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Discovering Plant Stress: Current Trends and Future Perspectives in Plant-Microbe Interactions

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Abstract. Many biotic and abiotic factors can cause stress in plants, posing a major problem for agricultural yields, environmental health and food security globally. Plant stress can be caused by a variety of factors, including drought, high temperatures, disease and environmental changes. Adverse outcomes include developmental delay, decreased yield and diminished quality, as well as increased plant susceptibility to pests and diseases. Traditional breeding methods, advanced biotechnology treatments, cultural practices and biochemical interventions are all used to reduce the effects of the disease. In the future, plant stress management will focus on the utilization of climate-smart agriculture, precision agriculture and cooperative studies, policies and industries. Understanding and effectively managing plant stress will help us achieve sustainable agriculture, improve food security and protect our delicate ecosystems. Examining the complex world of plant stress in this in-depth study, we examine its various causes, its negative consequences and the approaches currently used to minimize them.

Keywords: Abiotic, Biotic, Stress, Sustainability, Plant microbe interaction.

1. Introduction

Climate change is intensifying abiotic stresses including salt, drought, and high temperatures; these elements negatively affect plant health and agricultural output. Stressful plants have disturbances to their physiological systems, which reduces general vitality, yield, and growth. Along with global temperatures, the lack of water, and soil salinity, the frequency and intensity of these stresses are expected to rise and seriously jeopardize world food security[1].

Essential elements of sustainable agriculture are crop resilience and adaptation to demanding environmental conditions. Maintaining consistent food supplies and reaching agricultural sustainability depend on raising plant resistance to abiotic stresses. Resilient plants' capacity to survive temperature fluctuations, salt, and limited water supplies guarantees more stability in food systems and higher production[2].

Plant-microbe interactions are symbiotic relationships whereby the plants benefit from the microbes. Beneficial microbes necessary for enhancing plant development, nutrient absorption, and stress tolerance include rhizobacteria, mycorrhizal fungus, and endophytes. These bacteria are possible partners in the management of abiotic stresses in plants since their capacity to influence plant stress responses, boost nutrient and water absorption, and generate compounds that reduce stress. Furthermore, will be discussed about the most recent discoveries and creative methods using plant-microbe interactions to alleviate abiotic stress. Talking about the several beneficial bacteria, their purposes, and approaches to handling issues including drought, extreme heat or cold, and salt. The assessment will also include new advancements in the technology and possible future directions of this field [1].

2. Major Abiotic Factors Affecting Plants

Among abiotic stresses that seriously affect plant development and output are drought, salinity, and very high or low temperatures. Drought stress brought on by water shortage results in dehydration and disturbed physiological processes. Salinity stress caused by high soil concentrations of soluble salts throws off osmotic control and ion balance. Extreme temperature fluctuations affect cellular integrity and metabolic activities including both heat and cold stress[2].

2.1 Salty Environment

In dry and semi-arid countries, soil salinity increases 1% to 2% of fertile land annually, particularly in dry and semi-arid areas. Salinity affects 20% of agricultural regions and 7% of the planet. When soil electrical conductivity (EC) reaches 4 dS m^{-1} (40 mM NaCl), crop yields significantly decrease. Osmotic pressure is about 0.2 MPa. Global agriculture is limited by soil and irrigation water salinity[3].

Salinity lowers yield by affecting plant growth and development. In plants, it alters physiology, morphology, and metabolism among other things. Plants modify their shape, interact with water, photosynthesis, hormone profiles, ion distribution, and antioxidative reactions among other defense mechanisms against salinity [4]. While length of exposure, degree of salinity, and stage of plant development all influence the expression of these antioxidants, enzymes are crucial in mitigating the consequences of saline stress. Different plants are classified based on their salt tolerance level. Glycophytes find high amounts of salt tolerable; doses of NaCl between 100 and 200 mM either completely stop their growth or only slow down its growth. Halophytes, on the other hand, can tolerate large quantities of NaCl (300–500 mM) because of their special salt resistance systems. Halophytes control salt stress by means of processes comprising salt exclusion, removal, succulence, and redistribution [5].

2.2 Drought as Stress

Drought, sometimes referred to as water stress, is one of the most severe environmental conditions affecting crop yields and plant development. Among the several factors are extreme heat, strong light, little precipitation, and salinity. Commercial crops including rice, wheat, and maize are particularly sensitive to drought stress in a warmer climate, which causes significant output declines [6]. It affects plant photosynthesis, nitrogen absorption, and water relations. However, many plant species have developed morphological, physiological, and biochemical adaptations to thrive in arid environments due to drought defense mechanisms. Drought-resistant plants have evolved to avoid or withstand drought stress. A plant avoids drought and stress by finishing its life cycle before a drought. Rapid phenological development allows plants to grow and set seed before soil dries. Developmentally flexible plants grow little and produce few flowers and seeds when dry, but they grow much and produce many seeds when wet[6].

Plants can sustain higher tissue water levels in spite of decreased soil moisture by avoiding drought. One can help to reach this by using water-saving strategies including reducing leaf area and closing stomata to stop water loss. Among water-spending strategies are efficient water movement and large root systems meant to maximize water intake. These strategies show the range of ways in which plants have evolved to cope with water shortage, so allowing them to survive and procreate even in demanding environments [6].

2.3. Temperature as Stress

For higher plants, cold temperatures represent a serious environmental stressor in addition to drought stress. Based on the surrounding temperature, low-temperature stress is categorized as either freezing stress (0°C) or chilling stress (around 20°C). This stress impacts plant development and growth, as well as the plants' geographic dispersion[7] . Usually unable to acclimate to low temperatures, tropical or subtropical plants are sensitive to chilling stress. In addition, temperate plants that undergo a process known as cold acclimation can survive freezing temperatures once they have been in a non-freezing environment. Early spring and winter cold stress can be avoided by these plants, which also resist seasonal temperature swings. Plants react to cold stress by means of complex metabolic changes that protect cells from damage resulting from low temperatures [8]. Plants can tolerate freezing or extremely cold temperatures because signaling cascades cause the expression of genes that are sensitive to cold. Chilling tolerance is strongly linked to the increased antioxidant enzyme activity. Chilling causes oxidative stress, which results in lipid peroxidation and chlorophyll loss. Furthermore, plants under cold stress have altered morphology, which decreases growth and decreases yields.

