**Microbes – A Biological Tool to Alleviate Abiotic Stress in Plants**

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**Abstract**

Crop yield is mainly influenced by climatic factors, agronomic factors, pests and nutrient availability in the soil. Stress is any adverse environmental condition that hampers proper growth of plant. Abiotic stress creates adverse effect on multiple procedures of morphology, biochemistry and physiology that are directly connected with growth and yield of plant. Abiotic stress are quantitative trait hence genes linked to these traits can be identified and used to select desirable alleles responsible for tolerance in plant. Plants can initiate a number of molecular, cellular and physiological modify cations to react to and adapt to abiotic stress. Crop productivity is significantly affected by drought, salinity and cold. Abiotic stress reduce

water availability to plant roots by increasing water soluble salts in soil and plants suffer from increased osmotic pressure outside the root. Physiological changes include lowering of leaf osmotic potential, water potential and relative water content, creation of nutritional imbalance, enhancing relative stress injury or one or more combination of these factors. Morphological and biochemical changes include changes in root and shoot length, number of leaves, secondary metabolite (glycine betaine, proline, MDA, abscisic acid) accumulation in plant, source and sink ratio. Proposed chapter will concentrate on enhancing plant response to abiotic stress and contemporary breeding application to increasing stress tolerance.

Keywords: Abiotic stress, Quantitative trait, Osmotic pressure, Cations, Abscisic acid.

**1. Introduction:**

Plants in their physical environment face several types of variation. Animals use techniques to prevent the impacts of this variation but plants fail because of the sessile nature of the growth habit. Plants therefore, rely on their internal processes to survive changes in the external environment. Plants are affected to function in an oscillating environment and normal external changes are countered by internal changes without any harm to growth or development. The possibility of abiotic or environmental stress is to cause physical harm to the plant due to serious or chronic adverse environmental circumstances. Any adverse influence of inanimate factors on living beings in a fixed setting is described as abiotic stress. To substantially impact the organism’s demographic output or individual physiology, the non-living factor must alter the surrounding beyond its ordinary variation range. Due to the continuous climate change and environmental deterioration induced by human activity, physical surrounding stress has become a key threat to food security.

Stress in plants refers to external conditions that adversely affect growth, development or productivity of plants. Stresses trigger a wide range of plant responses like altered gene expression, cellular metabolism, changes in growth rates, crop yields, etc. A plant stress usually reflects some sudden changes in environmental condition. However in stress tolerant plant species, exposure to a particular stress leads to acclimation to that specific stress in a time time-dependent manner. Plant stress can be divided into two primary categories namely abiotic stress and biotic stress. Abiotic stress imposed on plants by environment may be either physical or chemical, while as biotic stress exposed to the crop plants is a biological unit like diseases, insects, etc. Some stresses to the plants injured them as such that plants exhibit several metabolic dysfunctions. The plants can be recovered from injuries if the stress is mild or of short term as the effect is temporary while as severe stresses leads to death of crop plants by preventing flowering, seed formation and induce senescence. Such plants will be considered to be stress susceptible.

However several plants like desert plants (Ephemerals) can escape the stress altogether. deficiencies) and temperature extremes are significant environmental limitations on productivity of crops all over the world. Plant growth and crop yield are majorly affected by cold, drought, salt, and heavy metals. Abiotic stress impacts plants to molecular levels from morphological levels and is visible at all phases of plant development where drought occurs [70]. There are three significant stages of plant: vegetative development, pre-anthesis and terminal phase that are impacted by the drought [78]. Plant physiological reactions to stress include wilting of the leaf, abscission of the leaf, decreased leaf region and decreased water loss through transpiration [58]. Under drought stress, crop development facilitates the issue of extreme water use in agriculture to a big extent. Turgor pressure is decreased, which is one of the most delicate physiological mechanisms that cause cell growth. Drought stress creates water flow disruption in higher plants from xylem to the neighboring elongating cells, thereby suppressing cell elongation. In addition, decreased leaf area, plant height, and development of crop result from drought pressure owing to cell elongation, impaired mitosis and expansion. Abiotic stress resistance contains escape avoidance and tolerance mechanisms. Detrimental impacts of stress can be decreased by osmotic modification, which helps with an active accumulation of solutes in the cytoplasm to maintain cell water balance [28].

Survival and geographical spreading of plants are also greatly affected by low temperatures. Significant loss of crop due to reduced plant growth and crop efficiency is usually caused by cold stress. Cell and tissue dehydration and cellular water crystallization are caused by cold stress, thereby reducing plant growth and productivity. Reduced membrane conductivity, increased water viscosity, and hydro active stomata closure is inhibited resulting in water stress and increased leakage of electrolytes at low temperatures. It also delays metabolism, dissipates energy, and causes free radicals to form as a result of oxidative stress [18]. For instance, up to 45 % of the world’s farming based land is encountered to frequent periods of time when there is scanty of rainfall in which 38 % of the world’s population resides and the world’s mapped area is affected by salinity in more than 3106 km2 area or about 6 % of the entire area of land. In addition, 19.5 % of irrigated agricultural land is classified as saline. In addition, about 1% of world agricultural land is deteriorated by salinity (2 million ha) each year, resulting in decreased or no crop productivity [19]. Major abiotic stress affects the plants during their growth and development arises due to water limitation caused by inadequate rainfall, cold condition, and salinity. The worldwide land region impacted by drought, cold and salinity is 64, 57, and 6 %, respectively. Comprehension of crop plant abiotic stress reactions has thus become component of plant studies to protect food security.

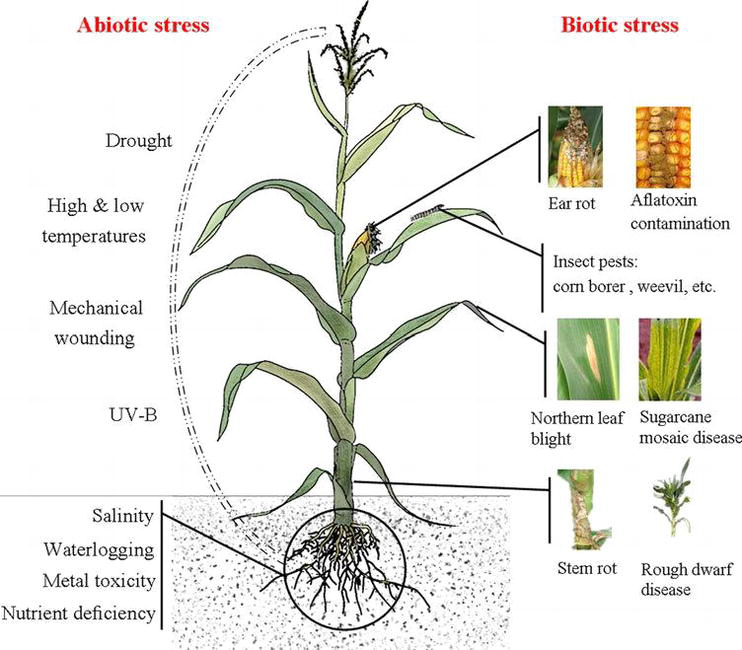
Abiotic stresses are interrelated and influence the relationships of plant water on the cellular and also the entire plant level, affecting certain and uncertain reactions resulting in a series of morphological, physiological, biochemical and molecular changes that affects the growth and development of plants adversely. These abiotic stresses characterize the main cause of crop fiasco globally, introducing more than 50% of the average returns for significant crops. Improving cultivation is therefore vital to fill the gap between population growth and food production, which is widening by initiating stress tolerance. Plants can introduce some molecular, cellular and physiological modifications to react to and acclimatize such stresses in order to deal with abiotic stress. Better knowledge of plant responsiveness to abiotic stress in both traditional and modern breeding application will assist to enhance stress tolerance. Studies with high stress tolerance on some wild plant species also make a significant contribution to our understanding of stress tolerance [28].

