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Biotic and Abiotic Stresses Affecting Plant Performance: Interactions, Mechanisms, and Adaptive Responses

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INTRODUCTION

Agricultural sustainability and crop cultivation continuously exposed to various abiotic and biotic factors. The non-living environmental factors such as water, light, temperature, salinity, atmospheric gases and soil nutrients are major abiotic factors affecting proper growth and development of the plants, whereas biotic factors include living organism such as weeds, pathogens, insects and pests also affects plant at various stage of development. The wide range of plant characteristics including growth rate, photosynthetic efficiency, biomass accumulation, flowering, grain filling, fruit setting has been influenced were observed in many crops (Pandey, et al., 2017). Most of the climatic events like rising global temperature, uncertainty of rainfall, change in precipitation patterns, and expanding the incidence of disease and pest hamper sustainable agricultural development across the world. Most of the human induced activities including deforestation destroy of natural resources, urbanization, and industrialization is the factors accelerating the negative impact of abiotic and biotic factors globally.

2. Abiotic Factors Influencing Plant Performance

Abiotic factors like water, light, temperature, soil conditions, and humidity contribute to the plant growth and productivity. These environmental factors influence physiological and biochemical processes of the plants at every stage of the growth and development. Most of the abiotic factors emerged as stress like drought, heat stress, soil salinity etc. and their cope significantly reduces plant productivity (Mittler, 2006). The effect of various abiotic factors on plant growth and productivity are summarized here.

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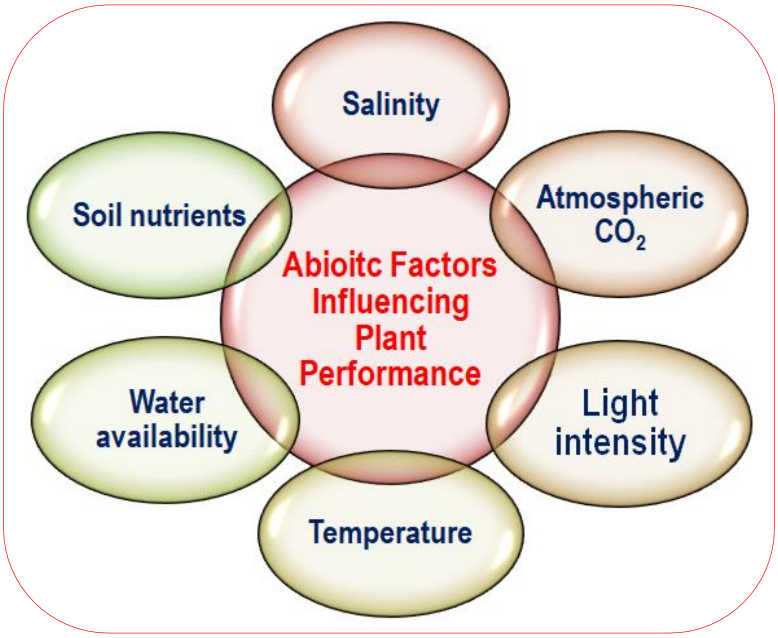

Fig.1: Environmental factors affecting plant growth and development.

2.1. Temperature: Temperature is one of the important abiotic factors regulates essential physiological and biochemical processes like respiration, photosynthesis, stomatal conductance, seed germination, flowering and fruiting (Calo, et al., 2006). Most of the plant species requires optimum temperature for proper growth, development as well as metabolic activities. Temperature below and above the optimum affects most of the physiological processes and cellular enzymatic activity inside the plants. The major effects of high and low temperature on plants are briefly described here.

2.1.1. Effects of High Temperature: High temperature significantly reduces crop productivity by disrupting most of the physiological and cellular mechanism. Growth and development of plants are affected by heat stress due to protein denaturation, cellular damage. The temperature higher than optimum may also limits energy production and biomass accumulation. Additionally, heat stress increases membrane instability leading to enhanced transpiration rates and result in the excessive water loss and cellular dehydration (Cvikrova, et al., 2013). In many crops, low level of pollen viability, limited fertilization rates and minimum seed formation has been observed due to cope of heat stress.