2.4. Heavy Metal & Stress

Human activity, industrial waste, and sewage disposal have combined to accumulate heavy metals including iron (Fe), manganese (Mn), copper (Cu), nickel (Ni), cobalt (Co), cadmium (Cd), zinc (Zn), mercury (Hg), and arsenic (As) in soils (Mitra et al., 2022). This pollution has gotten worse since the industrial revolution, which has spurred more scientific research in response. Heavy metals cannot be disappeared from the environment by nature since they are not biodegradable. Some are mobile and can be absorbed by diffusion, endocytosis, phagocytosis, or metal transporters; others stay stationary at the accumulation site. Mostly found in soil, these metals are consumed by plants and then enter the food chain [9] [10].

While some metals, including zinc, copper, and nickel, are essential micronutrients in trace levels and function as cofactor for some enzymes, some metals—such as lead (Pb) and cadmium (Cd)-which are present in pesticides have no use and become harmful above certain thresholds. Nutrient imbalance and shortage result from heavy metal interference with the distribution and absorption of essential nutrients. They also negatively impact biomass, photosynthesis, and plant development [11]. Reduced concentrations of heavy metals help plants avoid harmful effects. Elevated concentrations disrupt equilibrium and escalate the generation of reactive oxygen species (ROS) within plant cells. Redox-cycling reactions involving redox-active elements such as Fe, Cu, and Cr can result in the production of harmful hydroxyl radicals that cause harm to living cells. Different heavy metals are naturally bioaccumulated by plants from the soil and water.

Different types of plants have different rates of heavy metal accumulation and tolerance[12]. The symptoms of toxicity can include browning of the roots, decline, death, and chlorosis. Oxidative stress is exhibited by plants, which produce heat-shock proteins, hormones, antioxidants, and stress-related proteins. By detoxifying the metals or lowering their uptake, a variety of stress-resistance systems assist in preserving metal homeostasis and shielding plants from the toxicity of heavy metals. Cellular and root exudates serve as the initial line of defense, keeping metals out of the cell. Additionally, plants have special mechanisms for enclosing metal ions in compartments, so they are not exposed to delicate biological components. The secondary defense mechanism is detoxification, which includes metal sequestration, transport, and chelation [13].

2.5 Nutrients Deficiency as a Stress

Whether the soil is nutrient-rich or nutrient-poor, plant growth and development are inhibited by nutritional inadequacy. A number of variables, including soil salinization, competitive ion absorption, and ion transport or partitioning within the plant, may contribute to this imbalance. These problems may deactivate the physiological function of some nutrients, hence elevating the body's need for particular vital elements[14]. Much of the nutrients in the soil are insoluble in precipitates or bound to organic and mineral components, making them unavailable to plants. Unbalances in essential elements impair plant fitness by damaging plant cells and interfering with feeding and water retention. This can lower the general health and productivity of plants as well as cause a number of physiological diseases[15].

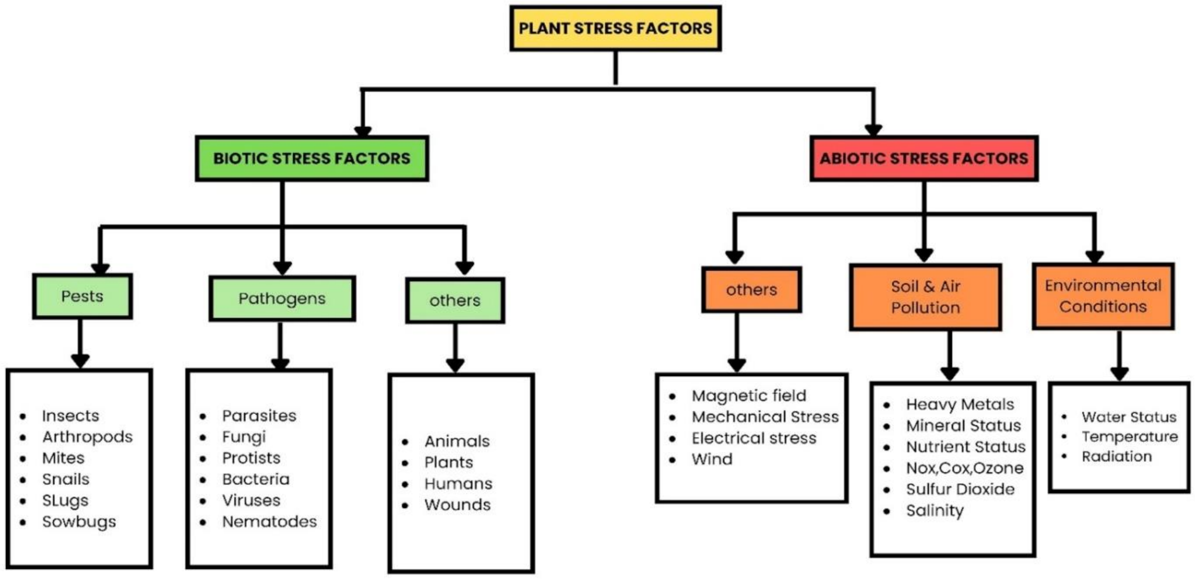

Fig. 1. A flow chart summarizes stress factors in plants.

3. Impact of Abiotic Stresses on Plant Physiology and Productivity

Drought, cold, excessive salt, heat, and other environmental conditions are examples of abiotic stresses that have a substantial impact on plant physiology and productivity, which lowers agricultural yields and quality. These stresses have an impact on several areas of plant metabolism, including as photosynthesis, water metabolism, substance and energy metabolism, and nutrient absorption, which in turn affects the general growth and development of plants[6]. Global food security is seriously threatened by the rising frequency and intensity of abiotic stresses brought on by climate change, which makes it necessary to develop techniques to increase plant productivity and stress tolerance. Comprehension of the molecular mechanisms, gene connections, and metabolic pathways involved in plant responses to abiotic stressors is essential to reducing the negative impacts on crop yield and guaranteeing sustainable farming methods in the face of shifting environmental circumstances[16].

Elevated soil salinity hinders plant development by influencing ion balance and water absorption. Osmotic stress is a result of the osmotic environment that saline soils create, which makes it harder for plants to absorb water. Furthermore, plants may be poisonous to excessive quantities of salts, especially sodium and chloride ions, which can cause ion toxicity and disturb cellular functions. The plant's capacity to absorb water and vital nutrients is diminished by this stress, which has an impact on cellular processes and the general health of the plant. Ion toxicity and osmotic stress together dramatically lower crop output and, in extreme situations, can kill plants [17].

Plant development patterns, enzyme activity, and metabolism all change with temperature-high and low. Through denaturing proteins, inactivating enzymes, and raising respiration rates, heat stress can cause energy depletion and cellular damage. High temperatures can induce oxidative stress as well as damage membrane integrity and encourage the synthesis of reactive oxygen species (ROS). But cold stress reduces enzyme activity, changes membrane fluidity, and damages the photosynthetic machinery-all of which impedes photosynthesis. Temperate plants experience a process known as cold acclimation-which raises their tolerance to freezing temperatures—after being under non-freezing conditions. This mechanism comprises complex biochemical and physiological changes enhancing the plant's cold stress resistance.