**2. Biotic Stress**

Biotic stress in plants is caused by living organisms, specially viruses, bacteria, fungi, nematodes, insects, arachnids and weeds. The agents causing biotic stress directly deprive their host of its nutrients can lead to death of plants. Biotic stress can become major because of pre- and postharvest losses. Despite lacking the adaptive immune system plants can counteract biotic stresses by evolving themselves to certain sophisticated strategies. The defense mechanisms which act against these stresses are controlled genetically by plant’s genetic code stored in them. The resistant genes against these biotic stresses present in plant genome are encoded in hundreds. The biotic stress is totally different from abiotic stress, which is imposed on plants by non-living factors such as salinity, sunlight, temperature, cold, floods and drought having negative impact on crop plants. It is the climate in which the crop lives that decides what type of biotic stress may be imposed on crop plants and also the ability of the crop species to resist that particular type of stress. Many biotic stresses affect photosynthesis, as chewing insects reduce leaf area and virus infections reduce the rate of photosynthesis per leaf area.

**3. Abiotic stress**

Abiotic stresses such as drought (water stress), excessive watering (water logging), extreme temperatures (cold, frost and heat), salinity and mineral toxicity negatively impact growth, development, yield and seed quality of crop and other plants. In future it is predicted that fresh water scarcity will increase and ultimately intensity of abiotic stresses will increase. Hence there is an urgency to develop crop varieties that are resilient to abiotic stresses to ensure food security and safety in coming years. A plants first line of defense against abiotic stress is in its roots. The chances of surviving stressful conditions will be high if the soil holding the plant is healthy and biologically diverse. One of the primary responses to abiotic stress such as high salinity is the disruption of the Na+/K+ ratio in the cytoplasm of the plant cell. The phytohormone abscisic acid (ABA) plays an important role during plant adaptation to environmental stress such as high salinity, drought, low temperature or mechanical wounding [58].



**Figure 1. An Overview of Major Biotic and Abiotic Stresses [81]**

**4. Crop plants and abiotic stresses**

Plants are encountered by number of abiotic stresses which impact on the crop productivity worldwide. These abiotic stresses are interconnected with each other and may occur in form of osmotic stress, malfunction of ion distribution and plant cell homeostasis. The growth rate and productivity is affected by a response caused by group of genes by changing their expression patterns. So, the identification of responsive genes against abiotic stresses is necessary in order to understand the abiotic stress response mechanisms in crop plants. The abiotic stresses occurring in plants include.

**4.1 Cold**

Cold stress as abiotic stress has proved to be the main abiotic stresses that decrease productivity of agricultural crops by affecting the quality of crops and their post-harvest life. Plants being immobile in nature are always busy to modify their mechanisms in order to prevent themselves from such stresses. In temperate conditions plants are encountered by chilling and freezing conditions that are very harmful to plants as stress. In order to adopt themselves, plants acquire chilling and freezing tolerance against such lethal cold stresses by a process called as acclimation. However many important crops are still incompetent to the process of cold acclimation. The abiotic stress caused by cold affect the cellular functions of plants in every aspect. Several signal transduction pathways are there by which these cold stresses are transduced like components of ROS, protein kinase, protein phosphate, ABA and Ca2+, etc. and among these ABA proves to be best.

**4.2 Salt**

Soil salinity poses a global threat to world agriculture by reducing the yield of crops and ultimately the crop productivity in the salt affected areas. Salt stress reduces growth of crops and yield in many ways. Two primary effects are imposed on crop plants by salt stress; osmotic stress and ion toxicity. The osmotic pressure under salinity stress in the soil solution exceeds the osmotic pressure in plant cells due to the presence of more salt, and thus, limits the ability of plants to take up water and minerals like K+ and Ca2+. These primary effects of salinity stress causes some secondary effects like assimilate production, reduced cell expansion and membrane function as well as decreased cytosolic metabolism.

**4.3 Drought**

Nowadays climate has changed all around the globe by continuously increase in temperature and atmospheric CO2 levels. The distribution of rainfall is uneven due to the change in climate which acts as an important stress as drought. The soil water available to plants is steadily increased due severe drought conditions and cause death of plants prematurely. After drought is imposed on crop plants growth arrest is the first response subjected on the plants. Plants reduce their growth of shoots under drought conditions and reduce their metabolic demands. After that protective compounds are synthesized by plants under drought by mobilizing metabolites required for their osmotic adjustment.

**4.4 Heat**

Increase in temperature throughout the globe has become a great concern, which not only affect the growth of plants but their productivity as well especially in agricultural crops plants. When plants encounter heat stress the percentage of seed germination, photosynthetic efficiency and yield declines. Under heat stress, during the reproductive growth period, the function of tapetal cells is lost, and the anther is dysplastic.

**4.5 Toxin**

The increased dependence of agriculture on chemical fertilizers and sewage waste water irrigation and rapid industrialization has added toxic metals to agriculture soils causing harmful effects on soil-plant environment system [28].

**5. Effect of abiotic stress on crops**

A complex set of biotic and abiotic pressures includes the natural environment of crops. Abiotic stresses are of greater importance because they include different environmental factors that cannot be prevented, that is, drought, salinity, cold, heat, metal, etc. The impacts of abiotic stress on crop manufacturing are hard to predict correctly. Plant reactions to abiotic stress are both dynamic and complicated and can be either elastic (reversible) or plastic (irreversible) [12].

**5.1 Drought effect on crops**

Drought stress affects the plants at all phenological developmental stages varying from morphological to molecular concentrations. In plants that determine yield, many physiological mechanisms are prone to drought [18]. Drought can trigger yield reductions in many plant species depending on their severity and period but the stress of drought after anthesis is detrimental to the output of grain regardless of its severity [5]. Prevailing drought stress limits the production of flowers and grain filling resulting in reduced quality and amount of grains. Micro and macronutrients like nitrogen (N), phosphorous (P) and potassium (K) are crucial for plant growth. Drought stress results in increased N significantly decreased P in spite of this it has no definitive effects on K [57]. Overall, water deficit reduces nutrient accessibility in the root zone, absorption at root hair, translocation in xylem and phloem vessels leading to impaired metabolism of nutrients in cells and tissues. The effectiveness of nutrient intake and utilization is also reduced due to less transpiration. Drought stress has significant on photosynthetic pigments like chlorophyll a, b, and carotenoid components and also impairs photosystem 1 and photosystem 2 [20]. It also reduces starch synthesis in plants by effecting Calvin cycle enzyme activity (Ribulose phosphatase).

