (2012a, b) observed positive response of nano-SiO_2 extracted from rice husk (15 kgha^{-1}) which enhances the silica concentration in maize leaves as well as organic compounds such as proteins, chlorophyll, and phenols compared with bulk silica and control. Haghighi et al. (2012) studied that nanosilica application to tomato seeds increases germination, root length, and plant dry weight by decreasing the deleterious effects of salinity on germination. Tripathi et al. (2017a, b) reported that bulk SiO_2 or SiO_2 NPs triggered the antioxidant defense system of wheat and protect the plant from UV-B stress which help balance photosynthesis and regulate the level of oxidative stress. However, Karimi and Mohsenzadeh (2016) reported that lower concentrations of SiO_2 (50 and 100 mgL^{-1}) had no negative effect on wheat seedling, but higher concentrations significantly decreased root and shoot fresh weight and dry weight, and low amount of chlorophyll a and b in leaves and carotenoids in leaves increased proline content and lipid peroxidation in leaves. Incorporation of nano-silicon in priming solution of sunflower at lower concentrations (0.2 and 0.4 mM) significantly reduced days to 50% germination and mean germination time and improved root length, mean daily germination, seedling vigor index, and final germination percentage (Janmohammadi and Sabaghnia 2015). Conversely, Wang et al. (2015) found a foliar application of SiO_2 NPs (2.5 mM) in rice which progressed the seedling growth, nutrient content (Mg, Fe and Zn), and chlorophyll a under Cd stress condition and proved that SiO_2 NPs have the ability to alleviate Cd toxicity in rice seedlings by decreasing Cd accumulation and Cd partitioning in the shoot and reducing malondialdehyde level.

27.6.2.3 Cu-Based Nanoparticles

Copper-based material is widely used, and plant nanotechnology's main aim is to increase productivity and bring sustainability by reducing toxicity. Dimkpa et al. (2012) studied the impact of commercial CuO (<50 nm) and ZnO (<100 nm) NPs on wheat (*Triticum aestivum*) and observed the increased lipid peroxidation and oxidized glutathione in roots and decreased chlorophyll content in shoots; higher peroxidase and catalase activities were also present in roots. Similarly, application of low concentrations of CuO NPs enhanced the expression of the exogenous gene encoding Bt toxin protein in leaves and roots of transgenic cotton providing an important benefit for Bt cotton insect resistance (Van Nhan et al. 2016). However, the nano-CuO induced stress in rice (*Oryza sativa*) reduced the seed germination and seedling growth due to modulation of the ascorbate-glutathione cycle, membrane damage, increase in ROS, higher H_2O_2, and proline accumulation (Shaw and Hossain 2013). Identical finding was obtained by Shi et al. (2014) in *Elsholtzia splendens* (a Cu-tolerant plant) and Perreault et al. (2014) in duck weed (*Lemna gibba*). Adams et al. (2017) observed CuO NP's (>10 mg $Cukg^{-1}$) exposure on wheat seedling causes inhibition of root elongation and proliferation of root hair formation due to redistribution of indole acetic acid (IAA) supplied through tryptophan metabolism by the root-colonizing bacterium, *Pseudomonas chlororaphis* O6. However, Wright et al. (2016) studied that CuO NP-induced stress in wheat could be minimized by a root-colonizing bacterium, *Pseudomonas chlororaphis* O6 (*Pc*O6). Meanwhile, the root growth of wheat seedlings elongated when with roots colonized by *Pc*O6 even in the stress caused by CuO NPs on the root of wheat.

27.6.2.4 Zinc Oxide Nanoparticles

Zn is a vital trace element and essential component for various enzymes, and without it, the plant is unable to complete its metabolic activity (Hassegawa et al. 2008). Zn controls the synthesis of indole acetic acid (IAA), chlorophyll synthesis, and carbohydrate formation (Vitosh et al. 1994). Zn deficiency is quite common in cereal-growing areas extended in many millions of hectares of the world, resulting in significant reductions in yield and quality of food crops (Graham et al. 1992). Extensive Zn deficiency found in calcareous soils of Bihar; vertisols and inceptisols of Andhra Pradesh, Tamil Nadu, and Madhya Pradesh; and aridisols of Haryana results in low crop yields. Lv et al. (2015) investigated the translocation of ZnO NP in maize plant, and the results demonstrate that the majority of Zn taken up was derived from Zn^{2+} released from ZnO NPs, and Zn accumulated in the form of Zn phosphate and small fraction of nano-ZnO NPs was observed in the epidermis, the cortex, and root tip cells, and few entered in the vascular system; however, no translocation of ZnO NPs was seen in the shoot.

The application of zinc sulfide nanoparticles (20 mgl^{-1}) generate new pores on seed coats that help in the invasion nutrients inside the seed which may lead to rapid germination (6 h only), higher germination percentage (70%), and increased growth rate of *Vigna radiata* Ganguly et al. (2014). Similarly, Mukherjee et al. (2015) found that soil application of 2 wt% alumina doped (Al_2O_3@ZnO NPs, 15 nm) at 250 $mgkg^{-1}$ increased Chl-*a* and carotenoid concentrations, while 1000 $mgkg^{-1}$ alters the protein and carbohydrate profiles of pea plant. Prasad et al. (2012) reported that seed treatment with 1000 ppm concentration of ZnO NPs (average size ~25 nm) in peanut enhanced seed germination rate and promoted seedling vigor, along with early flowering and higher leaf chlorophyll content compared to the chelated bulk $ZnSO_4^-$ exposed plant and control.

Singh et al. (2017) reported that application of nano-ZnO (1200 ppm) on maize seedling results in higher root length (13.43 cm), shoot length (10.43 cm), and seed vigor index (2186.25). A similar finding was observed by Sedghi et al. (2013) in soybean. Ramesh et al. (2014) reported that lower concentrations of ZnO NPs exhibited a beneficial effect on the seed germination and shoot-root growth in wheat (*Triticum aestivum*). Sprouted seed of *Vigna radiata* and *Cicer arietinum* absorbed ZnO NPs (20 ppm) and produced maximum root and shoot length and biomass but above 20 ppm is detrimental for seedling growth (Mahajan et al., 2011). In contrast, Boonyanitipong et al. (2011a) investigated that NP ZnO (>100 mg/l) causes significant phytotoxicity on rice roots indicated by reduction in root length and number of roots. Yoon et al. (2014) findings clearly demonstrated that exposure of soybean (*Glycine max* L.) to ZnO NPs (50 or 500 mg/kg) affected negatively the developmental and reproductive stages and plants did not form seeds. A similar negative effect of ZnO NPs was scrutinized by Hernandez-Viezcas et al. (2011) in soybean (*Glycine max*).