Other abiotic causes including nutritional imbalances, UV radiation, and heavy metals also influence plant stress conditions. Heavy metals including cadmium, lead, and mercury accumulated in soils where they could be taken up by plants and turn dangerous by industrial activities. By interfering with important metabolic processes, reducing enzyme activity, and generating reactive oxygen species (ROS), these metals induce oxidative stress and cellular damage. Particularly UV-B radiation, damage to DNA, proteins, and lipids brought about by UV radiation can lead to the synthesis of protective chemicals known as antioxidants and flavonoids [18].

Plant growth and development are impacted by nutrient imbalances, whether they are caused by excess or insufficiency. For instance, although shortages directly restrict physiological processes reliant on specific nutrients, excesses of one vitamin can cause deficiencies in others by interfering with their absorption. Plants have developed a variety of defense mechanisms against these challenges, such as the activation of genes associated to stress response, the synthesis of stress-related proteins, and physiological modifications to preserve homeostasis and guarantee survival in challenging circumstances.

3.1 Physiological Adaptations

In order to deal with environmental stress, plants use a variety of coping mechanisms, such as osmotic balance, stomatal regulation, and modified growth patterns. The tiny holes called stomata on a leaf's surface regulate both water loss and gas exchange. Under stressful conditions, like drought or excessive salinity, plants modify the opening and closing of their stomata to limit water loss while maintaining vital gas exchange. Stomatal closure lowers transpiration, allowing the plant to store water.

While this process is necessary for maintaining moisture and preventing withering under demanding conditions, it may also limit the absorption of carbon dioxide, so affecting photosynthesis and growth. Plants pick osmolytes—like proline, sugars, and other appropriate solutes-to protect cellular integrity and function under stress. These molecules help to keep the appropriate osmotic pressure inside plant cells by clinging to water, so preventing dehydration. Osmolytes also help to stabilize proteins and membranes, so protecting cellular structures from degradation linked to stress. By synthesis and accumulation of these molecules, the plant reacts adaptively to osmotic stresses including drought and too high salinity [19].

Environmental stress often changes plant development patterns, which helps to more properly allocate resources. During a drought, for instance, plants may grow less leaves and extend their root systems to search for water in a larger volume of soil. In the same line, when a plant is nutrient-deficient, it can change its root architecture to increase nitrogen absorption. These stress-induced modifications help plants to maximize their resources, so guaranteeing their survival and development in the face of hardship. The capacity to modify growth patterns in response to stress is one of the most crucial features of plant resilience and adaptability. All things considered, these strategies enable plants to resist and adapt to a variety of environmental stresses, so ensuring their survival and effective reproduction under demanding conditions [20].

3.2 Biochemical Pathways and Antioxidant Systems

To reduce environmental stress, plants use several biochemical pathways and molecules including secondary metabolites, the glyoxalase system, and ascorbate-glutathione pathway. A cytotoxic result of metabolic stress, methylglyoxal needs to be detoxified and the glyoxalase system is crucial for this mechanism. Under many different pressures, including drought, salt, and heavy metal exposure, methylglyoxal can accumulate and damage cells. The glyoxalase system-which consists of the enzymes glyoxalase I and glyoxalase II-protects plant cells from damage and preserves metabolic equilibrium by transforming methylglyoxal into less toxic compounds like D-lactate. The plant must undergo this detoxifying process if it is to survive in demanding conditions [21].

A key element of the plant's antioxidant defense system is the ascorbate-glutathione pathway, which focuses on scavenging reactive oxygen species (ROS) produced under stressful circumstances. Lipids, proteins, and nucleic acids can sustain oxidative damage due to ROS, which include superoxide radicals, hydrogen peroxide, and hydroxyl radicals. Ascorbate (vitamin C) and glutathione (GSH) work together in a sequence of processes known as the ascorbate-glutathione pathway to neutralize reactive oxygen species (ROS). Enzymes that are important for preserving the redox equilibrium and shielding biological constituents from oxidative damage include ascorbate peroxidase, glutathione reductase, and dehydroascorbate reductase [22].

A wide range of secondary metabolites, including phenolics, alkaloids, terpenoids, and flavonoids, are also produced by plants and play important roles in stress tolerance. These substances have a variety of uses, such as signaling molecules, UV protectors, and antioxidants. For example, flavonoids and phenolics can directly scavenge ROS and improve the antioxidative ability of the plant. Additionally, they support the structural integrity of cell walls, which increases a plant's resistance to environmental stressors and pathogen attacks. Secondary metabolites also have the ability to alter a plant's growth and development, which helps the plant respond to stress. By working together, these biochemical processes and substances give plants the ability to efficiently control and lessen the effects of a range of environmental stressors, protecting individual cells and promoting overall plant resilience[23].

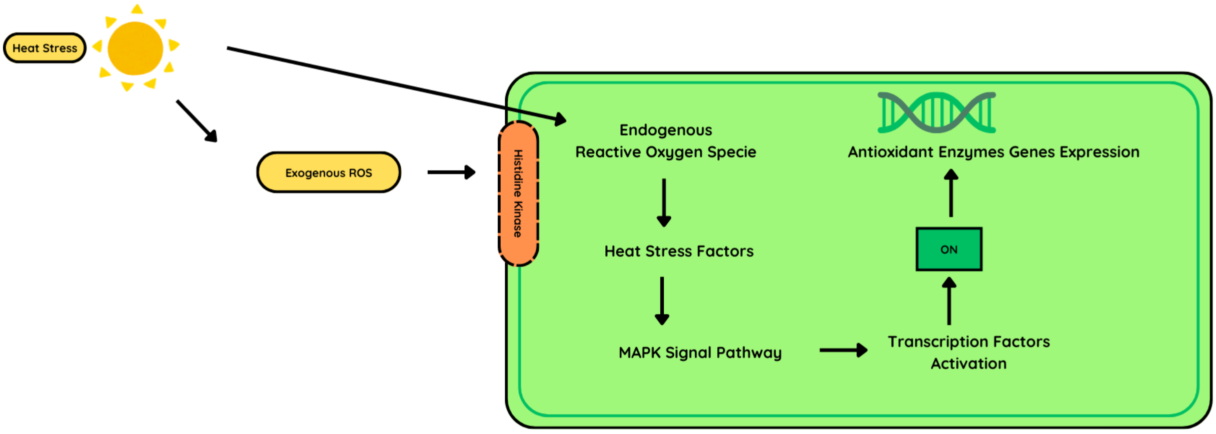

Fig. 2. Activation of Antioxidant genes due to heat stress.