**5.2 Salinity effect on the crops**

The magnitude of agricultural estate affected by high salinity is increasing worldwide as a result of both natural and agricultural occurrences such as irrigation schemes. In plant growth, salinity presents two primary concerns: osmotic stress and ionic stress. It also manifests oxidizing stress. The detrimental effects of salinity alter different physiological and metabolic processes of plants. Often, the answers to these modifications are accompanied by various symptoms such as decreased leaf area, increased leaf density and succulence, leaf abscission, root and shoot necrosis, and decreased internode lengths. Salinity stress inhibits growth and increases cell senescence during extended exposure. Inhibition of growth is the major injury resulting in other symptoms, while programmed cell death may also happen under serious salinity shock [48]. Plant growth is decreased due to salinity related nutrient disturbances by altering accessibility, transport and partitioning of nutrients. High salt concentration can result in nutrient deficits or imbalances due to Na+ and Cl− competition with nutrients such as K+, Ca2+ and NO3 −. Under saline circumstances there are specific ion toxicity of Na+ and Cl− and ionic imbalances influencing biophysical components and/or metabolism of plant growth. Most of the crops combat salinity stress by deposition of low molecular weight organic solutes like linear polyols (sorbitol, glycerol or mannitol), amino acids (proline or glutamate) and betaine (betaine glycine or betaine alanine), cyclic polyols (inositol and other derivatives of mono- and dimethylated inositol) [25].

**5.3 Cold effect on the crops**

Cold stress is a significant abiotic stress which affects growth and development of crops, leading to loss of strength and lesions on the surface. These symptoms are triggered by changes in the physical and chemical organization of cell membranes, among other metabolic procedures [3]. It is estimated that rises in extreme temperature frequency, severity, and duration are a prevalent feature of our setting. Climate change controls greater changes in temperature, leading in frequent cold periods. Susceptible plants with cold temperatures have reduced growth and growth, restricted use of precious varieties, and reduced yields. Plants use separate strategies to cope with stressful conditions and integrate a variety of physiological, metabolic and molecular adaptations. These methods initially generate modifications to safeguard the plant, followed by cold acclimatization, which increases the survival of the plant under cold stress [19]. While a lot of these mechanisms are facilitated by transcription factors (TFs) that stimulate gene expression associated to stress, the transcription network is not restricted to the reaction of plants to cold [28]. As a foremost element of plasma and endo-membranes, lipids play a significant organizational role in mitigating the effects of cold temperatures. Cold stress decrease plants growth and development that affects the physical and chemical structure of the cell membrane, causes leakage of electrolytes, and reduces protoplasmic streaming and changes in the metabolism of cell. Additional cold reactions comprise changes in nucleic acid and protein synthesis, water and nutrient equilibrium, enzyme affinity and conformation and deficiency in photosynthesis, specifically down-regulation and photo-damage of Photosystem II (PSII) [10].

Changes in the structure of proteins and lipid membranes assist restore homeostasis of metabolites and are regarded a mechanism by which cells feel cold temperatures. For its metabolic and physical function, the liquid state of the plasma membrane is a structural and functional asset. When low temperatures are present, the plasma membrane transitions from a liquid state at elevated temperatures into a stiff gel stage. Low temperature-mediated changes in the physical conformation of the membrane are mainly because of enhanced levels of unsaturated lipids, which increase the fluidity and stability of the membrane, enabling cells to adapt mechanically to cold [36].

**5.4 Heat effect on the crops**

The sequence of modifications in morphology, biochemistry, and physiology arising from high temperature stress also considerably disturbs growth and development of plant [74]. As a result of increasing atmospheric temperatures, heat shocks are currently primary limiting factors for crop productivity globally. This increasing temperature may result in changes in the phases of growth and distribution of agricultural plants [50]. High-temperature stress can cause serious protein damage, interrupt synthesis of protein, inactivate critical enzymes, and damage membranes. High temperature stress can have significant effects on the cell division process [63]. All of these harms can substantially restrict plant development and also promote oxidative damage. In addition, short exposure to elevated temperature in seed filling can lead to rapid filling, leading to low quality and lower yield. Under a restricted supply of water, the temperature rise is fatal. Overall, water loss due to heat stress is predominantly due to enhanced transpiration rate during the day, which eventually damages certain physiological procedures in crops. Heat stress also decreases the amount, weight and root growth and eventually decreases the accessibility of water and nutrients to the plant parts above the ground.

High heat stress has a significant impact on the activity of significant enzymes like sucrose phosphate synthase, invertase, adenosine diphosphate-glucose pyrophosphorylase, and starch and sucrose synthesis [12]. The reduced CO2 binding enzyme activation status, Rubisco, limits net photosynthesis in many species of plants. Although Rubisco’s catalytic activity rises with greater temperatures, its low CO2 affinity and O2 binding ability limit the rise in net photosynthesis speed [46]. Despite all these negative photosynthesis impacts of elevated temperature, with elevated concentrations of CO2 in the atmosphere, optimum photosynthesis temperature requirements are expected to rise [11].

**5.5 Heavy metal**

Heavy metals, a loosely specified group of components, constitute elements with an atomic mass exceeding 20 (excluding alkali metals) and specific gravity exceeding 5 [52]. Because of their differing solubility/bioavailability, heavy metals exist in different forms in soil. Many soil physicochemical characteristics change heavy metal geochemical conduct in soil, plant uptake, and effect on crop productivity. Excessive deposition of heavy metals in plant tissue is harmful to multiple biochemical, physiological, and morphological operations in plants either directly or indirectly and in turn affect crop productivity. Heavy metals decrease crop productivity by causing seed germination, accumulation, and re-mobilization of seed reserves during plant growth, germination and photosynthesis to deleterious effects on various plant physiological processes [67].

Heavy metal toxicity on the cell platform decreases the productivity of plants by forming reactive oxygen species, disrupting the redox equilibrium and causing oxidative stress. Metals mainly enter the plants through the root from the soil [51]. The cultivation of metals includes several processes, including desorption of metal from soil particles,, uptake of metals by roots, transportation of metals to plant roots and shoots [56]. Transport of heavy metal to aerial components of the plant is via the xylem and is most probably encouraged by transpiration [69]. The metals, after joining the central cylinder, move towards the aerial parts of the plant where evaporation of water occurs and metal stacks up through the water stream of the vascular system [39]. Only a slight percentage of heavy metals are translocated in most crops to the shooting tissues. In some cases, only if the plant is a hyper accumulator or chelate-assisted, there is sequestration of 95% or more of the metal in the plant’s roots [15].

**6. Crops tolerance against abiotic stress**

Plant resistance to abiotic stress includes escaping stress avoidance and tolerance. Escape: Before extreme stress begins, dry escape depends on efficient reproduction. The plants integrate brief life cycles with high growth rates and gas exchange, using the highest existing resources while soil moisture lasts. It also relies on escaping the unfavorable environmental conditions by shedding off the leaves, no germination, night time closure of stomata, compact growth, that is, shortening of any plant part [41].