Rosa et al. (2013) reported that Zn nanoparticles (NPs) affect seed germination and found that at 1600 mgl^{-1} ZnO NPs, germination in cucumber increased by 10%, and alfalfa and tomato germination were reduced by 40 and 20%, respectively. Similar findings were observed by Sunita (2013) in *Brassica juncea* and

Boonyanitipong et al. (2011b) in rice. Asadzade et al. (2015) investigated that foliar application of ZnO + SiO_2 (0.5:1000) increases the head diameter (7.89 cm, on average) of sunflower, i.e., 18.8% higher than the control under water stress condition. Moreover, Pandey et al. (2010) observed that nano-ZnO (size 20–30 nm) increased the germination and root growth of *Cicer arietinum* because of ZnO NP that is directly involved in the formation of phytohormone specially IAA which enhances its root growth. Dimkpa et al. (2015) demonstrated that the effect of ZnO NPs (250–1000 mg Znkg^{-1}) on bean (*Phaseolus vulgaris*) plant growth and nutrient balance was affected by a root-associated bacterium, *Pseudomonas chlororaphis* O6(PcO6). He found that the application of 250 mg kg^{-1} of ZnO NPs elongates the root, while of 1000 mgkg^{-1} shortens the root. Torabian et al. (2016) compared the nano-sized particles of ZnO to normal ZnO in sunflower cultivars under salt stress and observed that foliar application of nano-ZnO increased shoot dry weight, leaf area, photosynthesis parameters, and Zn concentration and decreased Na concentration of leaves in comparison to ordinary form.

The above findings show that ZnO NPs have the ability to influence seed germination and plant growth and development. However, some negative impacts are also associated with its application, which depend on plant physiological character and doses of NPs.

27.6.2.5 Gold Nanoparticles

Gold nanoparticles (AuNPs) have attracted special interest because of their many industrial and biomedical applications, which have a remarkable potential in plant growth (Soenen et al. 2012; Siddiqi and Husen 2016). Zuverna-Mena et al. (2017) explained the AuNPs uptake mechanisms by the plants and its role in geremination, effects on the growth, physiological and biochemicals, production and food quality and water balance of crops. AuNP uptake and distribution depend on both nanoparticle surface charge and plant species on exposure of the AuNPs to plant seedlings of rice, radish, pumpkin, and perennial ryegrass under hydroponic conditions; the positively charged AuNPs are readily taken up by plant roots, while negatively charged AuNPs are most efficiently translocated into plant shoots (including stems and leaves) from the roots. Radish and ryegrass roots generally gathered higher amounts of AuNPs (14–900 ngmg^{-1}) than rice and pumpkin roots (7–59 ngmg^{-1}) (Zhu et al. 2012). Likewise, Feichtmeier et al. (2015) investigated that the effect of citrate-coated AuNP (dia 2–19 nm) on barley (*H. vulgare*) and found that AuNP does not play a significant role in seed germination; however on application of solution in barley, decreased fresh biomass of plant turned leaves yellow and the roots brown, and these symptoms boosted with increasing the concentration of gold nanoparticles.

Aroraet al. (2012) in *Brassica juncea* reported that AuNPs (10 ppm) improve seed germination, number of leaves, leaf area, plant height, chlorophyll content, and sugar content, resulting in better crop yield. But in contrary, Gunjan et al. (2014) recorded citrate-stabilized gold nanoparticles (GNPs) ranging from 100 to 400 ppm decrease the overall growth of *Brassica juncea* with increase in the antioxidative enzyme activities, H_2O_2, and proline contents. This happens because GNPs free radical-mediated causes oxidative stress and cellular toxicity in the seedlings. Shabnam et al. (2014) reported that application of 1 mM solution of $HAuCl_4$ in cowpea (*Vigna unguiculata* L.) showed no visible influence on growth and weight of the root and shoot of seedling because the phenolics released by seed coat of germinating seeds possess potential to reduce toxic Au^{3+} to form nontoxic/less toxic Au nanoparticles. Rajeshwari et al. (2016) on onion using citrate-coated AuNPs exhibited several chromosomal aberrations in the root tips, besides inducing the generation of ROS in the onion root tips, resulting in lipid peroxidation. Eventally, the experimental studies established that AuNPs increased growth and seed yield of plants if applied in an optimized concentration; otherwise, it resulted in reduced growth and oxidation. There are additional instances where it has been reported that AuNPs control the morphological, physiological, and metabolic events in plants through regulating miRNA expression, which eventually affects their seed germination and antioxidant systems.

27.6.2.6 Silver Nanoparticles

Silver nanoparticles, which have high surface area and high fraction of surface atoms, have high antimicrobial effect compared to the bulk (Suman et al. 2010). Sharma et al. (2012) reported that application of 50 ppm silver metal nanoparticles on 7-day-old *Brassica juncea* seedlings increases 326% in root length and 133% in vigor index, decreases proline content, and improves the antioxidant status in seedling. Nair and Chung (2014) evaluated that rice seedlings' response to AgNPs at 0.5 and 1 mgL^{-1} caused significant increase in hydrogen peroxide formation and lipid peroxidation in shoots and roots, increase in foliar proline accumulation, and decrease in sugar content. Application of AgNPs 15 nm in size in soybean under flooding promotes soybean growth by regulating the proteins that are related to amino acid synthesis and wax formation (Mustafa et al. 2016). Mirzajani et al. (2013) studied that the effects of AgNPs on Asian rice (*Oryza sativa* L.) revealed that the application of NPs (concentration 30 μgmL^{-1}) accelerates root growth, root branching, and dry weight; however, 60 μgmL^{-1} of NPs was able to restrict root's ability to grow. The negative effect of AgNPs application has also been observed on mung bean observed on mung bean after exposure of 20 and 50 mgL^{-1} of AgNPs reduced the root elongation and weight and total chlorophyll content but increased the proline content (Nair and Chung 2015). Similarly, AgNP treatments (1000 μM and 3000 μM) significantly declined growth parameters, photosynthetic pigments, and chlorophyll fluorescence of pea (*Pisum sativum*) seedlings (Tripathi et al. 2017a).

27.6.2.7 Iron Nanoparticles

Iron is the most essential element micronutrient required for plant metabolism. It is simply found in earth's crust but not available for plant due to its low solubility. It is a key element in cell metabolism, and it is involved in photosynthesis, respiration, enzyme activity, etc. Iron is essential for plants' growth, and under Fe deficiency conditions, synthesis of chlorophyll is restricted, and plants show interveinal chlorosis, which appears first in younger tissues because iron is not easily translocated inside the plant body. The most common forms of iron oxide NPs have high supermagnetic properties, so they are used in biomedical applications, including tissue repair; drug delivery, magnetic resonance imaging (MRI), and hyperthermia Fe NPs are mainly of two types: maghemite (γ-Fe_2O_3) and magnetite (Fe_3O_4) (Arbab et al. 2003; Perez 2007).