3.3 Molecular Mechanisms

Plants use a variety of genetic techniques to increase their resistance to environmental stress. Stress-responsive genes are either up- or down-regulated in a basic response known as gene expression regulation. Plants can adjust through the production of proteins and enzymes that lessen the impacts of stress thanks to this regulatory mechanism. For instance, genes linked to osmotic balance and water retention become more active during droughts, improving the plant's capacity to store water and sustain biological processes [24].

This is further enhanced via genetic engineering, which modifies gene expression on purpose to increase stress tolerance. Certain genes can be added to plants or altered by scientists to provide them tolerance to environmental challenges like salt, drought, and high temperatures.

For example, overexpression of genes encoding Osmo protectants, such trehalose or proline, can increase a plant's ability to withstand drought. In a similar vein, genes that promote the synthesis of antioxidant enzymes can be added to a plant to increase its ability to combat reactive oxygen species produced under stress [25].

Advanced methods for comprehending stress-related gene expression on a broad scale are offered by transcriptomic analysis. The entire transcriptome, or the total collection of RNA transcripts generated by the genome, can be examined by researchers to determine which genes and how they are regulated are involved in stress reactions. The identification of novel genes and regulatory networks that are essential for stress adaptation is made possible by this high-throughput method. Through genetic engineering and breeding programs, insights from transcriptome analysis can be used to create crops that are more resilient to stress. When combined, these genetic techniques allow for a more thorough comprehension and accurate control of how plants react to environmental stress, which eventually leads to more resilient and sustainable farming methods [26].

4. Plant-Microbe Interactions

When the term "microbiome" was initially coined, it was used to characterize a unique microbial population with particular physical and chemical characteristics found in a particular habitat. Different definitions of the microbiome have evolved throughout time, from those that concentrate on the genomes and patterns of gene expression of microorganisms to those that take into account the ecological context and interactions between microbes and their surroundings. The Phyto microbiome is a dynamic and complex ecosystem, as evidenced by recent investigations, necessitating the development of new conceptual models and theories to better comprehend its diversity, interconnections, and roles[27].

Studies have demonstrated the importance of the Phyto microbiome, particularly in the rhizosphere zone—the area of soil that is immediately impacted by root secretions. This zone's microorganisms help plants establish roots by releasing hormones called auxins, collecting iron from the soil to solubilize phosphorus, and making more nutrients available to plants[28]. In addition to triggering defensive responses to shield plants from infections, nitrogen-fixing bacteria are essential for raising primary productivity in plants. Hence, microbial communities known as Phyto microbiomes offer a variety of advantages to the plants they inhabit.

Plant microbiome interactions involve a wide range of beneficial bacteria that are essential for the growth and well-being of plants. Arbuscular mycorrhizal fungi (AMFs), plant-growth-promoting rhizobacteria (PGPRs), and endophytes are examples of plant growth-promoting microorganisms (PGPMs). Legumes and rhizobia work together symbiotically to fix nitrogen, and mycorrhizae help plants absorb more water and nutrients. Furthermore, endophytic bacteria and fungi inhabit different sections of plants, affecting the fitness of the host through mutualistic, parasitic, or commensal relationships. These advantageous microorganisms support the improvement of plant defense systems, the reduction of abiotic stresses, and the sustainability and productivity of agriculture as a whole. The significance of these bacteria in sustainable agriculture techniques is highlighted by the fact that their interactions with plants are critical for nutrient uptake, stress tolerance, and disease resistance. Here are some ways in which Phyto microbiomes influence plant health and productivity:

4.1 Nutrient Acquisition

Microbes help plants obtain important nutrients that are necessary for their growth, such as phosphate and nitrogen. Numerous bacteria are responsible for fixing atmospheric nitrogen and transforming it into forms that plants can use, which is essential for the growth and development of plants. Furthermore, several bacteria solubilize phosphorus in the soil, increasing plant availability. Plant growth and primary production are enhanced by these interactions[29].

4.2 Plant Growth Promotion

Microbes secrete substances that promote plant growth and development, primarily hormones and enzymes. Auxins, for instance, are produced by specific bacteria and encourage the growth of roots. Certain bacteria release enzymes into the soil that decompose complex organic substances and make them available to plants, encouraging both upward and lateral plant development[30].

4.3 Disease Suppression

Certain microbes produce antibiotics or outcompete plant pathogens for resources, protecting plants from disease. Certain fungal species, for example, invade plant roots and protect them from infections. The health and production of plants are enhanced by this natural defense system[31].

4.4 Environmental Stress Tolerance

Supporting plant resilience to environmental stress is largely dependent on the phyto microbiome. Osmo protectants, such as trehalose or glycine betaine, are produced by some microbes and aid in the growth and development of plants in harsh environments such as droughts and high salinities. These osmoprotectants keep stress-induced cellular damage at bay and stabilize plant membranes[32]. Additionally, several microbes create substances like antioxidants or phytohormones that aid plants in surviving environmental stress. Gaining an understanding of these relationships can help with the development of methods that improve plant productivity and resilience in difficult environmental situations[33].

5. Microbial Strategies for Stress Management

By scavenging damaging ROS in a variety of ways, plants use antioxidant enzymes to minimize oxidative stress and withstand salt stress. These enzymes employ electron donors to dismutate superoxide into hydrogen peroxide and oxygen, and then use thiol-mediated pathways with nucleophiles like glutathione (GSH), thioredoxin (TRX), or glutaredoxins (GRX) to convert hydrogen peroxide to water[34].

5.1 Role of Specific Microbes in Enhancing Water Uptake and Retention

Plants that experience hyperosmotic stress and water shortage are caused by high soil salinity, which is elevated by prolonged irrigation, insufficient rainfall, and soil weathering. Certain plants that can withstand drought and salinity produce and store osmolytes like proline or raffinose, which scavenge reactive oxygen species (ROS), stabilize proteins, and maintain cell turgor pressure by osmotic adjustment[35]. While Lobularia maritima collects and detoxifies salt through compartmentalization, some halophytes, including Thellungiella halophila, fight salt stress by blocking salt entrance through membrane filtration. In order to withstand drought and salinity stress, succulents belonging to families such as Aizoaceae, Cactaceae, and Crassulaceae display morphological traits such as thick, fleshy stems, decreased stomata, Crassulacean acid metabolism (CAM), and waxy or prickly exterior surfaces[36].

