Abiotic Stresses in Agriculture: An Overview

1

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Abstract

Agriculture production and productivity are vulnerable to abiotic stresses. These stresses emerge due to drought, temperature extremes (heat, cold chilling/ frost), radiation (UV, ionizing radiation), floods in addition to edaphic factors which include chemical (nutrient deficiencies, excess of soluble salts, salinity, alkalinity, low pH/acid sulfate conditions, high P and anion retention, calcareous or gypseous conditions, low redox, chemical contaminants—geogenic and xenobiotic), physical (high susceptibility to erosion, steep slopes, shallow soils, surface crusting and sealing, low water-holding capacity, impeded drainage, low structural stability, root-restricting layer, high swell/shrink potential), and biological (low or high organic contents) components. These stresses are the major challenges for production of crops, livestock, fisheries, and other commodities. Only 9% of the world's agricultural area is conducive for crop production, while 91% is under stresses which widely occur in combinations. While losses to an extent of more than 50% of agricultural production occur due to abiotic stresses, their intensity and adverse impact are likely to amplify manifold with climate change and over exploitation of natural resources. Fragile agroecosystems like the dryland areas are highly vulnerable to such disastrous impact. To mitigate the effects/impact of multiple stressors, proposed strategies include improved agronomic management, while the breeding of stress tolerant genotypes can enhance capacity for adaptation to stress environments. However, a holistic integrated multidisciplinary approach in systems perspectives is a need of the hour to get

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the best combination of technologies for a particular agroecosystem. Therefore, this compendium through different comprehensive chapters conveys relevant updates on trends in abiotic stresses and their impact in addition to scientific interventions for stress management through mitigation and adaptation options. The compendium also explains scope for modern science to mitigate abiotic stresses and improve adaptation through genetic improvement and some of the policy support endeavors. The way forward includes information on implementation of existing technologies and gaps to be filled through future research for abiotic stress management.

The food and nutritional security warrants the availability of adequate and quality food to meet the dietary and nutritional requirements for a healthy and productive life. The global food production has been increasing in line with and even sometimes ahead of demand in recent decades though many countries are still confronting problem of inadequacy of food supply. The world population is growing at an alarming rate and is anticipated to reach about 9.6 billion by 2050 from the present about 6 billion. Specifically the developing countries would be the major contributors to rise in population. For instance, India will be the most populous country by 2050, and its population is predicted to reach 1.6 billion from the present of about 1.3 billion. The predictions are that demand for food would increase by 70% and would even double in some low-income countries (FAO 2009). This of course is related with population rise, but the per capita food consumption coupled with its quality would also improve with growing economies. Therefore, enormous efforts are required to achieve the expected growth rate (44 million tons per annum) to ensure food security especially when agriculture is losing the productive lands due to urbanization and industrialization. Moreover, the past endeavors for improving agricultural productivity to meet the food demands were accompanied by land degradation and the impact of episodic climate variability; those have consequently increased the components, frequency, and magnitude of abiotic stresses. The abiotic stresses like drought, temperature extremes, floods, salinity, acidity, mineral toxicity, and nutrient deficiency have emerged as major challenges for production of crops, livestock, fisheries, and other commodities. These in fact are the principal causes of crop failure worldwide, dipping average yields for most major crops by more than 50% (Wang et al. 2007), mostly shared by high temperature (20%), low temperature (7%), drought (9%), and other forms of stresses (4%). Only 9% of the area is conducive for crop production, while 91% is under stresses in the world. Various anthropogenic activities are accentuating the existing stress factors. Thus, the abiotic stresses cause losses worth hundreds of million dollars each year due to reduction in crop productivity and crop failure. Specifically substantial agricultural land in tropics and subtropics, e.g., in India, is more challenged with penultimate combinations of abiotic stresses. Since these stresses threaten the very sustainability of agriculture, there is enhanced apprehension among the farmers, scientific communities, and policy makers regarding the intensity and adverse impacts that are likely to amplify manifold with climate change and due to over exploitation of natural resources.