Nano-oxide of iron is smaller than the common iron oxides and easily available for the plants (Mazaherinia et al. 2010). Fe deficiency is quite common in calcareous and high pH soil (Fernandez and Ebert 2005; Wiedenhoeft 2006), and foliar spraying of nano-iron may be the solution of the problem (Bakhtiari et al. 2015). Afshar et al. (2013) evaluated the foliar application of nano-iron (1.5 mgl^{-1}) on cowpea crop under irrigation deficit condition that significantly increases the numbers of seed pod^{-1}. Armin et al. (2014) carried out foliar application of nano-Fe in wheat (*Triticum aestivum*) at 2%, 4%, and 6% and observed an increase of 12%, 22.09%, and 19.07% grain yield, respectively, over the control. Bakhtiari et al. (2015) studied that foliar spraying of nano-Fe oxide gave the highest values of spike weight (666.96 g), 1000-grain weight (37.96 g), biological yield (8895.0 $kgha^{-1}$), and grain yield (3776.5), and protein content (16.44%) was achieved in 0.04% Fe concentration, and the lowest values were achieved in the control. Alidoust and Isoda (2013) observed positive effects of Fe_2O_3 nanoparticles (IONPs) via foliar application than by soil treatment. They investigate the effect of foliar spraying of Fe NPs in soybean and observed significant positive effect on root elongation and high photosynthetic rate due to increases in stomatal opening rather than increased CO_2 uptake activity at the chloroplast level. Ghafari and Razmjoo (2013) reported that 2 gl^{-1} nano-iron oxide has increased chlorophyll content, antioxidant enzyme activities, and protein and carbohydrate content of wheat due to increased antioxidant enzyme activities of wheat. A similar finding was observed by Harsini et al. (2014) that foliar application of iron nano-chelated fertilizers Fe (8.9%), Zn (0.92%), Mg (0.96%), Na (9.9%), and brimstone (9.5%) increased the spike number, 1000-grain weight, grains $spike^{-1}$, biological yield, grain yield, and harvest index in wheat crop than control.

27.6.2.8 Titanium Dioxide Nanoparticles

Nano-TiO_2 has the capacity to increase the light absorbance, hasten photosynthate transportation and conversion of the light energy, protect chloroplasts from aging, and extend the photosynthetic time of the chloroplasts (Hong et al. 2004). Titanium dioxide is a strong photocatalyst that can break down organic compound into CO_2 and water when exposed to sunlight (Frazer 2001). Similarly, Chao and Choi (2005) observed the pro-oxidant and antioxidant properties of TiO_2 and also uncovered that TiO_2 prop up photosynthesis and metabolism, thus increasing crop yields. Moreover, Mahmoodzadeh et al. (2013) also reported that the application of TiO_2 NPs (20 nm) at 2000 mgl^{-1} resulted in better seed germination (75%) and enhanced radical and plumule growth of canola seedlings due to increases in nitrate reductase enzyme and enhancement of antioxidant system. Similarly, seed treatment of wheat with 10 ppm of TiO_2 promotes early germination (0.89 days) and higher shoot length, seedling length, and root dry matters in comparison to bulk TiO_2, but higher concentrations had inhibitory effect (Feizi et al. 2012). Morteza et al. (2013) observed on corn (*Zea mays* L.) that spraying of TiO_2 at reproductive stage significantly increases chlorophyll content (a and b), total chlorophyll (a + b), chlorophyll a/b, carotenoids, and anthocyanins than the control because nano-TiO_2 could improve the structure of chlorophyll and protect the chloroplasts from aging in flowering times.

Owolade and Ogunleti (2008) concluded that spraying of 125 $ccha^{-1}$ of nano-TiO_2 increases the seed number pod^{-1}, 1000-seed weight, grain yield, leaf area, pod number $plant^{-1}$, and pod length of *Vigna unguiculata* due to the photocatalyst ability of the NP TiO_2 which leads to an increased photosynthetic rate and also reduced severity of foliar and pod diseases. In a similar study, spraying of titanium nanoparticle (0.02%) in *triticale* increases grain yield and 1000-grain weight; leaf chlorophyll content grown in cadmium (Cd) contaminated soil because nano-TiO_2 has the capacity to alleviate the deleterious effects of Cd on physiological processes through increasing antioxidant enzyme activity, which trim down the lipid peroxidation and stabilize the chlorophyll pigments (Ghooshchi 2017). Raliya et al. (2015) studied that foliar spraying of nano-TiO_2 in 14-day-old mung bean plants increases the shoot length (17.02%), root length (49.6%), root area (43%), root nodule (67.5%), chlorophyll content (46.4%), and total soluble leaf protein (94%). Moaveni et al. (2011) found that foliar spraying of nano-TiO_2 (0.03%) gave the highest grain yield (33903.9 t/ha), weight of spikelets (5.8 m^{-2}), and number of spikelets (678.5 m^{-2}) in barley (*Hordem vulgare* L.). TiO_2 NPs noticeably promote Ribulose-1,5-bisphosphate carboxylase (Rubisco) activity and boost photosynthesis and also increase light absorbance and help in protecting chloroplasts from aging, helping plant growth and development (Yang et al. 2006). Clement et al. (2012) stated that soaking of flax seeds in TiO_2 NP suspension (100 mgl^{-1}) upbeats the seed germination and root growth due to antimicrobial properties of anatase crystalline structure of TiO_2 that increases plant's resistance to stress. Similarly Azimi et al. (2013) confirmed that seed soaking of wheat grass (*Agropyron desertorum*) in suspension of TiO_2 nanoparticles (5 ppm) gave a positive effect in seed germination percentage by 9% compared to the control. The probable reason may be that nano-TiO_2 has the capacity to photosterilize and photogenerate active oxygen like superoxide and hydroxide anions which enhanced seed stress resistance and encouraged capsule penetration for intakes of water and oxygen needed for quick germination (Khot et al. 2012). Under water deficit stress condition, foliar spraying of 0.02% of nano-TiO_2 increased all agronomic traits including gluten and starch content in wheat (Jaberzadeh et al. 2013).

27.6.3 Nanopesticides

27.6.3.1 Nanoherbicide for Effective Weed Control

Weeds cause huge damage in agriculture and reduced crop yield to a great extent. So, there is no other option but to eradicate them. Nanotechnology has the potential to get rid of weeds by using nanoherbicides in an ecofriendly way, without leaving any toxic residues in the soil and environment (Perez-de-Luque and Rubiales 2009). The high penetration efficiency of nanoherbicides helps in eliminating the weeds before resistance could develop.