The majority of crops do not have well developed morphological or physiological traits to endure unfavorable drought conditions. But by generating plant growth regulators or hormones like cytokinin (CK), gibberellin (GB), indole-3-acetic acid (IAA), salicylic acid (SA), abscisic acid (ABA), and jasmonic acid (JA), root-associated microorganisms can help plants withstand drought and salinity stress[37]. These hormones enhance photosynthetic capacity, membrane stability, root system growth, and nutrient uptake while decreasing oxidative stress damage. They also boost plants' ability to produce exopolysaccharides and accumulate suitable osmolytes. In agriculture, using beneficial microorganisms that can withstand salinity and drought can help plants become more resilient to stress and produce higher-quality crops[38].

For farmers in sub-Saharan Africa who frequently experience droughts, drought-tolerant maize varieties (DTMVs) offer a promising adaptation method that could improve agricultural sustainability. DTMVs are not commonly grown despite their advantages, and their financial benefits are not entirely recognized. This study assesses the scalability of direct seed marketing initiatives (DTMVs) in Tanzania under three conditions: seed availability, affordability, and DTMV awareness. The economic surplus model, which makes use of household production and consumption data from important regions of Tanzania, projects that by 2032, the adoption of DTMV might result in cumulative gains for producers and consumers of up to $499 million, with the ability to raise 1.6 million people out of poverty. 60% of the advantages would go to producers and 40% to consumers, with considerable gains going to important maize-producing regions, like Dar es Salaam[39]. The cities of Dodoma, Geita, Simiyu, Singida, and Kagera would yield the maximum returns on investment. These results confirm that in order to expand DTMVs in Tanzania, both governmental and private investment is required[40].

As indicated by current research findings. Research conducted in Iraq has discovered particular varieties of wheat, such as Iraq, Tamoz, and Abba-99, that are able to withstand drought conditions[41]. These varieties have been found to exhibit various patterns of gene expression in response to different levels of drought stress. Maize varieties in Iran exhibited varying responses to drought stress, with Maxima demonstrating superiority in terms of fodder quality attributes when faced with limited water availability. This emphasizes the significance of carefully choosing suitable varieties for places prone to drought. Maize plants subjected to drought circumstances displayed modified distribution of biomass, with roots and fruits exhibiting higher biomass[42]. This suggests that the plants have adopted adaptive techniques to promote growth in response to stress. Furthermore, a study conducted on oat-maize hybrids exposed to drought stress demonstrated notable decreases in the amount of photosynthetic pigments and attributes associated to crop productivity. This highlights the intricate relationship between genetic backgrounds and environmental pressures in how crops respond to drought.

5.2 Mechanisms Through Which Microbes Help Plants Cope with High Salinity

A study compared the responses of two rice genotypes, BRRI dhan29 (salt-sensitive) and BINA dhan-10 (salt-tolerant), to varying levels of salt stress at the vegetative stage. BINA dhan-10, the salt-tolerant variety, demonstrated higher salt tolerance in physiological parameters compared to BRRI dhan29. Both genotypes experienced significant reductions in growth, yield components, and grain and straw yields due to salt stress. Additionally, nutrient uptake (NPS) and the K+/Na+ ratio decreased significantly in both genotypes under different salt stress conditions. However, BINA dhan-10 maintained a higher K+/Na+ ratio compared to BRRI dhan29, indicating more effective salt tolerance mechanisms. Overall, the findings suggest that salt stress adversely affects growth, yield, and nutrient uptake in rice genotypes, with the salt-tolerant BINA dhan-10 exhibiting better resilience to salinity stress compared to the salt-sensitive BRRI dhan29[43].

The growth of *Gracilaria birdiae*, a type of macroalgae, is greatly affected by salinity. The study has determined the specific limits of salinity that the macroalgae can tolerate. The growth of G. birdiae is adversely affected by salinity levels of 0 and 60 ppt, but salinities ranging from 20 to 50 ppt are most conducive to its development. The growth of the species is negatively impacted by lower salinity levels of 0 and 10 ppt, showing its susceptibility to these circumstances. The results indicate that *G. birdiae* thrives best within a salinity range of 20 to 50 ppt[44]. This information provides significant knowledge for the possible cultivation of *G.*

birdiae in either monoculture or multitrophic systems. This study emphasizes the significance of salinity as a critical element in regulating the growth of *G. birdiae* and emphasizes the necessity of carefully controlling salinity levels in the cultivation of this macroalgae species[44].

5.3 Microbial Contributions to Heat and Cold Tolerance in Plants

Research on plant responses to saline-alkali stress has made progress, underlining the need for more research. Although genes implicated in plant responses to saline-alkali stress have been identified, little is known about how plants perceive this stress. Understanding how plants detect variations in HCO3−/CO32− levels is vital for identifying saline-alkali stress sensors. Saline-alkali stress causes ion toxicity because plants accumulate more Na than salt stress. Identifying Na transporters unique to this stress is crucial[45]. The research examines how NHX proteins promote salt tolerance in plants, but the methods by which they respond to saline-alkali stress are unknown. Saline-alkali plants have metabolic problems from oxidative stress. ROS scavenging systems safeguard the plant's metabolic activities and reduce oxidative stress[46][47]. In addition, cold-adapted bacteria utilize strategies such as the production of cryoprotectants and cold shock proteins to endure high temperatures and enhance agricultural output. Psychrophilic and psychrotolerant phosphate-solubilizing bacteria (PSB) have demonstrated potential in improving low-temperature conditions and promoting plant growth by providing vital nutrients such as phosphorus. Microbial interactions are crucial for enhancing plant tolerance to temperature extremes, providing essential knowledge for devising solutions to alleviate the negative impacts of climate change on crop yield.