2.1.2. Effects of Low Temperature: Chilling stress and chilling injury is the main case of low temperature. The temperature below to optimum adversely affects seed germination and vegetative growth of the plants. Most of the physiological activities and biochemical processes have been suspended due to low degree of temperature. In cold season, metabolic processes and enzymatic activities inhibited due to very low temperature. Severity of low temperature causes chilling injury in the plant tissues due to ice crystal formation in the cell's causes' structural damage (Zhan, et al., 2015). Cellular and structural damage due to very low temperature leading to reduced plant vigor.

2.2. Water Availability: Water plays important role for plant growth, nutrient transport, and other cellular metabolic processes. Water deficit condition causes drought, whereas excess water causes submergence are reducing growth and crop productivity. Both conditions are significantly

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affecting plant health. Therefore, proper water management is very essential for sustaining crop productivity (Blum, 2009). When plant subjected to water deficit condition, it reduces water loss by stomatal closure and restricts carbon dioxide uptake leading to reduce photosynthesis. In submergence conditions, excess water accumulated in the soil and creates oxygen deficit condition near to plant roots. The anaerobic condition near reduces root functions and leading to root damage (Shah, et al., 2024).

2.3. Salinity: Accumulation of sodium and potassium salts in the soil is the main cause of salinity stress. Long-term accumulation of salt concentration in the soil creates osmotic stress and reducing ability of plants to absorb water efficiently. Salt stress negatively affects plant growth and productivity by disrupting several physiological and biochemical mechanism. Moreover, salinity also causes nutrient imbalance by interfering essential mineral absorption (Goudarzi, et al., 2011). Osmotic adjustment, ion compartmentalization is the mechanism to reduce the effect of salinity stress up to certain level.

2.4. Atmospheric Carbon Dioxide (CO_2): Carbon dioxide (CO_2) is the primary substrate for photosynthesis and responsible for the growth and development of plants. Increased Carbon dioxide concentration enhances photosynthesis rate and improve plant growth have been observed in many species. Further, the higher concentration of carbon dioxide improves water use efficiency because plant can maintain photosynthesis while reducing stomatal opening.

2.5. Light Intensity: Light intensity is the important abiotic factors essential for photosynthesis. Long-term light intensity accelerates photosynthesis and supplied the energy required for growth and development of plants. Light intensity is highly influenced by environmental factors and affecting chlorophyll synthesis, seed germination, flowering, anthesis and other responses related to photoperiod. Therefore, adequate light intensity promotes proper growth and development of plants for crop sustainability.

2.6. Soil Nutrients: Nutrients are fundamental requirement of the plants for normal growth and development. Deficiencies of nutrients are expressed as symptoms on the external organs of the plants can be easily visualized. Due to lack of the proper supply of nutrients, most of the metabolic activities of the plants related to growth and development affected. Some nutrients required in large quantity are called macronutrients, whereas some are also essential but requires in limited amount are considerable known as micronutrients (Jedmowski, et al., 2015). The major essential nutrients vita for physiological and biochemical prioresses are illustrated below.

2.6.1. Macronutrients for plants: Macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium and sulfur. These elements are required by plants in large quantity for their proper growth and development. Nitrogen (N) is most important elements essential for chlorophyll formation and promotes photosynthetic efficiency, whereas phosphorus (P) accelerates rood development and energy transfer. Potassium is another essential element enhances stress tolerance by water balancing. Additionally, calcium (Ca) for cell wall, magnesium (Mg) for chlorophyll and sulfur (S) is necessary for enzymatic function and protein synthesis.

2.6.2. Micronutrients for plants: Micronutrients required minimum amount for plant growth and metabolism. Iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) and boron (B) involved in the chlorophyll synthesis, enzyme activity, nitrogen and phosphorus metabolism, reproductively and cell wall formation respectively. Deficiency of these elements can affect photosynthesis and economic yield of the plant.

2.7. Interaction of Abiotic Factors: Abiotic factors affect every stage of the growth and development of plants including seed germination, tillering/branching and reproductive stage. Most of the abiotic facts are related to multilayered environmental conditions rather than single factors (Prasad, et al., 2011). Key environmental factors include salinity, light intensity, temperature, water availability, and soil nutrients. Thus, effective management of these factors is very important for accelerating crop yield by maintaining plant health may support to the agricultural sustainability for insuring global food security under adverse climatic conditions.