Nanoherbicides contain many trillions of particles of active ingredient per liter. Nanomaterials or nanostructures material-based formulations could improve the efficacy of the herbicide, enhance its solubility, and reduce its toxicity in comparison with conventional herbicides. The extra surface area created by the reduction in particle size boosts effectiveness, accelerates uptake by the plant, increases solubility in the spray tank, and reduces or even eliminates the risk of settling and separation. Less amount of herbicide will be used if active ingredient is combined with a "smart" delivery system. Having size in nano-dimensions, these will blend with soil particles and prevent the growth of weed species that have become resistant to conventional herbicides. Herbicides available in the market are designed to control or kill the aboveground part of the weed plants. Herbicides inhibit the activity of viable underground plant parts like rhizomes or tubers, which act as a source for new weeds for next season as well as persistency in soil damage the succeeding crops. Nanoherbicide is a target-specific herbicide molecule encapsulated with nanoparticle and has aimed for specific receptor in the roots of target weeds, which enter into root system and translocated to parts that inhibit glycolysis of food reserve in the root system. This will make the specific weed plant to starve for food and gets killed (Chinnamuthu and Boopathi 2009). The continuous use of the same herbicide for persistent period of time leads to evolution of weed resistance against that particular herbicide. Up to 88% detoxification of an herbicide "atrazine" by carboxymethyl cellulose (CMC) nanoparticles has been reported (Satapanajaru et al. 2008). The nanoparticles are target specific so that they can be used to kill the weeds and destroy it to get better yield (Prasad et al. 2014). Application of polye-psilon-caprolactone (PCL) nanocapsules containing trazine at 1 mg mL^{-1} on 30-day-old mustard plant significantly reduced the weed biomass due to decrease of net photosynthesis and PS-II and an increase of leaf lipid peroxidation, leading to shoot growth inhibition, without affecting the mustard (Oliveira et al. 2015). Similarly, Grillo et al. (2012) observed that PCL-loaded triazine herbicides (ametryn, atrazine, and simazine) improved efficiency of about 84% than the commercial formulation. Adsorptive stripping voltammetry process was developed to detect herbicide fenclorim with carbon nanotubes at pH 4.0 with the adsorption techniques on the electrodes for effective control of weeds. Atrazine is the widely used herbicide in order to kill the weeds and unwanted grass growing near the crops; continuous use of herbicides makes soil lose all the nutrients and make them resistant to the plants; therefore application of modified silver with nanoparticles and carboxymethyl cellulose makes degradation of herbicide easier (Susha et al. 2008).

Polye-psilon-caprolactone nanocapsules containing ametryn and atrazine increase the herbicidal efficiency by modifying its release system and effectively controlling the target *Brassica* sp. and showed lower toxicity to the nontarget organisms, e.g., algae *Pseudokirchneriella subcapitata*, compared to the herbicide alone (Clemente et al. 2014). Additionally, Sousa et al. (2018) observed that poly (ε-caprolactone) (PCL) nanocapsules carrier of atrazine effectively controls the

Amaranthus viridis (slender amaranth) and *Bidenspilosa* (hairy beggarticks), in comparison with a commercial formulation of atrazine due to greater decrease in the photosystem II activity.

Silva et al. (2011) studied the effect *alginate*/chitosan nanoparticle carrier for the herbicide paraquat on the release profile of the herbicide, as well as its interaction with the soil, and found that this system controls the release of paraquat and ultimately reduces the negative impacts caused by paraquat as compared to control. Silver nanoparticle-chitosan (100 nm)-encapsulated paraquat showed controlled-release properties and improved herbicidal activity against *Eichhornia crassipes* by the formation of necrotic lesions without affecting soil macro- and micronutrients, soil enzymes, soil microflora, and seedling emergence and is nonphytotoxic against *Vignamungo* (Amasivayam et al. 2014).

27.6.3.2 Nano-insecticide for Insect Control

The major constraint in attaining high production in crop yield is the damage imposed by insect pests. Indiscriminate use of pesticides causes environmental pollution, emergence of agricultural pests and pathogens, and loss of biodiversity (Ghormade et al. 2011). The right choice of chemical pesticides in pest control is not governed by its toxicity alone but depends on their safety to natural enemies in the ecosystem and the environment too (Stanley 2007). Registered pesticides which provide adequate control of the pests require repeated application in higher doses and might result in adverse effects on the environment, pollinating insect, and human health. So, nanopesticides are being considered as the best alternative because they not only reduce the doses with higher efficacy but reduce the chances of resistance development in pests (Shivanna et al. 2012; Mousavi and Rezaei 2011). It is reported that a very small amount (less than 0.1%) of pesticide reaches the sites of action, and the rest are lost in air during application or as run-off, spray drift, off-target deposition, and photodegradation which not only contaminate the environment but also increase the application costs (Pimentel 1995; Castro et al. 2014).

NP-loaded pesticide formulations increase the solubility of scantily soluble active ingredient and help in releasing the active ingredient slowly triggered by the environment (Lauterwasser 2005; Debnath et al. 2011). Stadler et al. (2010) reported that inorganic nanostructured alumina can be used as a cheap and reliable alternative for pest management. They found that nanostructured alumina dust LD (50) at 127–235 mgkg^{-1} in wheat showed significant mortality on two stored insect pests *Sitophilus oryzae* L. and *Rhyzopertha dominica* (F). Debnath et al. (2011) attempted to determine the efficacy of silica nanoparticle (<1 μ) against rice weevil (*Sitophilus oryzae*) as compared with bulk-sized silica, and observed that silica nanoparticle causes 90% mortality of weevil. Similarly Arumugam et al. (2016) reported the efficacy of silica nanoparticles (SNPs) against pulse beetle (*Callosobruchus maculates*) which controlled the infestation in the stored seeds of *Cajanus cajan*, *Vigna mungo*, *Vigna radiata*, *Cicer arietinum, and Vigna unguiculata*. Chandrashekharaiah et al. (2015) invented DNA-tagged CdSnano-TiO_2 and nano-Ag at 150 and 2400 ppm and were tested against *S. litura*. Results revealed that the highest mortality was caused by DNA-tagged CdS (93.79%) followed by nano-TiO_2 (73.79%) and nano-Ag (56.89%) at 2400 ppm, and the lowest mortality was found at 150 ppm. Zahir et al. (2012) reported the insecticidal property of silver nanoparticles (25–80 nm) which are synthesized by using aqueous leaf extracts of *Euphorbia prostrate* against rice stem borer (*Sitophilus oryzae* L.).

Yang et al. (2009) examined polyethylene glycol (PEG)-coated nanoparticles loaded with garlic essential oil against stored pest *Tribolium castaneum* which causes 80% mortality up to 5 months due to the slow and continuous release of the active components. Yasur and Rani (2015) studied the impact of silver nanoparticles (AgNPs) on growth and feeding responses of two lepidopteran pests, namely, Asian armyworm (*S. litura*) and castor semi-looper, (*Achaea janata* L.) (*Lepidoptera*: *Noctuidae*) and found that larval and pupal body weights decreased along with the decrease in the concentrations of AgNPs. Shoaib et al. (2018) observed that dust spraying of nanosilica powder on diamondback moth (*Plutella xylostella*), which is the most destructive pest of cruciferous crops, at 1 mg cm^{-2} caused mortality a rate of 85% at 72 h after treatment.

Shi et al. (2010) studied the toxicity of chlorfenapyr (nanopesticide) on mice. It was reported that the chlorfenapyr nanoformulation from 4.84 to 19.36 mg kg^{-1} was less toxic to mice than the common formulation. Thus, such nanoformulation pesticides may decrease adverse environmental and human effect as compared to classical pesticides. In order to ensure health and environmental safety, further studies on the biosafety of the nanopesticides are needed.