5.4 Stresses Like Heavy Metal Toxicity and Their Microbial Mitigation Strategies

Heavy metal poisoning is a notable yet frequently disregarded form of abiotic stress. Specific microorganisms possess the ability to neutralize heavy metals and mitigate their harmful impact on plants. These microorganisms capture, convert, or immobilize heavy metals, thereby decreasing their capacity to enter living organisms and their harmful effects[48][49]. Phytoremediation is highly efficient in the process of isolating, removing, or neutralizing metal contaminants. Plants utilize many tactics, including as storing harmful metals in their cells and tissues, releasing anions to limit metal mobility, or transforming metals into non-reactive forms. Plants such as Polygonum sachalase, Thlaspi, Chenopodium, Urtica, and Alyssim have the ability to gather and store metals such as Cd, Cu, Ni, Pb, and Zn. This approach offers several benefits as it is cost-effective, does not necessitate the use of costly equipment, and minimizes soil erosion caused by water and wind. Nevertheless, it is a more time-consuming procedure that is not ideal for rapid cleaning and is constrained by seasonal and temperature variations. Microbial remediation utilizes the interactions between microorganisms and metals, with a specific emphasis on converting the metals rather than breaking them down. Microorganisms have the ability to convert metals or metalloids into forms that can dissolve in water, potentially causing leaching. Microorganisms frequently come into contact with a variety of metals, such as vanadium, manganese, chromium, copper, cobalt, nickel, molybdenum, lead, silver, iron, zinc, gold, arsenic, antimony, and selenium. These metals, commonly found in the form of cations, oxyanions, oxides, or salts, perform multiple purposes in microorganisms[50]. These tasks include providing structural support, acting as catalysts, donating or accepting electrons, and serving as important nutrients. Microorganisms require several essential metals, such as calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), potassium (K), magnesium (Mg), manganese (Mn), iron (Fe), sodium (Na), zinc (Zn), and nickel (Ni)[51]. These metals play a critical role in catalysis, stabilizing protein structures, maintaining cell wall integrity, and regulating osmotic balance. In contrast, non-essential metals such as aluminum, cadmium, silver, gold, mercury, and lead do not serve any biological function. Anthropogenic activities have caused a rise in the pollution of the environment with heavy metals, which has posed difficult circumstances for bacteria[52]. Consequently, bacteria have developed ways to resist these conditions. These systems aid bacteria in regulating the concentration of harmful metals within their cells. The resistance to metals is frequently associated with antibiotic resistance and can be spread together through horizontal gene transfer, as metal resistance is typically carried on plasmids. Gaining a comprehensive understanding of these interactions and mechanisms is of utmost importance in order to make progress in bioremediation approaches and effectively reduce environmental contamination[53].

A study compared biological and nonbiological approaches for protecting soil quality at a former Manufactured Gas Plant (MGP) site, focusing on the effectiveness and cost-efficiency of two technologies. The results demonstrated that biological strategies, particularly phytoremediation, were highly efficient with minimal disturbance to the surrounding areas. Phytoremediation proved to be a suitable and cost-effective method for remediating MGP sites contaminated with multiple metals[54]. The study underscored the importance of considering biological interventions like phytoremediation as viable solutions for soil reclamation at heavy metal-contaminated sites. Overall, the findings suggested that biological remediation techniques could be advantageous in addressing soil pollution issues caused by co-contamination at MGP sites, offering a promising approach for sustainable soil quality protection. A green technology, for remediating contaminated soil and water ecosystems by leveraging plant-microorganism interactions. Rhizospheric microorganisms, such as bacteria and fungi, play a crucial role in removing noxious contaminants from polluted soils by accumulating, transforming, or detoxifying toxic substances[55]. The study highlights microorganism-assisted phytoremediation as a safe and innovative method for addressing toxic substances, where rhizosphere microbes aid plants in tolerating metal-induced toxicity and promoting growth. Emphasizing the importance of understanding heavy metal-induced toxicity, microorganism-plant interactions, and the role of microorganisms, the paper underscores the potential of plant-based reclamation for contaminated soils[56].

6. Innovative Approaches and Technologies

6.1. Development and Application of Microbial Consortia as Bioinoculants

Plant stress tolerance is being improved by the development of bioinoculants, which consist of helpful microbial consortia. These consortia consist of various microbial strains that have complementary functions, resulting in a synergistic impact on plant growth and the ability to withstand stress. Recent progress has been directed towards improving the composition and practical use of these bioinoculants to achieve the highest level of effectiveness[57].

Recent progress has been made in creating bioinoculant formulations that guarantee the survival and effectiveness of microorganisms in real-world agricultural settings. Encapsulation and carrier-based delivery techniques have enhanced the stability and efficacy of microbial consortia. The efficacy of these bioinoculants in improving crop yield and resilience has been proven through field studies[58].

Currently, farmers are seeing a decline in agricultural crop productivity as a result of soil infertility and inadequate farming techniques. The utilization of chemical fertilizers has adverse effects on both soil fertility and human health[59]. The improper utilization of chemical fertilizers results in a swift decrease in production levels in numerous regions across the globe, hence requiring the implementation of sound farming techniques[60]. Biofertilizers, unlike chemical fertilizers, sustain soil fertility over an extended period of time. Consequently, their utilization is crucial for enhancing worldwide agricultural output. Implementing a low-input strategy is viable for attaining agricultural sustainability by utilizing biological and organic fertilizers [61]. This review examines the utilization of microbial inoculants and microbial consortia as biofertilizers for the purpose of improving crop yield, with a specific focus on their contribution to sustainable agriculture and soil well-being.

Studying the specific connections between microorganisms is crucial for developing a consortium that functions effectively. In several studies, researchers commonly employ in vitro 'dual-culture' methods to assess the compatibility between fungi and bacteria, specifically examining antagonistic activity. This approach involves the co-cultivation of two strains in Petri plates containing a culture medium to observe the presence of inhibition zones around the region where the two strains overlap and proliferate. The potential interactions identified using this approach encompass compatible mixtures, partially compatible mixes, invasion or replacement, inhibition at the contact point, and distant inhibition resulting from antibiosis. These interactions play a crucial role in assessing the possibility of developing efficient microbial consortia.

The United Nations' 2030 Agenda for Sustainable Development emphasizes the importance of attaining global well-being by implementing collaborative efforts and partnerships across different sectors to address worldwide issues. The Global Sustainable Development Report (GSDR 2019) emphasized the lack of sustainability in the existing development model, highlighting concerning patterns such as growing disparities, climate change, loss of biodiversity, and escalating waste levels[62]. Achieving the Sustainable Development Goals (SDGs) relies heavily on agricultural sustainability, as soil plays a crucial role in various biological processes that are critical for the health of the planet. These activities include nutrient cycling, waste decomposition, and nitrogen fixation[63].

6.2. Leveraging Genetic Engineering to Enhance Microbial Efficacy

Beneficial bacteria are being genetically engineered to improve their ability to withstand stress. Scientists can enhance the capabilities of microbial strains by including certain genes, resulting in improved production of stress-alleviating chemicals, nutrient solubilization, and interaction with plant roots. These genetically modified microorganisms present novel opportunities for enhancing the ability of plants to withstand stress[64]. In the face of climate change and a burgeoning human population, there is an anticipated surge in the global need for enhanced food output. Plant-microbial mutualism is essential for sustainable agriculture as it improves plant health and productivity while also providing resistance against both biotic and abiotic challenges [65].