Avoidance: reversible physiological changes involve decreasing water loss (closing stomata, decreasing light absorption through rolling leaves and condensed canopy leaf region) and growing water absorption (increasing root investment, morphological changes occurring in crops to decrease transpiration, re-allocation of nutrients stored in older leaves and greater photosynthesis rates [9].

Tolerance: abiotic stress tolerance appears to be the consequence of cellular and molecular level coordination of physiological and biochemical changes. These changes may include osmotic adjustment, stiffer cell walls, or smaller cells [75]. Changes happening rapidly at the concentrations of mRNA and protein consequence in an intolerant state. Various morphological, physiological, biochemical and molecular modifications happen in crops in order to fight different abiotic stresses [34].

**6.1 Morphological changes**

Under stress, roots extend their length in the soil in order to seep water around themselves and absorb a sufficient amount of water to persist against stressed conditions. Due to an increase in length and more absorption of water through soil, roots biomass also increases in abiotic stress conditions. Shoot length is higher due to sufficient transpiration and translocation mechanism whereas in water deficit plants, shoot length observed was comparatively dwarf as plants need to overcome water and nutrient deficit conditions caused by drought. Shoot dry weight depends on the inner mass and tillers of wheat. Irrigated plants can accumulate water inside tissues due to a sufficient amount of landed water whereas water deficient cannot do so due to which inner mass decreases in case of water stress plants [76].

**6.2 Physiological changes**

Plants facing abiotic stress, respond at the molecular, cellular and whole plant levels through a number of physiological modifications.

**6.2.1 Relative water content (RWC)**

A leaf’s relative water content (RWC; or’ relative turgidity’) is measuring its real water content at complete turgidity relative to its peak water holding capacity. RWC provides a measurement of the decline in leaf water content and may involve a degree of stress in water deficit and heat stress. RWC includes leaf water potential (another helpful estimation of plant water status) with the impact of osmotic adjustment, a powerful mechanism for preserving cell hydration as a measure of plant water status. The development of leaves relies on the water content and the rate of transpiration. With the absorption of water from roots and passing on to leaves, plants will have high rates of transpiration and water content in leaves will elevate effectively in irrigated plants unlikely in water deficit plants and water potential reduced in drought-stressed plants [41].

**6.2.2 Relative stress injury (RSI)**

It is the relative injury caused to plants under stressed conditions. Relative stress injury is actuated under stressed conditions providing a measurement of injury caused to plants. Plants under such stressed conditions try to become resistant towards the extraneous factors where plants activate some genes and provide tolerance towards the environment. Abiotic stress tolerance appears to be the result of cooperation at the cellular and molecular levels between physiological and biochemical alternation. These modifications may include more rigid cell walls, osmotic adjustment, or smaller cells. There are rapid changes in the mRNA and protein concentrations that result in tolerance towards stress [76].

**6.2.3 Water use efficiency (WUE)**

Efficiency in water use (WUE) is a crucial variable responsible for the productivity of plants under restricted supply of water. In agronomic terms, it is defined as the percentage of total dry matter (DM) generated (or harvested) to (or applied) used water. Physiologically speaking, nevertheless, WUE is well-defined as the proportion between the set carbon rate and the transpired water rate. The connection between water use and crop production rate is defined as water use efficiency. It is measured in terms of biomass generated by transpiration unit. Greater biomass generated by limited amount of water under stress circumstances is crucial for higher crop yield. Combined stress can also occur to the plant at same time, for example, water shortage can lead to drought and salinity stress simultaneously, uttermost significant factors limiting crop effectiveness and yielding worldwide. Drought resistance in plants can be improved by escaping or avoiding drought condition using WUE mechanism to maintain water level or growing drought tolerant plants [5].

**6.2.4 Osmotic adjustment**

Osmotic adjustment (OA) is the net elevation of intercellular solutes in response to water stress that allows turgor to be conserved at a lower water potential. OA has been considered as the primary mechanisms in adaptation of plant towards drought as it promotes the tissue’s metabolic activity and enables for regeneration but varies considerably between genotypes. The efficiency of plants in arid conditions has been linked with OA in many species such as sorghum, wheat and oilseed brassicas. High levels of ions can critically inhibit cytosolic enzymes of plant cells [65]. Throughout osmotic adjustment, ion accumulation appears to be limited to the vacuoles where ions are kept out of contact with cytosol or subcellular organelles [30]. Because of this ion compartmentation, other solutes such as sugar alcohol, amino acid proline must be assembled in the cytoplasm in order to preserve the cell’s water potential balance [62].

**7.3 Biochemical changes**

Under stress, crops experience a number of cellular and molecular-level biochemical modifications.

**7.3.1 Chlorophyll and carotenoid**

Chlorophyll and carotenoid content depend on ATP, photosynthetic reactions, NAD. Chlorophyll cannot capture sunlight straight, so it gives sunlight to chlorophyll with the aid of carotenoid, which is an accessory pigment, and transfers it to photosystem I and photosystem II, which transforms light energy into chemical energy acquired in the form of ATP and NADPH. Now, with the help of end products of photosystems and fixed carbon dioxide, plants produce glucose. So, we can say that in wheat more the carotenoid present in the chloroplast, more will be the sunlight captured and thus more will be the chlorophyll [18].

**7.3.2 Starch**

Starch also evolves as a main molecule in enabling the response to abiotic stresses by plants like water deficit, salinity or extreme temperatures. When photosynthesis is limited under stress conditions plants have a tendency to use starch as energy source. Adverse effect of stress is reduced in plant by releasing some compatible solutes, osmoprotectants, derived sugars and other metabolites to encourage plant growth [38].

**7.3.3 Amino acid**

Under stress circumstances, amino acids such as proline and arginine play a significant role in controlling osmotic pressure. Proline acts as an osmoprotectant and its accumulation can lead to improved synthesis of cells and their reduced degradation. This behaviour of higher accumulation of proline is because of the expression of the gene encoding pyrroline-5-carboxylate synthase. Additional proof for proline’s defensive function was discovered in transgenic crops, where proline overproduction improves tolerance to osmotic stress. In addition to proline, the reaction to osmotic stress also involves other amino acids. Arginine was found to operate as a compatible solution to enhance stress tolerance in leaves. The enzyme involved in arginine biosynthesis is enhanced under hyperosmotic circumstances. In addition, osmotic stress in sunflower and wheat causes enhanced expression of asparagine synthase genes. Glutamine synthase overexpression enhances tolerance of osmotic stress in rice. These findings indicate that changes in osmotic pressure-induced amino acid levels may be due to modified gene expression encoding the enzymes engaged in their metabolism [2].