3. Biotic Factors Influencing Plant Performance

Biotic factors are governed by insects, pests and pathogens that interact with plant organs in term of positive or negative interaction. Rather than these factors, weeds are also challenging for crop production up to certain level. Harmful interaction of plants with pathogens reduces plant growth, nutrient availability and yield by damaging plant tissues. Most of the biotic factors affecting plant organs and reducing yield are discussed here.

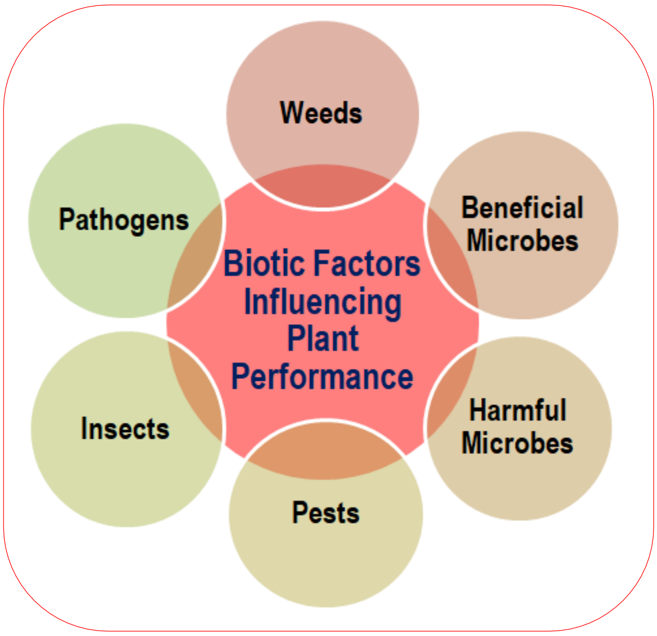

Fig.2: Biotic factors affecting plant performance.

3.1. Weeds: Some unwanted plants grow in the field with agricultural crops and compete with crops by utilizing soil moisture, water, soil nutrients, sunlight, and space are denoted as weed. Certain weed species exhibit allelopathy, releasing chemical substances into the environment that suppress the germination, growth, or development of nearby plants. Thus, effective management of these unwanted plants is essential for reducing losses, increasing crop performance and insuring production sustainability.

3.2. Insects: In nature both beneficial and harmful insects are available. Pollinators support plant reproduction and enhance crop yields by facilitating fertilization. Conversely, herbivorous insects damage leaves, stems, roots, flowers, and fruits, reducing plant vigor and productivity. Severe infestations can weaken plants, impair growth, and increase susceptibility to diseases and environmental stresses, ultimately affecting agricultural production and ecosystem health. Natural enemies of pests, such as predators and parasitoids, help control harmful insect populations. Decomposer insects aid in breaking down organic matter, recycling nutrients, and improving soil fertility, supporting sustainable plant growth. Harmful insects negatively affect plant growth by feeding on various plant parts. Such damage

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reduces plant vigor, lowers yields, and often creates entry points for pathogens, increasing disease susceptibility.

3.3. Pests: Pests, including insects, rodents, birds, and other animals, damage plants by feeding on tissues or spreading diseases. Pests cause significant agricultural losses through direct feeding injury, which damages plant tissues and reduces growth. Integrated Pest Management (IPM) is widely adopted as a sustainable approach that combines biological, cultural, mechanical, and chemical methods to effectively manage pest populations while minimizing environmental impacts.

3.4. Pathogens: Organism like viruses, fungi, bacteria and nematodes infect plants and disrupt physiological and biochemical functions are considerable called as pathogens. The infection caused by these organisms reduces crop growth and decrease economic yield. Most of the pathogens are infectious in nature and spread rapidly in the nearby areas. Some of the microbes are soil borne in nature and creating challenges for agricultural production and food security. Use of disease resistant crop cultivars and effective cultural practices can minimize the pathogen-related losses. Additionally, crop rotation, sanitation practices and biological control agents help to reduce disease incidence and minimize crop losses (Scherm and Coakley, 2013).

3.5. Beneficial Microorganisms: Beneficial microorganisms enhancing plant growth, productivity and soil health. Some of the microorganism found symbiotic with plant roots accelerates physiological and biochemical processes. Nitrogen-fixing bacteria are one the example of beneficial microorganism convert atmospheric nitrogen into plant viable form and enhancing soil fertility. Plant Growth-Promoting Rhizobacteria (PGPR) produces hormones are viable for plants.