For assessing the magnitude of the problems related to abiotic stresses, the initial section is dedicated for an overview and opportunities for alleviating the impacts of the atmospheric, drought, and edaphic factors on agricultural and horticulture crops, livestock including poultry, fisheries, etc. The environmental stresses like temperature (heat, cold chilling/ frost) and radiation (UV, ionizing radiation) are responsible for major reduction in agricultural production (Chap. 2). Moreover, the catastrophic events like droughts, floods, hailstorms, cyclones, etc. are occurring frequently and cause widespread land degradation apart from heavy monetary losses and serious setbacks to agricultural development. The nature and severity of impacts from extreme weather events like drought and hailstorms depend not only on their extreme features but also on duration of exposure to these stresses and extent of vulnerability of natural resources, livestock, and humans. Adverse impacts become disasters when they produce widespread damage and severely alter the routine functioning of communities or societies. Specifically the fragile dryland ecosystems, which support substantial population, are highly vulnerable to food insecurity since these are characterized by limited and erratic rainfall, intense pressure on resource use, and sensitivity to climatic shocks (Chap. 3). Emergence of widespread multiple nutrient deficiencies, depletion of organic carbon stocks, development of secondary salinity and waterlogging in canal-irrigated areas, low input use efficiencies (nutrient and water use), decreasing total factor productivity of fertilizers, etc. are all the consequences of application of component-based technologies for short-term yield gains (Chap. 4). Corrective measures and precautions both in short term and in long term should allow effective management of these situations which potentially limit the productivity of crops and dependent agricultural enterprises. Such efforts need community interventions particularly in cases of severely fragmented land holdings.

Development and promotion of strategies to minimize the impact of abiotic stresses are fundamental for sustaining agriculture. The proposed strategies include both the improved agronomic management and breeding novel genotypes with improved capacity for adaptation to stress environments. The major challenge is to enable accelerated adaptation and mitigation without threatening the sensitive agroecosystems that support livelihood of inhabitants striving to cope with abiotic stresses. The multi-thronged strategies are required to accomplish this task based upon the analysis of current situation and development and use of newer technologies including diversification of the production systems. Though the edaphic constraints are mostly coupled with intrinsic soil-forming processes, some of the anthropogenic causes like poor land management practices, e.g., overexploitation and lack of restorative measures aggravate these constraints. Except few, the processes leading to edaphic constraints are generally insidious and show up only gradually as the problem becomes more severe to cause yield declines. Farmers may ultimately be forced to either shift to less remunerative crops or soils can turn unfit for agriculture in extreme cases. Several resource conservation and cropping system-based strategies including conservation agriculture, integrated farming systems, watershed management, and other restorative measures are available to reduce the effects of edaphic stresses and for securing favorable soil conditions (Chaps. 5 and 6). Recent NRM technologies concentrate more on improving the whole farming systems at field or watershed level rather than only the productivity of specific commodities. Contingency crop plans have also been advocated for stabilizing agricultural production under the situation of weather aberrations especially the drought. Salinity and waterlogging have now emerged as global phenomena, which are adjunct of irrigated agriculture. The global annual cost of salt-induced land degradation in irrigated areas has been estimated to be US$ 27.3 billion because of lost crop production (Qadir et al. 2014). Soils are also getting increasingly polluted with toxic elements from geogenic or anthropogenic sources like sewage, industrial effluents, urban solid wastes, etc. The heavy metal toxicities not only impair productivity or agricultural crops, but these enter the food chain and become potential hazards to health of humans and animals. Remedial measures through engineering techniques and bioremediation have so far met with varying degrees of success (Chaps. 7 and 8). For promotion of growth and development under stress conditions, exogenous application of plant bio-regulators (PBRs) and other nutrient supplements has been tried under both controlled and actual field conditions (Chap. 10). These promote the ability of plants to cope with the stress conditions by mediating growth, development, nutrient allocation, and source sink transitions. Mainly the PBRs with thiol-groups, which are involved in redox signaling, can help alleviate stress for crops grown under drought, salinity, and heat stress (Chap. 11).

There are increasing evidences for climate change, which is happening and hence further global warming seems unavoidable (IPCC 2014). Agriculture sector is one of the most sensitive areas that are being afflicted by global warming and associated weather variability (Chaps. 2, 9 and 12). For instance, global production of maize, wheat, rice, and soybean is projected to decline up to 40–60% by 2090 (Rosenzweig et al. 2014). Climate change may impact the agricultural crops in four ways (Easterling and Apps 2005). First the agroecological zones may be altered with changes in temperature and precipitation. An increase in potential evapotranspiration and increased length of rainless periods are likely to intensify the drought stress especially in semiarid tropical and subtropical regions. The increased carbon dioxide is expected to have positive impact due to higher rate of photosynthesis and higher water use efficiency. The water availability (or runoff) is also a critical factor for determining the impact of climate change. Since the precipitation determines the length of growing season, the effect of climate change on total rainfall and interval between the rainfall events ultimately decide if the effects on agricultural crops are the positive or the negative. The losses in agriculture can result from climate variability, and there may be increase in frequency of extreme events like droughts, floods, etc.