**8.4 Molecular changes**

**8.4.1 Late embryogenesis abundant proteins (LEA)**

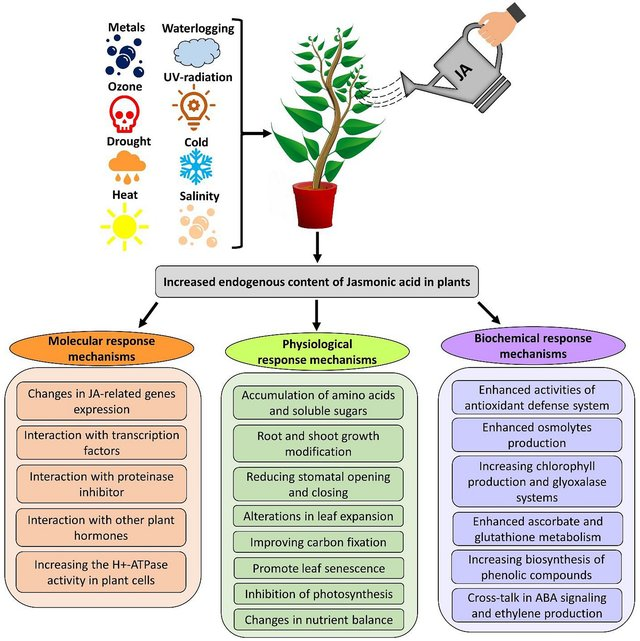
LEA proteins are the group of elevated molecular weight proteins that are abundantly present during early embryogenesis and collect in reaction to water stress during seed dehydration. There are different LEA protein groups. The proteins belonging to group 3 are considered to play a part in the sequestration of focused ions between these groups during cell dehydration. LEA proteins of group 1 are expected to have increased water-binding ability, whereas LEA proteins of group 5 are presumed to be appropriate ions during water loss [21].

**8.4.2 Detoxifying genes**

Also, there are certain detoxifying genes that help to combat abiotic stress. Plants can be protected from damage by increase tolerance towards stress by the accumulation of some attuned solutes and reactive oxygen species (ROS) are scavenged. This action helps to maintain protein structures and functions. The genes responsible for activation of these three enzymes: ascorbate peroxidase, glutathione peroxidase, and glutathione reductase have revealed to have some effect on various abiotic stresses [14].

**8.4.3 Heat shock protein genes**

An increase in the transcription of a set of genes by heat exposure or other abiotic stress in all species is a heavily maintained biological reaction. The reaction is promoted by the heat shock transcription factor (HSF) in the form of a monomeric, non-DNA binding type current in unstressed cells. It is caused by stress in the form of a trimeric shape that can bind heat shock gene promoters. Gene stimulation encoding thermal shock proteins (Hsps) is one of the most noticeable responses in organisms that are subjected to high molecular temperature [71].



**Figure 2. Major physiological, biochemical and molecular responses of crop plants under abiotic stress** [82]

**8.5 In reaction to abiotic stress, various genetic mechanisms begin in the crops**

**8.5.1 ABA pathway**

Many genes responsible for response to stress are triggered under abiotic stress conditions. Abscisic acid (ABA) is a main plant stress-signaling hormone and its accumulation automatically increases as the harsh conditions are faced by plant to fight the stress effect. Two pathways are triggered in plant under osmotic stress condition, that is, ABA-dependent and ABA-independent pathways. In ABA-dependent pathway, a mixture of transcription factors, ABRE binding protein/ABRE binding factors (AREB/ABFs) demonstrate critical functions. A cis-element, dehydration-response element/C-repeat (DRE/CRT) and DRE-/CRT-binding protein 2 (DREB2) transcription factors play a main part in the expression of ABA-independent genes in response to osmotic stress. Continuous increase in expression of AREB1/ABF2, AREB2/ABF4 and ABF3 is triggered by drought and salinity in vegetative tissues. Over-expression studies indicate that in conditions of drought stress, these three AREB/ABFs are useful signals from ABA regulators. As shown in the figure, AREB/ABF transcription factors result in gene expression of the genes involved in abiotic stress reaction and tolerance.

**8.5.2 Cold stress pathway**

CBF/DREB1 homologs have been acknowledged in various species. CBF/DREB1 may bind CRT/DRE cis-elements (A/GCCGAC) in the promoter area of COR genes to control the expression of COR genes belonging to the transcription factor family ERF/AP2 (ethylene-responsive factor/APETALA2). The CRT/DRE cis-acting components express the RD29A gene that is believed to be involved in abiotic stress reaction and tolerance [60].

**8.5.3 SOS pathway**

The SOS signaling path includes three significant enzymes, SOS1, SOS2, and SOS3. SOS1 protein codes for Na+/H+ anti-porter plasma membrane. This protein is essential for cell-level regulation of Na+ efflux. Na+ long-distance transportation from root to shoot is also facilitated. This protein’s overexpression is related to plant salt tolerance [59]. Salt stress-stimulated signals from Ca2+ activate the SOS2 gene encoding serine/threonine kinase. This protein includes a correctly established catalytic N-terminal domain and a regulatory C-terminal domain. In the C-terminal regulatory domain of the SOS2 protein, FISL motif is present (also known as NAF domain) that is approximately 21 lengthy sequence of amino acids, and helps to interact with the Ca2+ binding SOS3 protein. Kinase activation is the consequence of the SOS2–SOS3 protein interaction. The kinase caused then phosphorylated SOS1 protein thus enhancing its initially identified yeast transportation activity. SOS1 protein is defined by a long cytosolic C-terminal tail composed of a putative nucleotide binding motif and an auto inhibitory domain, which is roughly 700 amino acids long [35]. The target site for SOS2 phosphorylation is this auto inhibitory domain. In relation to salinity tolerance, it regulates trafficking of membrane vesicle, pH homeostasis and functions of vacuole [29].

Abiotic stress management in plants needs to be taken up on a priority basis, keeping in mind that the technology adopted should be ecofriendly as well as cost-effective. This is a major challenge for agriculture. To this end, extensive research is being carried out worldwide to develop strategies to cope with abiotic stresses, through development of heat- and drought-tolerant varieties, shifting the crop calendars, resource management practices etc. However, while many of these technologies, because of their high cost, may not reach the farmers, there is another strategy that has high potential to help plants withstand abiotic stresses, is highly ecofriendly and cost effective. This strategy involves the utilization of multi-faceted traits of several microorganisms with an established role in plant growth promotion, nutrient management and disease control.

**9.1 Role of Plant Growth-Promoting Rhizobacteria in Alleviation of Abiotic Stresses**

Soil, consisting of both inorganic and organic matter, is specialized because of the metabolic activities of the millions of microbes present therein. In spite of the high metabolic activity in the soil, the living microbes occupy less than 5% of the total space. These microorganisms are involved in the decomposition of organic matter as well as solubilization of nutrients, which become available to the roots. However, microbial activity is not uniform throughout the soil, but is concentrated in the region of the root, known as the rhizosphere [40, 49]. These soil microorganisms are thus important resources in agriculture and play significant roles in maintenance of life. Many of these bacteria are beneficial, and have the ability to promote growth of plants. These are generally termed as plant growth promoting rhizobacteria (PGPR). These bacteria are known to remain associated with plant roots and act in the soil for growth promotion, either directly, or indirectly, through a number of mechanisms [23]. Among rhizobacteria there is a gradient of root proximity and intimacy as follows: (i) bacteria that live in close proximity to the roots, utilizing metabolites leaked from roots as carbon and nitrogen sources; (ii)  bacteria colonizing the rhizoplane (root surface); (iii) bacteria residing in root tissue, inhabiting spaces between cortical cells; and (iv) bacteria living inside cells in specialized root structures, or nodules, which generally fall into two groups, the legume-associated rhizobia and the woody plant-associated Frankia species [26]. Rhizobacteria that establish inside plant roots, forming more intimate associations, are endophytes. Interestingly, quite a number of these beneficial bacteria, both free living rhizospheric as well as endophytic, have several mechanisms have been proposed for the observed alleviation of abiotic stresses in plants by different microbes. Some of these have been discussed below.