27.6.3.3 Nanopesticides for Disease Control

Plant diseases are mainly caused by viruses, bacteria, fungi, or nematodes, resulting in decreased yield and poor quality of plant products. For disease management various approaches are used including genetic breeding, cultural schemes with sanitation, host indexing, enhanced eradication protocols, new pesticide products, and integrated pest management. Nowadays, nanoparticles are used as a physical approach to alter and improve the effectiveness of some types of synthetic chemical pesticides or in the production of biopesticides directly for the disease management of crops (Hameed and Al-Samarrai 2012). Mondal and Mani (2012) found the antimicrobial property of nano-copper (0.2 ppm) which inhibits the growth of *Xanthomonas axonopodis* pv. *punicae.* Similarly, Kala et al. (2016) reported that CuNPs (5–15 nm) biosynthesized from leaf aqueous extract of *Datura innoxia* inhibited the growth of *Xanthomonas oryzae pv. oryzae* causative organism of bacterial leaf blight of paddy. Giannousi et al. (2013) analyzed the antifungal property of nano copper (11–55 nm) against *Phytophthora infestans* in Tomato. Lamsal et al. (2011) evaluated the effect of silver nanoparticles (100 ppm) as fungicide against six *Colletotrichum* species associated with pepper anthracnose under different culture conditions and found that AgNPs inhibited the growth of fungal hyphae as well as conidial germination in vitro when compared to the control. A similar finding was observed by Pinto et al. (2013) that Ag nanoparticles (NPs) form composite film which shows strong inhibitory action on fungal spores of *Aspergillus niger.* Park et al. (2006) determined the antifungal property of nano-sized silica-silver composites which minimized the pathogen attack within 3 days of spraying in plants. Meanwhile, nano-sized silica-silver composites at 10 ppm concentration was effective for 100% growth inhibition of *Pythium ultimum*, *Magnaporthe grisea*, *Colletotrichum gloeosporioides*, *Botrytis cinerea*, and *Rhyzoctonia solani*, whereas *Bacillus subtilis*, *Azotobacter chrococuum*, *Rhizobium tropici*, *Pseudomonas syringae*, and *Xanthomonas compestris pv. vesicatoria* showed100% growth inhibition at 100 ppm concentration. Jo et al. (2009) reported that application of AgNPs (200 mgl^{-1}) reduced 50% colony formation of pathogenic fungi that caused disease in ryegrass. He et al. (2011) showed ZnO NPs (<70 nm) significant inhibition of two postharvest pathogenic fungi *Botrytis cinerea* and *Penicillium expansum* and concluded that ZnO nanoparticles cause deformation of fungal hyphae and prevent the conidiophores and conidial development which ultimately leads to the death of fungal hyphae. Kamran et al. (2011) reported that the nano silver and nano TiO_2 have good potential for removing of the bacterial contaminants in the tobacco plant because NPs exposure causes toxicity to bacteria by preventing replication and protein synthesis.

27.7 Nanotech Sensor

Nanosensors are emerging as promising tools for the applications in the agriculture and food production. Nanosensors can be used for determination of microbes, contaminants, pollutants, and food freshness (Joyner and Kumar 2015). Nanosensors are also used for sensing of soil conditions (e.g., moisture, soil pH); a wide variety of pesticides, herbicides, fertilizers, insecticides, and pathogens; and crop growth aiming to remove plant protection product applications, reduce loss of nutrients, and enhance crop yields through good nutrient management. With the help of portable nanosensors, the presence of insects, diseases, pathogens, chemicals, and soil contaminants are easily detected in the field (Brock et al. 2011).

Yao et al. (2009) reported that fluorescence silica NPs in combination with antibody can detect easily *Xanthomonas axonopodis pv. vesicatoria*, the causal organism of bacterial spot disease in *Solanaceae* plant. Similarly, nano-gold-based immune sensors have the ability to detect Karnalbunt (*Tilletia indica*) in wheat plants by using surface plasmon resonance (SPR) sensor (Singh et al. 2010). In stress condition, many physiological changes occur in plants which are regulated by hormones like jasmonic acid, methyl jasmonate, and salicylic acid. Wang et al. (2010) developed gold electrode modified with copper nanoparticles to measure the salicylic acid in rape infected with *Sclerotinia sclerotiorum*. By using this electrode, salicylic acid can be accurately measured. Nanotechnology is also used to determine the pollutant levels in the environment and quantity of air dust by using nano-smart dust and gas sensors (Scott and Chen 2003).

27.8 Problems and Prospects

The main objective of nanotech in agriculture and food sector is to trim down the use of plant protection products, reduce nutrient losses in fertilization, and increase yields through optimized nutrient management. Although nanotechnology is quite a recent discipline, still there are several ethical and societal concerns starting from health and environmental safety to consumer perception and intellectual property rights which need to be addressed. Besides its high potential, there are various problems associated with nanotech application in field crops. There are 7000 cultivated plant species in agriculture, so a huge research in the field of nanotechnology is needed (Khoshbakht and Hammer 2008). Each plant has different types of physiology which affect its interaction with nanoparticles, making the research more complicated. Moreover, the production cost of nanomaterials is very high which hampers their application in the fields. There are some concerns about the use of nanoparticles for the safety of environment and human/animal consumption. Koo et al. (2015) reported that application of certain metal/oxide nanoparticles or nanotubes for edible crop is not good for human health and have risk of entering into the food chain.

Nanotechnology has great potential to be used for various applications in agriculture, but more studies are needed in this field to enhance crop production and avoid hazardous and toxic materials. Nowadays, nanotechnology is in its early stages, and a lot of questions about their function in plants are being investigated. By better monitoring and targeted action, nanotechnology has potential to maximize output with minimum inputs. NM application in the field of agriculture includes nanosensors for detecting pathogens and soil quality and plant health monitoring, nanocapsules for agrochemical delivery, nano-enabled fertilizers for slow release and efficient dosage of water and fertilizers, and nanocomposites for plastic film coatings used in food packaging. The future research for further investigation on the role of NMs for crop disease suppression are needed to expand their possible applications in agriculture, though this review displays the potential of NMs for different agronomical crops.

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Role of ICT in Crop Management

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Abstract

Every day, new and crucial difficulties and challenges are encountered in agriculture. Using information and communication technologies (ICTs) can be a key facilitation for more efficient crop production. Simply ICT is defined as hub of technologies that support in storage, processing data/information, communication of data/information, and distribution of data. ICT therefore comprises technologies such as computers (desktop and laptop), mobile phones, Internet connection, peripherals, and software that are projected to perform information processing and communication purposes. The application of ICT in agriculture

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is becoming progressively important. E-agriculture is a developing field aiming on the improvement and development of agricultural and rural sector through enhanced information and communication processes. More importantly, e-agriculture involves the concepts, design, development, assessment, and application of advanced methods to use information and communication technologies (ICT) in the rural area, focusing on crop production. All stakeholders of crop production system need information and understanding about these stages to manage them efficiently.

Keywords
Information and communication technologies · Agriculture · Remote sensing · Modeling

28.1 Introduction of ICT

Information and communication technology (ICT) indicates the technologies which allow access to information via telecommunications medium such as computers, cell phone, satellites, television, radio, and Internet including email, video conferencing, messaging, and social networking sites. These technologies help users around the world to communicate with each other and provide quick access to share ideas and information increasingly being used in all areas of human activity, including agriculture.