The presence and makeup of microbiota contribute distinct attributes to the host plant, creating selective influence in both natural and controlled settings. A study elucidated the impact of rhizospheric microbial diversity in artificial ecosystems on plant provenance. Their study emphasized the significance of feedback mechanisms at the interface between plants, soil, and microbes in influencing the variation within plant species in depleted habitats. In a study conducted empirically proven that the opposite theory is true. They showed that the genetic makeup of plants can have an impact on the composition of rhizosphere microbiomes, leaving behind phylogenetic imprints. This discovery highlights the interaction between the effects of host genetics and environmental conditions in improving plant performance.

In the same way, modifying the cell walls of bacteria found inside bananas (Enterobacteriaceae) with 1-aminocyclopropane-1-carboxylate (ACC) deaminase has shown potential as a strategy to make bananas resistant to Fusarium wilt. A study was conducted where they examined the priority effects and keystone species in the phyllosphere of a gnotobiotic Arabidopsis model system using a synthetic microbial community. This approach facilitates the testing of fundamental principles that influence the organization of communities in the phyllosphere. Consequently, manipulating the many microorganisms that are linked to host plants is an essential process in comprehending the structure of microbiota and the roles of genes. Here are some strategies that can alter or design advantageous microbiome functions and services to guarantee plant productivity across numerous generations. Microbial communities that are connected with hosts establish mutually beneficial connections and display collective behaviors that have important consequences for human food security, biodiversity, and agricultural productivity. These interactions have an impact on the host's physiology and help to solve pressing environmental problems, which makes them a desirable focus for in situ microbial engineering.

The regular utilization of microbial communities as bioinoculants has been extensively recorded for their functions in mobilizing nutrients, enhancing stress tolerance, and stimulating plant growth. Studied have extensively emphasized these uses [66]. Study developed a group of phosphate rock-solubilizing bacteria to assess their ability to solubilize phosphate, produce biofilms, and colonize roots. Their investigation showed that selected biocompatible multispecies consortia can enhance the growth of maize seedlings in low-phosphorus soil amendments, as observed under greenhouse settings [67] Research examined the impact of bioinoculants on young oil palm plants. According to their findings, the use of microbial-based crop amendments successfully influenced the behavior and ability of microorganisms in the soil surrounding plant roots, leading to the growth of healthy oil seed crops.

It is crucial to incorporate reductionist methods, such as the vertical transmission of microbial species, in agricultural environments. This process enhances plant growth and development by strategically influencing genetic, biochemical, physical, and metabolic factors within the plant system[68].

Therefore, plant microbiome engineering presents an alternative yet largely untapped strategy that can significantly enhance plant health, growth, and productivity, especially under extreme conditions[69]. Recently, various accessible approaches have been proposed for plant microbiome. engineering One promising avenue is to leverage variations in plant exudation patterns to boost beneficial rhizosphere microbiomes[70].

The microbiome can be manipulated using conventional techniques, such as adding organic and inorganic supplements to the soil and implementing specific agricultural practices to enhance microbial diversity, functions, and interactions with the desired host[69]. The improvement of plant health and growth can be achieved by directing attention towards the living components of the rhizosphere. This is because the interactions between living organisms and their environment have a significant impact on these aspects[71]. In order to attain sustainable agricultural production, several cutting-edge tools could have a significant impact on the progress of microbial bioengineering, offering advantageous alternatives to detrimental agrochemical compounds. This method not only seeks to raise crop yields but also guarantees sustainable agriculture practices that safeguard and enhance soil health.

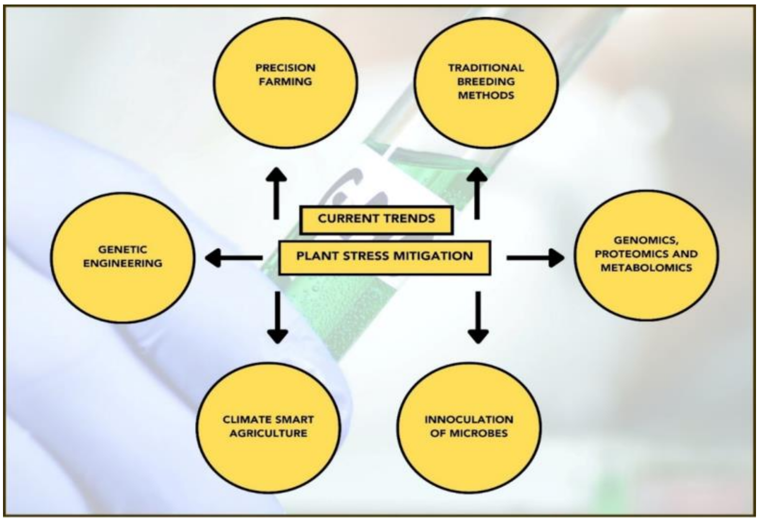

Fig. 3. Current trends used in plant stress mitigation.

6.3 Genomics, Proteomics, and Metabolomics Improve Plant-Microbe Interactions

Genomic, proteomic, and metabolomics tools reveal plant-microbe interactions. Genomics discloses advantageous features' genetics, proteomics finds stress-responsive proteins, and metabolomics tracks stress-induced metabolic alterations. These technologies are essential for studying plant-microbe molecular pathways and improving their efficacy [72].

Agriculture and food security are greatly affected by climate change and population increase. Agriculture is vital to economic prosperity, yet these variables may reduce global food production. Insufficient attention to contemporary technology and balanced fertilization has caused staple crop nutritional insecurity. These issues must be addressed for global food systems and climate resilience[73]. Recently developed omics methods can improve crop yield by studying plant-microbe interactions. Genomic, transcriptomic, proteomic, and metabolomics methods reveal these relationships' biochemical, physiological, and molecular aspects. Integrating multi-omics data improves biological process comprehension, especially under stress.

Ecosystem dynamics and sustainable agriculture depend on plant-microbe connections. Omics techniques disclose the molecular details of these symbiotic connections, shedding light on arbuscular mycorrhizal fungi-non-mycorrhizal microbe interactions. Understanding positive plant-microbe connections can alter sustainable agriculture with these technologies. Plant-microbe interactions in polluted rhizospheres trigger plant defense systems, according to multi-omics and bioinformatics. Understanding phytohormones and secretory metabolites can help create new microbial inoculants. Sequencing methods help study rhizosphere chemistry and plant response to environmental stress[74].

Integrating multiple omics strategies can overcome their drawbacks. This paper discusses how omics technologies have transformed plant-microbe interactions and ecosystem dynamics and sustainable agriculture. The review shows how omics technologies are used in nitrogen fixation, systemic resistance, mycorrhizal connections, and pathogen-host interactions by synthesizing studies. Data analysis and interpretation are easier using web-based omics technologies. Omics can increase crop quality, disease management, and sustainability while addressing data integration and ethics, revolutionizing agricultural practices.