**9.2. Bacteria in Abiotic Stress Tolerance**

Numerous bacterial families have been shown to be involved in the improvement of plant growth under stressful conditions. Some of these bacterial-induced tolerances have been associated with an increase in mRNA transcription of the drought-response gene early responsive to dehydration 15 (ERD15), the production of 1-aminocycloropropane-1-carboxylic acid (ACC) deaminase, stronger proline synthesis, and an improvement of relative and absolute water content. The priming with two PGPR strains, *Bacillus amyloliquefaciens* 5113 and *Azospirillum brasilense* NO40, attenuated drought-induced stress results in wheat plants by increasing the activity of antioxidant enzymes (glutathione peroxidases (GPXs)) against ROS. These findings supported the potential of the use of PGPR in controlling drought stress and increasing crop production.

**9.3 Fungi in Abiotic Stress Tolerance**

**9.3.1. Arbuscular Mycorrhizal Fungi in Alleviation of Abiotic Stress**

In addition to bacterial involvement in stress tolerance, fungi have also been implicated in adapting plants to various habitats, including those that are affected by abiotic stresses such as salinity, chilling, drought, heat, toxic metals, and flooding [14]. Two types of fungi are involved in stress tolerance, these include arbuscular mycorrhiza (AM) and ectomycorrhiza (EM) fungi. AM live inside the host plant without causing any harm and have been reported to evoke various stress tolerances.

**9.3.2. Ectomycorrhiza in the Alleviation of Abiotic Stress**

While most studies have been conducted on the amelioration of abiotic stress by endomycorrhizal fungi AM, there is little information available on ectomycorrhizal involvement. The reason for this is that endomycorrhizae prevail on most herbaceous and woody species. However, the ability of ectomycorrhizal fungi to alleviate abiotic stress has been demonstrated. The ectomycorrhizal fungi that attenuate the detrimental effects of salt stress by increasing biomass production, water conductance, and limiting the loading of Na+ into the xylem while increasing that of K+. Ectomycorrhiza has also been implicated in the alleviation of drought stress. It has been hypothesized that ectomycorrhiza improves drought stress effects by enhancing osmotic adjustment, enhancing tissue elasticity, and regulating gene expression. While it is often assumed that ectomycorrhizal fungi die when soils dry out, studies have shown that some ectomycorrhizal species persist in dry soils and characteristically confer tolerance to drought stress in plants.

**9.3.3. Alleviation of abiotic stress in plants by rhizosphere and endophytic bacteria:**

Besides developing mechanisms for stress tolerance, microorganisms can also impart some degree of tolerance to plants towards abiotic stresses like drought, chilling injury, salinity, metal toxicity and high temperature. In the last decade, bacteria belonging to different genera including *Rhizobium*, *Bacillus*, *Pseudomonas*, *Pantoea*, *Paenibacillus*, *Burkholderia*, *Achromobacter*, *Azospirillum*, *Microbacterium*, *Methylobacterium*, variovorax, Enterobacter etc. have been reported to provide tolerance to host plants under different abiotic stress environments. Use of these microorganisms per se can alleviate stresses in agriculture thus opening a new and emerging application of microorganisms. A variety of mechanisms have been proposed behind microbial elicited stress tolerance in plants. Production of indole acetic acid, gibberellins and some unknown determinants by PGPR, result in increased root length, root surface area and number of root tips, leading to enhanced uptake of nutrients thereby improving plant health under stress conditions [16].

Many aspects of plant life are regulated by ethylene levels and the biosynthesis of ethylene is subjected to tight regulation, involving transcriptional and post-transcriptional factors regulated by environmental cues, including biotic and abiotic stresses [31]. In the biosynthetic pathway of ethylene, S-adenosylmethionine (S-AdoMet) is converted by 1-aminocyclopropane-1-carboxylate synthase (ACS) to 1-aminocyclopropane-1-carboxylate (ACC), the immediate precursor of ethylene. Under stress conditions, the plant hormone ethylene endogenously regulates plant homoeostasis and results in reduced root and shoot growth. In the presence of ACC deaminase producing bacteria, plant ACC is sequestered and degraded by bacterial cells to supply nitrogen and energy. Furthermore, by removing ACC, the bacteria reduce the deleterious effect of ethylene, ameliorating plant stress and promoting plant growth [24]. PGPR containing ACC deaminase, in stress agriculture. Inoculation with ACC deaminase containing bacteria induce longer roots which might be helpful in the uptake of relatively more water from deep soil under drought stress conditions, thus increasing water use efficiency of the plants under drought conditions [77]. The complex and dynamic interactions among microorganisms, roots, soil and water in the rhizosphere induce changes in physicochemical and structural properties of the soil [33].

**9.3.4. Dual symbiotic systems for alleviation of abiotic stress in plants:**

Besides rhizosphere and endophytic bacteria and symbotic fungi, role of virus in conferring tolerance to host plant against abiotic stress has also been reported. An endophytic fungi *Cuvularia* sp. isolated from the *Dichanthelium lanuginosum* grown under geothermal soils could impart thermo-tolerance (constant 50 oC soil temperature for 3 days and intermittent soil temperature as high as 65 oC for 10 days) [54]. Neither the fungus nor the plant could grow at temperature above 38 oC, when grown separately. The ability of *Curvularia protuberata* to confer heat tolerance to the host plant was related to the presence of a virus named as *Curvularia thermotolerance* virus (CatahTV). Plants inoculated with the virus-infected wild type isolate of fungus tolerated intermittent soil temperatures as high as 65 oC for 2 weeks (10 h of heat per day) whereas both non-symbiotic plants and plants inoculated with the virus free isolate of the fungus became shriveled, chlorotic and died. The ability of C. protuberata isolated from a monocot, to confer heat tolerance to tomato (a dicot) was tested and similar results to those obtained with *D. lanuginosum* were observed. Several possible mechanisms could confer thermotolerance. In plants, the fungal endophytes produce cell wall melanin that may dissipate heat along the hyphae and/or complex with oxygen radicals generated during heat stress [13]. Alternatively, the endophyte may act as a biological ‘‘trigger’’ allowing symbiotic plants to activate stress response systems more rapidally and strongly than non-symbiotic plants [54].