The stress signal is first perceived at the membrane level by the receptors and then transduced in the cell to switch on the stress-responsive genes for mediating abiotic stress tolerance. Hence, deep insight into the mechanism of stress tolerance mediated by a plethora of genes involved in stress-signaling network is important for crop improvement (Chaps. 12 and 13). Each stress leads to multigenic responses of plant, and therefore it may result in alteration of a large number of genes as well as their products. A deeper understanding of the transcription factors regulating these genes, the products of the major stress-responsive genes, and cross talk between different signaling components will be an area of intense research activity in the future. The knowledge generated through these studies should be utilized in transforming the crop plants that would be able to tolerate stress condition without showing any growth and yield penalty. Attempts should be made to design suitable vectors for stacking relevant genes of one pathway or complementary pathways to develop durable tolerance. These genes should preferably be driven by a stress-inducible promoter to have maximal beneficial effects avoiding possible yield penalty during favorable season. Additionally, due importance should be laid on the physiological parameters such as the relative content of different ions as well as the water status in plant tissues for designing stress-resilient crop plants for the future.

Cereal food grains like rice and wheat have been the first priority for improvement by plant breeders since these continue to be the important staple food across the world. Therefore, these crops witnessed significant progress in improvement of germplasm, breeding lines, high-yielding cultivars, and yield stability. In addition, there have been ample efforts for diversification through cultivation of drought-tolerant crops like barley, sorghum, etc. With growing needs toward development of potentially resilient genotypes for emerging abiotic stresses (heat, drought, salinity, etc.), genetic alterations of these cereals are being attempted through genomics, bioinformatics, high-throughput phenomic tools, etc. (Chaps. 13, 14, 15, and 16). In the wake of climate change, recent developments in molecular genetics and biotechnology are also aiding acceleration of breeding process for adaptation in other crops like vegetables, sugarcane, etc. which are also an important component of human diets (Chaps. 17 and 19). Integration of proper crop management strategies with improved cultivars is essential to meet the goals of stress management in fruit crops in tropical and subtropical regions (Chap. 18).

Abiotic stresses also threaten the availability of feed resources for livestock from land-based production systems (Chap. 20). Specifically the drought conditions usually endanger the very sustainability of livestock in arid and semiarid regions. Moreover, the animal health is projected to be impacted by climate change via animal-related diseases with thermal stress and the extreme weather conditions. Therefore, vulnerability of ruminants and possibilities of improved nutrition and other management issues have been discussed (Chaps. 21 and 22).

The strategies that help to minimize the impacts of abiotic stresses include sound governmental policy and political will for post-disaster recovery and reconstruction for improving adaptive capacity. The under investment and market distortions especially in the regions having preponderance of abiotic stressors have been mainly responsible for poor R&D, weak institutions and infrastructure, and non-pragmatic pricing of inputs and natural resources. Hence, policies are identified which can shape development, dissemination, and marketing of technologies to sustain agricultural outputs using resource efficient methods in harsh agroecologies (Chaps. 23 and 24).

Keeping above in view, different chapters are compiled in a mode to bring out the latest developments on emerging techniques to tackle the complex problems related to abiotic stresses. Interventions of these technologies require appropriate knowledge of abiotic factors essential for developing preparedness measures suitable for socioeconomic and environmental conditions prevailing in the agroecosystem under consideration. So far the earlier compilations on abiotic stresses had focus on basic physiological and transgenic issues but not on problem-solving approaches and techniques; those are essential for inducing medium- to long-term resilience in production systems. Besides sustainable livelihood security to poor families, adaptation and mitigation strategies can provide an immense scope for ecosystem services. The authors trust that with the synthesis and integration of knowledge and experiences of experts from different disciplines, this book will open new vistas in the versatile field of abiotic stress management and will be useful for different stakeholders including agricultural students, scientists, environmentalists, policy makers, and social scientists.

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