3.3.1 Genomics

Genomic advances have revealed the complexity of plant-microbe interactions, which go beyond symbiotic partnerships to include many biotic interactions. Next-generation sequencing has made whole-genome sequences, de novo assemblies, and strain resequencing affordable. These technologies revealed the genetic mechanisms of nitrogen fixation and growth-promoting chemical production. Metagenomic methods reveal microbial community variety and function, illuminating their significance in plant health[72].

6.3.2 Epigenomics

Epigenomics is essential for investigating plant-microbe interactions through the examination of epigenetic modifications and genetic alterations in plants and microbes. This technique investigates heritable modifications in gene expression that occur without any changes in the DNA sequence. It provides valuable information about how organisms adapt to their environment and the impacts that can be passed down to future generations on the characteristics of plants and microorganisms[75]. Utilizing techniques such as EpiEffectors, targeted epigenome editing enables precise alterations to enhance plant tolerance against diseases and stresses.

6.4 Transcriptomics and Meta Transcriptomics

Transcriptomics, employing next-generation sequencing, uncovers gene expression patterns and sequences in biological samples, establishing connections between gene functions and specific situations[76]. This method offers valuable information about changes in regulation, careful examination of mutations, variations in gene expression, and alternate forms of splicing. Meta transcriptomics investigates gene expression in whole microbial communities, providing immediate information about mRNA expression in environmental samples [44]. These methods provide insight into the dynamic roles of microbial populations and their impact on the well-being of plants.

6.5 Proteomics and Meta Proteomics

Proteomic studies examine the genes that are actively being expressed, emphasizing the significance of proteins in microbial metabolic activities in various environments. Proteomic study provides valuable information about the maintenance of cellular balance, communication networks, and defense mechanisms in plant-microbe interactions[77]. Functional proteomics is a field of study that focuses on examining protein-protein interactions. This is done using methods such as the yeast two-hybrid system. By utilizing these approaches, researchers can gain significant insights into the activities and connections of proteins. Metaproteomic plays a crucial role in the research of soil fertility, nutrient cycling, and bioremediation. It provides valuable information about how microorganisms use carbon substrates and their involvement in interactions between plants and microbes.

6.6 Metabolomics

Metabolomics is a valuable technique for studying the interactions between plants and microbes. It offers both qualitative and quantitative information about the mechanisms involved in symbiotic relationships. Untargeted metabolomics is a method used to detect alterations in the levels of metabolites that are linked to the absorption of nutrients, reactions to stress, and the ability of plants to resist diseases[78]. This method uncovers the metabolic characteristics of plants and microorganisms during their interactions, which helps in the creation of efficient strategies for protecting crops.

Genomics, proteomics, and metabolomics are crucial in understanding the intricate relationships between plants and microorganisms. The omics techniques provide a thorough understanding of the biochemical, physiological, and molecular components of these interactions, offering vital information to improve plant health and productivity. By utilizing these technologies, scientists can create novel approaches for sustainable agriculture, enhancing crop quality, and controlling diseases. This eventually helps to ensure global food security and environmental resilience.

7. Conclusion

In light of climate change, plant stress management is essential for maintaining agricultural productivity. Pseudomonas, Bacillus, Burkholderia, and Trichoderma are examples of beneficial bacteria that improve plant health and stress tolerance. Sustainable agriculture is promoted by the economic and environmental advantages of using biofertilizers. The development of robust crops is aided by the insights that omics technology offers into the mechanisms behind stress tolerance. Sustainable agriculture requires a comprehensive understanding of the interactions between microbes and plants. Products like Acadian Plant Health^{TM} are examples of success stories that highlight useful advantages. Innovative farming methods and cutting-edge research can improve agricultural productivity and soil fertility while maintaining resilience against environmental pressures, even in the face of implementation obstacles.

7.1 Future Perspective

In the future, endophytic bacteria and fungi such as *Pseudomonas*, *Bacillus*, *Burkholderia*, and *Trichoderma* will be used in plant stress management and microbe interaction. These microorganisms support plant growth, stress tolerance, and heavy metal bioremediation. For sustainable agricultural practices to be established that can increase crop output in spite of climate change, an understanding of plant-microbe interactions under stress is essential.

In hostile conditions, beneficial microbes have evolved to preserve mutualistic relationships and shield plants from stress. Using omics to investigate the molecular basis of endophyte-mediated stress tolerance can aid in the development of crops that are climate resilient.

By assisting in the understanding of stress tolerance mechanisms and the development of crops that are climate-adaptive, omics techniques have also revolutionised agriculture. The epigenetic regulation of plants, which has been recently found in response to stress, may disclose genes or pathways that can be targeted for the advancement of agriculture and environmental sustainability. Microbial engineering and innovative farming techniques will boost plant resistance, production, and health, paving the way for international and sustainable agricultural practices.

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اكتشاف إجهاد النبات: الاتجاهات الحالية وآفاق المستقبل في تفاعلات النبات والميكروبات

ناديه السلمي

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المستخلص. يمكن أن تتسبب العديد من العوامل الحيوية وغير الحيوية في حدوث إجهاد لدى النباتات، مما يشكل مشكلة كبيرة للإنتاج الزراعي وصحة البيئة وأمن الغذاء على مستوى العالم. يمكن أن يكون إجهاد النباتات ناتجًا عن مجموعة متنوعة من العوامل، بما في ذلك الجفاف وارتفاع درجات الحرارة والأمراض والتغيرات البيئية. تشمل النتائج السلبية تأخر النمو، وانخفاض الإنتاجية، وتدهور الجودة، بالإضافة إلى زيادة تعرض النباتات للآفات والأمراض. تُستخدم طرق التربية التقليدية، وعلاجات التكنولوجيا الحيوية المتقدمة، والممارسات الثقافية، والتدخلات الكيميائية الحيوية جميعها لتقليل آثار الأمراض. في المستقبل، ستركز إدارة إجهاد النباتات على الاستفادة من الزراعة الذكية مناخيًا، والزراعة الدقيقة، والدراسات والسياسات والصناعات التعاونية. سيساعد فهم وإدارة إجهاد النباتات بشكل فعال في تحقيق الزراعة المستدامة، وتحسين الأمن الغذائي، وحماية نظمنا البيئية الحساسة. من خلال دراسة عميقة لعالم إجهاد النباتات المعقد، نستعرض أسبابها المختلفة، وعواقبها السلبية، والنهج المستخدمة حاليًا لتقليلها.

الكلمات المفتاحية: اللاحيوية، الحيوية، الإجهاد، الاستدامة، تفاعل النباتات والميكروبات.