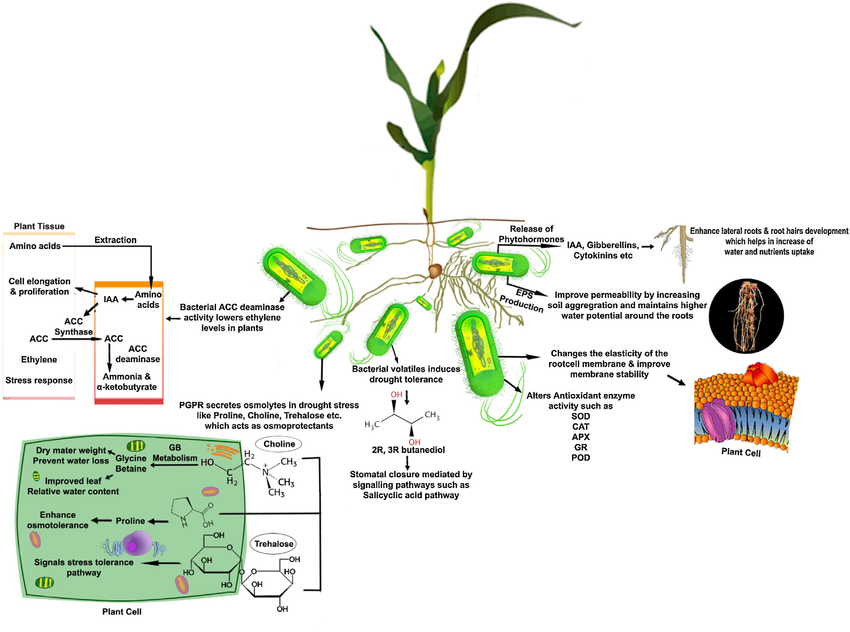
**9.4 Mechanisms of Stress Alleviation by Microbes**

Abiotic stresses caused due to water deficit, excess salt, extreme temperature variations and other environmental conditions affect plants at various levels. Production of reactive oxygen species (ROS) during such stresses leads to cellular damage involving metabolic toxicity, membrane damage and also inhibition of photosynthesis, changes in hormone levels etc. However, plants are able to overcome these stresses to a great extent, mainly due to the array of defence mechanisms that can become activated under such conditions. Some of the defence mechanisms include regulation of plant hormones, ROS scavenging mechanisms, compartmentation or exclusion of excess ions which cause osmotic disbalance as well as accumulation of metabolites, which protect the cells against osmotic damage. Several mechanisms have been proposed for the observed alleviation of abiotic stresses in plants by different microbes.

**9.4.1 Hormones**

Since lateral root formation is associated with a number of abiotic stresses, and auxin induces lateral root formation, it is believed that many of the responses induced by the stresses may be mediated through the action of auxins. Changes in auxin metabolism induced by abiotic stresses have been mostly shown to be through changes in its transport and catabolism [4]. It has been reported that expression of PIN genes are altered during drought or salinity affecting auxin transport and inhibiting polar auxin transport. It is also probable that the hydrolysis of auxin conjugates leads to increases in free auxin, which in turn inhibits root elongation and provides protection against stresses. Inoculation with *Azospirillum*, a plantgrowth promoter, consistently led to changes in root morphology, which has been linked to the production of growth hormones, with auxin being the most important.

The involvement of auxin in enhancement of lateral growth was further confirmed by comparing IAA-attenuate mutants with their parental wild types. IAA-mediated improvement in root growth may be direct, or again may be through the reduction in levels of ethylene as a relationship exists between IAA and ACC, which is the precursor of ethylene. Since ethylene is involved in several regulatory processes, its biosynthesis is under both transcriptional and post-transcriptional regulation, being affected by a number of environmental factors [31]. The beneficial effects of several plant growth promoting bacteria are due to their ability to produce ACC deaminase, which degrades ACC to nitrogen with release of energy. Thus ACC availability for ethylene production becomes lessened, which in turn leads to a lessening of the deleterious effects of ethylene. Such bacteria that inhibit ethylene biosynthesis induce better roots, which in turn would be of help to the plants in increasing their water uptake capacity under drought.



**Figure 3. Plant drought stress tolerance induced by bacteria [91]**

**9.4.2 Protective metabolites**

Certain specific metabolites such as specific proteins, glycine betaines, certain amino acids, amides, imino acids and polyamines generally accumulate during drought and salt tolerance in plants. When plants face salt stress, proline accumulates in the cell and helps substantially in cytoplasmic osmotic adjustment. Under salt stress, proline also helps the plant cell by stabilizing subcellular structures such as membranes and proteins, scavenging free radicals and buffering cellular redox potential. High accumulation of proline during stress documented in several plant species might be either due to increased biosynthesis or decreased degradation [6].

It is clear from several studies using mutants or transgenics, that proline metabolism during stress is very complex and it may play multiple roles to help plants survive under stress conditions. It may provide a carbon and nitrogen store, act as osmolyte or exhibit an antioxidant property for scavenging ROS. Another proposed function of proline is to act as molecular chaperone and stabilize protein structures, as well as enhancing certain enzyme activities. In cases where inoculation of plants subjected to abiotic stresses with PGPR led to alleviation of these stresses, increased proline biosynthesis was observed by several authors [68]. However, increased synthesis of proline and/or other compatible solutes which provide protection to plants against osmotic stress requires additional energy and may occur at the expense of growth.

**9.4.3 Maintaining ion homoeostasis**

Salinity causes an imbalance in the ratio of ion homoeostasis in the plant system. With excess NaCl in the soil, it is quite natural that the uptake of Na+ is enhanced while that of K+ is reduced. Potassium is essential for several metabolic processes, such as stomatal movements and protein synthesis, where it is required for the binding of tRNA to ribosomes. Plants try to maintain low salt composition in the cytosol by extrusion through the plasma membrane using the SOS pathway or by scavenging in the vacuole through NHX1 antiporters. Salinity impedes the ratio of Ca2+ and K+ in the cell. However, an increase in K+ concentration can alleviate the deleterious effect of salinity on growth and yield [22].

**9.4.4 Nutrient up-take enhancement**

Stress tolerance of plants depends to a great degree on the plant’s health, and plants with enhanced nutrient uptake capacities have been shown to have greater tolerance. It is thus not surprising that several bacteria and fungi, which have the ability to improve growth through different mechanisms, including enhanced nutrient uptake, also have the ability to induce tolerance against abiotic stresses. One of the causes for the adverse effects of abiotic stresses on plant growth and development being the imbalance of nutrient uptake and metabolism, it was reported in several cases that addition of macronutrients exogenously leads to a certain degree of stress alleviation. Phosphorous nutrition is one of the most important in plants, second only to nitrogen, as it is not only involved in metabolic processes but is also a part of the structural make-up of plants, being components of membrane phospholipids, phosphoproteins, as well as nucleotides. Salinity tends to decrease phosphorous uptake and accumulation in plants, leading to deficiency symptoms. In the soil, phosphorous can exist either as inorganic salts or as part of the organic composition, but has limited mobility and solubility [32]. Hence, solubilization and mobilization of insoluble phosphates into soluble forms generally improves plant growth as well as ability to withstand abiotic stresses.

**9.4.5 Antioxidant mechanisms**

Normal cellular metabolism such as respiration and photosynthesis release ROS in very low quantities as by-products which have certain signalling roles during growth and development. However, the concentration of such ROS increase during various abiotic stresses and at high concentrations these become toxic to cellular metabolism and cause cell and tissue damage. Plants have evolved an array of mechanisms to counteract these ROS, which help in scavenging the ROS and minimize their damage [7], from their studies on wheat, showed that in susceptible varieties GY and MW, both superoxide dismutase (SOD) and catalase (CAT) declined from the onset of drought; application of either *Bacillus safensis* or *Ochrobactrum pseudogregnonense* helped to maintain higher levels of the two enzymes and thus helped alleviate drought. Besides, even in those varieties where there was an initial increase in enzyme activities followed by a decline, bacterial treatments helped maintain higher levels of activities of these enzymes. One of the mechanisms of alleviation of drought may be the ability to tilt the balance from oxidatively stressed condition to a more antioxidative state, thereby providing tolerance against stress.