Agriculture is an art and science of all businesses associated with crop cultivation and animal husbandry for providing food and shelter and raising the standard of living for manhood. Agriculture is vital for mankind because it provides raw material, food, and employment for industries; others are source of income, foreign exchange, afforestation, provision of shelter, and regional development. In developing countries most of rural population depend upon agriculture. Agriculture sector is facing a major provocation of increasing production because natural resources are dwindling rapidly which are essential for production. However, the growing demand for agricultural products provides more opportunities for manufacturers to support and ameliorate their standard of living. ICTs play a significant role in defining these provocations and raising the standard of living of the rural people. Due to the urgent need for research in application of new and innovative technologies in agriculture, knowledge of agricultural scientists should be transformed into computer-understandable representation (Fig. 28.1) (Kumar 2013).

28.1.1 GIS and Remote Sensing

Geographic information system (GIS) is a combination of hardware, data, and software which provide acquisition, analysis, management, and presentation of

Fig. 28.1 Application of ICT in agriculture

geospatial (geographically referenced) information. In a GIS, layers of spatially accurate data are associated with tabular (attribute) data in relational databases and authorize the user to visualize and analyze patterns and trends.

ICT has been using GIS and remote sensing technologies to ensure viability and crop management (Fig. 28.2). Additionally, GIS applications have been widely used for environmental management, watershed management, and environmental impact assessment (EIA). GIS group also generate digital elevation model (DEM) using stereo pairs, land use maps, large-scale base maps, and terrain analysis. ICT has distinguished technical and non-technical resources (both hardware and software) and highly qualified professionals with extensive knowledge and experience to work on such digital/spatial data. Several national and international projects have

Fig. 28.2 Plant monitoring by remote sensing

been successfully completed using an extensive range of data including aerial photographs, satellite imageries, and GPS-guided topographical surveys (ICT 2018).

28.1.2 Computer Mapping

Computer mapping or geographic information systems (GIS) operations have diverse services in crop production and management. Any data can be mapped if it is associated with land address or located in space by latitude and longitude. One attains not only an attractive map but also a new level of spatial analysis useful in program and policy decision-making.

Crops mapping and identification is necessary for multiple purposes. Maps of crops are created by considerable number of national and multinational agricultural and insurance agencies and by regional agricultural research centers to organize a directory of what and when was cultivated in particular areas. This provide the aspiration of predicting yield, assisting crop variation and rotation records, mapping soil productivity, collecting crop production statistics, identification of factors inducing crop stress, evaluation of crop destruction due to hazards and disasters, and monitoring and analyzing farming activities.

Major computer mapping activities determine crop types and describing the amount of cultivation in acers or hectares. Traditionally this information is obtained by census and ground surveying methods. However, for standardize measurements (especially for international agencies and consortiums), remote sensing can deliver general strategies for data collection and withdrawal of information (CCRS 2002), (2010).

28.1.3 Telephone Network

To compete, telecommunications rely on a smooth workflow that includes information about marketing, demand forecasting, designing, engineering, costumer management, operation support, and fleet management. Although telecommunications are usually an information provider for workflow management, it is different from company to company (ESRI 2001).

28.2 Role of ICT

28.2.1 Role of ICT in Plant Physiology

ICT is used to develop scientific devices for plant physiologists. The devices shown in Fig. 28.2 are designed for continuous and long-term monitoring of equipment. This has a great advantage over portable devices that are used only for on-site measurements. By constantly monitoring installations, you can record various and complex reactions to environmental exposures when they actually occur.

ICT has long been recognized as a huge potential for improving decision-making process in plant physiology. Information technology (IT) has joined the world globally and is currently dynamically changing our standard of living and social awareness. In all stages of the agricultural sector, information technology is fundamental to the management and business success. Agriculture is also significantly influenced by IT.

Information technologies are becoming rapidly visible in society and agriculture. IT refers to how we use information and how we evaluate and share information. User must have computer or smart mobile phone to participate in e-agriculture. One can make informed decisions; also a person can collect, process, and manipulate data of agriculture sector (ICT International 2014).

28.2.2 ICT and Agriculture in Future

Agriculture is of strategic importance for maintaining the livelihoods. The growth of e-agriculture has the potential to accelerate the development of agriculture and rural areas, ensure food security, and diminish rural poverty in emerging markets.

Although farmers and their machinery continue to play a key role in agricultural industry, ICT is playing a more significant role in enriching communities over the world. Basic computer training enables farmers to use ICT to increase efficiency, sustainability, and profitability of farming. ICTs can help farmers to build relationships with reliable suppliers of seeds and fertilizers; aggregation of purchases (i.e. when multiple buyers are involved) can lead to lower prices, better access to cultivation information, finest practices and a general decrease in labor costs and wastage (Theunissen 2015).

28.2.3 ICT Initiatives for Agricultural Development

E-agriculture is developing and handling advance ICT techniques in the rural areas, focusing on agriculture (Amin et al. 2015). It is a rising field aiming on improvement and development of rural and agricultural areas through communication and

Fig. 28.3 Instruments for plant monitoring

advance information. In this regard, ICT is a generic term covering all technologies and tools such as devices, applications, networks, and services, which include advance technologies and sensors of Internet era to other preexisting tools such as radios, televisions, landline telephones, and satellites. E-agriculture is constantly evolving as new ICT applications for agriculture sector. Particularly, e-agriculture includes the designed models, engineering, evaluation, development, and application of innovative methods of applying ICT in rural areas focusing on agriculture sector (Fig. 28.3). Its aim is to provide standards, methodologies, norms, and tools to upgrade individual and institutional capacities and supporting policies (Wikipedia 2018).

28.3 Water Management Through ICT

ICT-supported irrigation is demonstrated here as "application of water to a tree based on monitoring the need of each tree to optimize its yield." ICT monitors real-time water and nutrient consumption and the needs of each tree. The system (shown in Fig. 28.4) in turn remotely activates and provides a continuous, optimized supply of water and nutrients suitable for the farmer's current climate, soil conditions production plan. ICT is one of the most effective means to increase food production by improving land, crop, and water management. Since the ICT and automation are involved in management of water supply and irrigation system, it has been shown that there is an excellent improvement in water use efficiency in countries facing severe water shortages. It increased water use efficiency by 10–50%, increased per unit yield of land and water by 20–100% in irrigation, and improved agricultural productivity. ICT and automation allow optimizing pressure regimes in water supply networks, saving water and energy, and charging users to his actual consumption. Practically, ICT and automation ensured the adoption of volumetric (three-dimensional) approaches of water application in agriculture. These successes have facilitated to expand irrigated area, increase food production, and maximize profits for farmers (Amarasingam 2017).

Fig. 28.4 Water management methods

ICT is a strategic factor in the process of developing innovative solutions to address the problems of water scarcity. By collecting and analyzing environmental data, ICT facilitates researchers and climatologists to create more precise models for weather forecasting (ITU News 2015).

28.4 Role of ICT in Nutrient Management

The use of ICT is now being felt at the farm level. A rice farmer or extension worker who has a cell phone connected to the Internet can download an application called Nutrient Manager. He can log in and answer a series of questions. Based on the information he submits to a cloud server, instruction of fertilizer is automatically sent through his phone either as an image or as an SMS message. Similarly, a crop

Fig. 28.5 Nutrient management

advisor, extension worker, or a farmer who has access to a personal computer can also download the same application from the Internet through a web browser to get the same fertilizer guideline (Fig. 28.5).