3.6. Harmful Microorganisms: Harmful microbes, including pathogenic bacteria, fungi, and other microorganisms, adversely affect plant health and agricultural productivity. These organisms infect various plant parts such as roots, stems, leaves, and fruits, disrupting normal physiological functions (Allah, et al., 2010). Their presence often results in symptoms including wilting, leaf spots, rotting, chlorosis, and stunted growth. Harmful microbial infections can reduce photosynthesis, destroy plant tissues, impair nutrient and water transport, and ultimately lower crop yields.

4. Interactions between Abiotic and Biotic Factors

Plants are rarely exposed to a single stress factor; instead, multiple biotic and environmental stresses often occur simultaneously. Drought may increase vulnerability to insect attacks, high temperatures can promote pathogen growth, nutrient deficiencies may weaken disease resistance, and salinity can alter microbial communities. These combined stresses frequently produce effects different from those caused by individual factors. Biotic components such as weeds, insects, pests, pathogens, and microbes interact in complex ways, influencing plant health and productivity. Beneficial organisms can enhance resistance, while harmful ones intensify stress. Understanding these interactions is essential for effective crop management, sustainable agriculture, and ecosystem conservation.

5. Physiological and Molecular Mechanisms of Plant Response

Plants developed complex defense mechanisms to survive in the diverse environment by facing various stresses. Some signaling molecules like calcium ions, reactive oxygen species (ROS), nitric oxide, and various plant hormones are found defensive when plants subjected to adverse environmental conditions (Tyagi, et al., 2022). For example; Abscisic acid (ABA) promotes drought tolerance by inducing stomatal closure, Salicylic acid (SA) increases resistance against pathogens and Jasmonic acid (JA) is associated with defense mechanism against insect herbivores. Additionally, ethylene contributes to stress adaptation and regulates senescence-related processes. Recent advances in genomics, molecular biology, and biotechnology have greatly improved the identification and characterization of genes associated with stress tolerance. Understanding these defense mechanisms provides valuable insights for developing resilient crop varieties capable of maintaining productivity under challenging environmental conditions and supporting sustainable agricultural systems.

6. Implications for Sustainable Agriculture

Understanding biotic and abiotic factors is fundamental for sustainable crop production and agricultural resilience. Climate-smart agriculture promotes drought-resistant varieties, efficient irrigation systems, and conservation practices to enhance adaptation to environmental stresses. Integrated Pest Management combines biological control, cultural practices, resistant cultivars, and responsible pesticide use for effective pest suppression (Balota, et al., 2005). Soil health management through organic amendments, cover crops, crop rotation, and microbial inoculants improves fertility and productivity. Additionally, precision agriculture employs advanced technologies for site-specific nutrient management, water optimization, early disease detection, and efficient resource utilization, supporting sustainable and productive farming systems.

7. Future prospective

Future research should prioritize understanding plant responses to combined biotic and abiotic stresses and exploring beneficial plant–microbe interactions to enhance resilience. Developing climate-resilient crop varieties through genomics, molecular breeding, and biotechnology will be essential for sustaining agricultural productivity. The integration of artificial intelligence and precision agriculture technologies can improve resource management, stress detection, and decision-making. Additionally, research should focus on promoting sustainability while maintaining high yields and environmental quality. Interdisciplinary approaches combining biology, technology, and agronomy will be crucial for addressing future agricultural challenges.

CONCLUSION

The dynamic interaction of abiotic and biotic factors directly governed plant performance and collectively affects growth, development by influencing physiological and biochemical processes. Most of the abiotic threats like water, temperature, salinity, CO2 concentration, light intensity regulates the plant life cycle. Similarly, the biotic threats such as insects, pests, diseases, and weeds may also affect plant health and hampers productivity. Therefore, understanding plant response to multiple and interacting stressors is viral for development of resilience and agricultural sustainability. Additionally, the precision agricultural practices can enhance the productivity by minimizing the impacts caused by environmental factors. So, integration of biotic and abiotic causes is very important for ensuring long-term ecosystem sustainability to ensure global food security.

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