**10. Direct Mechanisms:**

In direct mechanisms, PGPRs help to promote plant growth in the absence of the pathogen. Rhizospheric microbial activity also affects the rooting and nutrient-availability pattern. Some direct mechanisms of PGPRs for plant growth are discussed hereunder.

**10.1 Nitrogen fixation**

The plant growth and productivity depend on the availability of vital nutrients such as nitrogen (N2). Nitrogen-fixing microorganisms play an important role in biological nitrogen fixation under mild temperatures [17]. Nitrogen-fixing organisms are classified into symbiotic and non-symbiotic N2-fixing bacteria. Symbiotic N2- fixing bacteria include leguminous and non-leguminous plants such as rhizobia and Frankia. Meanwhile, non-N2-fixing bacteria refer to cyanobacteria such as *Nostoc, Azotobacter*, and *Azocarus* [1]. The symbiosis connection may lead to the production of nodules [64]. The nitrogen-fixation mechanism is carried out by an enzyme nitrogenase complex. For nitrogen fixation and the regulation of the enzyme, genetic control is present in such bacteria and nitrogenase genes are required. Meanwhile, for the synthesis and regulation of enzymes, regulatory genes are required; nitrogenase genes are also required. Moreover, regulatory genes are required to synthesize and regulate the enzymes. Structural genes are involved in activating Fe protein, iron–molybdenum cofactor biosynthesis, and electron donation [73].

**10.2 Phosphate Solubilization**

Under stress conditions, plants usually face a shortage of nutrients such as phosphorous. It is mostly present in the soil in both forms, i.e., organic and inorganic [43]. The shortage of phosphorous in plants occurs due to the presence of insoluble P in plants, but plants can only absorb it as monobasic and diabasic ions. Phosphate-solubilizing bacteria can work as a source of phosphorous in the form of biofertilizers. Some phosphate-solubilizing bacteria are *Azotobacter, Microbacterium, Bacillus, Burkholderia, Enterobacter, Flavbacterium, Erwinia, Rhizobium, and Serratia* [45]. As plants cannot absorb inorganic P, Rhizobacteria have the potential to solubilize it, thus enhancing plant growth and yield. However, another cause of P solubilization could be due to the synthesis of organic acids by rhizospheric microorganisms. In plants such as the potato, tomato, wheat, and radish, phosphorous was solubilized by microbial species such as *Azotobacter chroococcum*, *Enterobacter agglomerans*, *P. putida*, *Bradyrhizobium japonicum*, *Cladosporium herbaru*, and *Rhizobium leguminosarum* [37].

**10.3 Siderophore production**

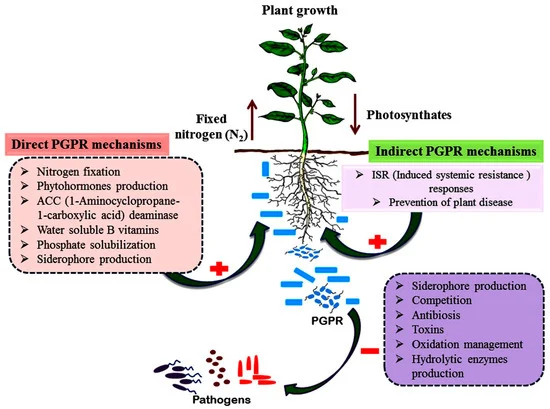
Iron is present abundantly in nature, but it is still unavailable for plants. Mostly, iron is found in the form of Fe3+. PGPRs help to solubilize it by the secretion of siderophores, which are low-molecular-weight iron-binding proteins that help in the chelation of ferric iron (Fe3+). The bacterial cell membrane dissolves siderophores and Fe3+ in a 1:1 complex. This Fe3+ is reduced to Fe2+ and then released from siderophores to the cell. PGPRs enhance plant growth by releasing siderophores, which also help mitigate various plant diseases. Microbial siderophores act as a metal-chelating agent, which helps to control the iron availability in the rhizosphere [61].

**10.4 Phytohormone production**

It is well-known that microbes help in the synthesis of phytohormone auxin, also known as indole-3-acetic acid (IAA). Many microorganisms that are isolated from multiple crops have the ability to synthesize IAA as a secondary metabolite. IAA plays a significant role in the interaction of rhizobacteria and plants. The synthesis of IAA affects plat cell division and helps to stimulate seed and tuber germination and the formation of adventitious roots. The secretion of bacterial IAA provides higher access for plants to nutrients by increasing their root surface area and length. Mostly, Rhizobium species produce IAA, which upregulates cell division and the formation of vascular bundles. Several environmental stress factors, such as an acidic pH, osmotic stress, and carbon limitation, cause the modification of IAA synthesis in bacteria [42].

**11. Indirect Mechanisms**

The environmentally friendly method to control diseases is the application of microorganisms . In PGPRs, biocontrol activities mostly influence nutrient availability, induction of systemic resistance, and the release of antifungal metabolites. It was observed that various rhizobacteria produce antifungal metabolites such as HCN, pyoluteorin, pyrrolnitrin, viscosinamide, 2,4-diacetylphloroglucinol, and tensin. Rhizobacteria interact with the plant roots, leading to the resistance against pathogenic bacteria, fungi, and viruses. This is known as induced systemic resistance (ISR). Various bacterial components can induce ISR, such as lipopolysaccharides; cyclic lipopeptides; homoserine lactones; flagella; siderophores; and volatile compounds, e.g., acetoin and 2,3-butanediol [47].



**Figure 4. Various microbial plant growth mechanisms**

**12. Conclusion(s):**

It is quite apparent that a gamut of environmental conditions such as extremely variable climatic conditions, water scarcity, urbanization, over-population, salinization, global warming, etc. to name a few, has been putting enormous pressure on survival and productivity of plants in general, and crop plants in particular. Thus with increasing abiotic stress conditions, appropriate techniques for management would be needed to ensure sufficient crop productivity for feeding the millions of hungry mouths. Among the potentially useful management systems, those based on cost-effective, low-cost technologies, utilization of microorganisms with multifaceted traits for improvement of crop growth and yield, as well as abiotic/biotic stress alleviation offer a tempting prospect. There have been innumerable studies which have brought out the efficacies of certain bacteria and fungi in crop protection and growth improvement. Their mechanisms of action, both in the soil, and within the plant, have been worked out in several crop systems. It can thus be hoped that, in coming years, such microorganisms could be routinely used in the field for sustainable agriculture and these will be available to farmers as low-input technologies. However, further studies are required at molecular level to understand the exact mechanism of stress tolerance imparted by the various microbial community. Moreover, the search for even more potential stress tolerant microbes and application of those microbial consortia on field conditions has to be extensively researched in the future which will be of prime importance in solving the future food security worldwide.

**13. Conflict of Interest:**

Authors have declared that no competing interests exist.

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