Meanwhile, a farmer calls a specially assigned phone number using a simple GSM mobile phone to access the Nutrient Manager's voice recording via an IVR. After responding to the queries in the voice recording by pressing numbers keys on the telephone directory, he also receives a personalized fertilizer guideline.

Nutrient Manager is a decision support tool that uses innovations in ICT and transforms site-specific nutrient management (SSNM) principles into easy-to-apply nutrient management guidelines for farmers. Developed by International Rice Research Institute (IRRI) through partnerships with Asian organizations, it delivers scientific principles for defining field- and crop-specific requirements of fertilizer (FFTC 2018).

28.5 Role of ICT in Pest Management

ICT has proved to be a powerful tool in pest forecasting as a prop to giving priority to prevention, as pest forecasting involves data acquisition, processing, and information dissemination. ICT can also be very helpful in terms of enforcing integrated pest management (IPM).

The use of information technology (IT) in pest management has gone through sensational developments over the last decade. IT has increased the efficiency of data collection and analysis, identification of pest, choice of control agent, and field

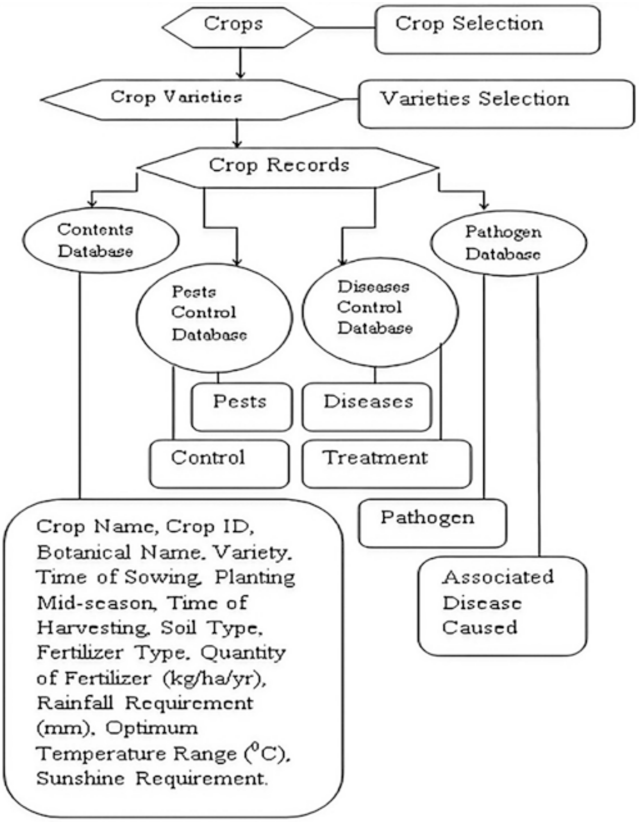

Fig. 28.6 Pest management by ICT

applications of pesticide (shown in Fig. 28.6). In addition, IT has improved our capabilities in research, training, education, and information circulation and management. We monitor pests for early warning, development of models for forecasting pests and decision support systems, which are crucial for the design and implementation of successful integrated pest management programs. Developing countries instantly need to create agrometeorological networks for specific crops with the main goal of predicting pests using models and decision support systems (Xia Roger and Suiter Ronald 2007), (Okpara 2015).

28.6 Factors Affecting Use of ICTs for Agriculture Extension

By the innovation in ICTs and its mechanism, rural expansion and advisory services will be dependent on ICTs so that they can find more effective, suitable, accurate, and innovative means to provide most advance agricultural expertise to farmers. Additionally, ICT-based information and advisory services have an important role in providing agricultural expertise to farmers. ICTs' importance in agricultural progress is essential to promote the distribution of information through ICT to increase agricultural productivity and on the other hand provide a mechanism for the sustainable provision of information to agriculture. Introduction of ICTs in agriculture is quite complex and critical, because it includes numerous phases and factors of farmer life. Socioeconomic profile of farmer is one of the prominent factors because it influences adoption of ICTs by farmer in agriculture. Several studies have been engaged to examine socioeconomic profile of farmer that influences the behavior of farming community in relation to agricultural advisory services, methods, and other ICT-based social activities. These factors promote policies to adopt ICT-based agricultural practices by farmers in order to increase agricultural production. Contrarily, study has shown a significant correlation between statistical data such as age and education of farmers and their adaptation to technological knowledge (Yaseen et al. 2016).

28.6.1 Lack of Knowledge

NGOs do not have sufficient capacity to support and promote the active use of ICT for development. They have lack of experts, knowledge, or organizational capacity. IT use is often regarded as an acute problem to back office systems. Additionally, ICT has doubtful reputation due to previous unproductive or costly initiatives.

28.6.2 Pace of Change

In recent NGOs structures, staff and function have a strong impulse that is not easy to break or to lead. It is comparatively easy to use ICT to maintain and improve existing organizational structures and approaches, to achieve beneficial but gradual improvement. It is extremely hard to find new methods of working with organizational structure which are basically changed from current situation and need a change regarding strategies, capability, skills, and organizational structure.

28.6.3 Funding

Proper planning and funding the use of ICTs in development programs are also a serious problem, due to cyclical donor for funding and need to reduce administrative and management costs. It is often difficult for NGOs to invest financial and human resources in ICT as a major potential for planning and using development programs.

28.6.4 Changing Roles and Norms

The emergence of new ICTs may raise more number of necessary and far-reaching issues that challenge or even undermine the assumptions made by NGOs. When we think about why NGOs were formerly created, we can identify multiple specific gaps between rich and poor communities in the world. For example, when we think about gaps in understanding and lack of information, traditionally NGOs helped us understand the needs of communities in the poorest parts of the world. There are also gaps in access, communication, and resources where NGOs have done efficient work in the past (Devex 2013).

28.7 Information Needs of Farmer

Growing crops is a complex process that includes multiple activities such as tillage, land preparation, irrigation, planting, nutrient management, pest control, harvesting, marketing, etc. The entire crop production cycle requires a lot of information from farmers. Despite many efforts that have been made over the years of distributing agricultural knowledge and transferring it to the farmers, the majority of experts and specialists are still unavailable. Agricultural knowledge can be stored in a corporate database or remain undocumented in the minds of researchers or even stored in places unknown to most of the organizations employees. A significant part of farming community, especially the rural population, does not have access to the knowledge gained by extension centers, agricultural universities, and research centers. In this regard the biggest problem is the search for knowledge and its application in decision-making process related to development of agriculture. Currently the main problem for an organization is to identify, locate, and apply this specialized knowledge, embedded in organizational databases, to develop as a different production aspect to raise productivity and competitiveness.

28.7.1 Variety Selection

This subsystem advises users on the varieties most suitable for their plantation, based on the specific conditions of the farms and user's requirements. The knowledge of the subject area of this subsystem holds two models, namely, suggestion and selection. The evidence-based knowledge holds three inference steps, namely, specify, select, and count. The proposed model defines a relationship between the environmental conditions and the suitable varieties used by "specify" inference step to offer paddy varieties suitable for the environments. The selected model defines relationship between user needs and varieties used by "select" inference stage to select the most appropriate varieties that meet the user requirements. The "count" inference step just counts the number of varieties.

28.7.2 Land Use Planning and Management

Sustainable agriculture is a combination of methods that specify present and future social requirements for food/fiber without threatening land degradation (Hammad et al. 2018). GIS offers the possibility of combining several information layers, from diverse sources, in one spatial representation. GIS is especially useful when a spatial planning consensus is reached and when users have different values and preferences for a particular area. Similarly, RS techniques are important tools for observing land resources (e.g., water bodies, vegetation, etc.), particularly when a single object is responsible for monitoring a large area. Soil cultivation provides specific recommendations to the user about preparation of particular land for cultivation and appropriate planting techniques according to particular user's inputs data. The field model of this subsystem holds two models: establishment plan and assignment. The scientific knowledge holds three inference steps: establish, assign, and select. The organizational structure model contains a relationship among farm description and strategic plans, which is used by organizational structure to create a recommended plan and an alternative.

28.7.3 Soil Quality Assessment

Soil quality assessment can be conducted at farm level and at regional level. At the regional level, this may be based on land, climate, and land use. Some beneficial technologies help to understand nature of soil and its problems associated with agricultural and management practices. In recent years ICTs have developed dramatically. Assessment of soil quality is carried out with the help of some beneficial technologies, like RS (remote sensing).

28.7.4 Input Procurement

Farmers often acquire information about the various resources they need in the field, like seeds, labor, pesticides, fertilizers, transport, etc. regarding cost, quality resources, and availability.

28.7.5 Strategic Information

During cultivation farmers need information at several stages to support planning and minimize risk. Information regarding the agricultural practices like characteristics of various varieties, pest control techniques, planting, irrigation and harvesting schedule, mechanization, inter-cropping, etc. can be attributed to strategic information. Information of appropriate technologies for protection and production is required for optimal and sustainable agriculture.

28.7.6 Past Trends

Background information in terms of varieties, area, production, pest infestation, climatic conditions, utilization, environmental problems, etc. are very helpful in decision-making for cultivation. For example, previous climatic trends can help farmers to plan crop cultivation techniques for optimal production and stress management.

28.7.7 Government Policy Decisions

Government policies regarding agriculture, labor laws, land ownership, products marketing, rural development, etc. are key factors while decision-making. This information should be obtained by farmers in the shortest possible time, so that a farmer can make accurate decision for maximum productivity and revenue. Currently, IT tools are now available to record and distribute decision support information and provide information about support facilities and government policies.

28.7.8 Expert System

An expert system is an IT-based intelligent computer database, which uses interventions and knowledge to deal with those problems that are quite complex and need considerable mortal experience. Expert system for production and protection of a crop is a modern innovative tool for farmers in decision-making process. It can recommend an appropriate crop variety, irrigation, field preparation methods, sowing methods, and fertilizer application. Expert system also offers farmers diagnosis and treatment of disorders in crops.

28.7.9 Simulation and Modeling

Simulation and modeling and technologies help to simulate an ideal crop situation and growth prediction by extrapolation and other methods by taking into account a particular crop environment (Mubeen et al. 2013; Amin et al. 2017a). Crop models can be designed to characterize environment, improve crop management and disease and pest management, study the impacts of climate change and effective crop scheduling, predict crop yield, etc. (Amin et al. 2017b, 2018a, 2018b). After one is assured that model mimic the real world effectively, the system can be controlled and managed by performing computer experiment for hundred or even thousands of times for particular environment. For example, decision support system for agrotechnology transfer (DSSAT) was designed to operationalize this approach and make its application available worldwide. DSSAT assist decision-makers to save time and resource to analyze complex alternate decisions (Tsuji 1998; Jones et al. 2003).

28.7.10 Multimedia Tools

Multimedia is a term which means number of media like text, video, graphics, animations, music, narrated sound, and special effects. They are controlled, integrated, and coordinated by a computer. Simply multimedia is multiple forms of media that are integrated with each other. It contains encyclopedia, instructional tools, videos, tutorials, etc. which help improve not only the text messaging but also the understanding, receiving, and retention of information (FAO 2017).

28.7.11 Agricultural Advisory

Information priorities of farmer consist of precise weather forecasts, specific crop advisory depending on the phases of crop cycle, and marketing information. Using ICT, one can get real-time weather data through remote sensors, track raw material prices using mobile technologies, and update crop-related research findings obtained from web platforms of agricultural universities and research centers.

The collected information is stored in a database and automatically activated to distribute as personalized and localized information about weather, prices of goods, equipment's and raw material personalized, and cultivated crop among registered farmers through short messaging service (SMS) and interactive voice response (IVR). This updated information empowers farmer to be more informed and prepared to use resources for better revenue.

28.7.12 Financial Services

Availability and access to adequate, timely, and low-cost credit from banks are of great importance for sustainable and profitable farming. The challenges to bring all farmers within the banking reach at affordable cost have been fulfilled through remote bank transactions assisted by handheld biometric transaction devices.

The banks facilitate financial services such as savings, credit, insurance, and remittance with the help of these devices accessed through smart cards. Smart cards hold farmers' information regarding the land details, crop history, and financial transactions, which help bank to process and sanction crop loan faster. Thus, the farmer needs to initiate the loan procedure through the handheld device available at the village and visit the bank to collect the loan amount upon confirmation on loan sanction. This saves the farmer's valuable time and energy to obtain institutional loans.

28.7.13 Agricultural Marketing

The coverage and size of agricultural market have improved over the years due to connections with distant and foreign markets. Farmers use multiple ICT platforms like mobile phones, information kiosks, web-portals, electronic markets, etc. for product marketing. ICT platform provides market analysis and enables farmer's confidence in understanding the product demand and increase ability to manage production and supply chains. It also facilitates farmers to directly deal with wholesalers, exporters, and processors instead of small-scale dealers.

ICT platforms help to develop a wide network of contacts which will facilitate farmer to make better decision regarding cheaper resources, supply and demand, price, location, transportation, and logistics (Mathur 2015).

28.8 Conclusion

ICTs can facilitate farmer to access relevant and precise information to improve agricultural methods and production. Information access is critical in farming families, which is conflicting, mainly family-based labor, production of diversified goods, and defined access to productive resources.

ICTs, particularly smart phone applications, facilitate every single farmer about cultivation, management, and marketing of crops. The digital financial services (DFS) revolution have great impact on the family business with the proliferation of smart mobile phones in the remote areas of the world; efforts are strengthening farmers to use innovative mobile technology for better agriculture practices and outcomes. The combination ovgeographic information system) and mobile technology provides specific, accurate, and micro information of soil, water, and nutrients to farmers for decision-making,

enabling ICT connectivity of rural areas with globe through sound policies and strategies and ensuring low-cost and high-quality access to technologies, which will support smooth exchange and distribution of agricultural information to farmers.

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