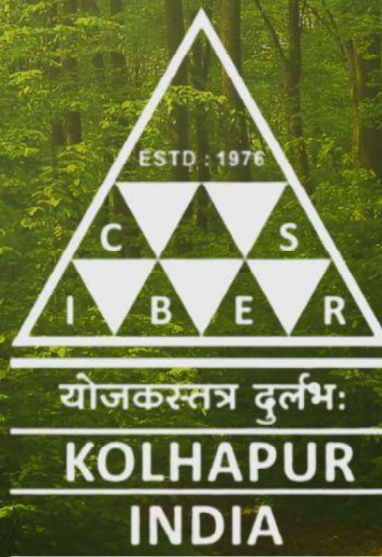




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## Biofertilizers in Crop Production and Stress Management for Sustainable Agriculture

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### Abstract

With the increase in world population, the demography of humans is estimated to be exceeded and it has become a major challenge to provide an adequate amount of food, feed, and agricultural products majorly in developing countries. The use of chemical fertilizers causes the plant to grow efficiently and rapidly to meet the food demand. The drawbacks of using a higher quantity of chemical or synthetic fertilizers are environmental pollution, persistent changes in the soil ecology, physiochemical composition, decreasing agricultural productivity and cause several health hazards. Climatic factors are responsible for enhancing abiotic stress on crops, resulting in reduced agricultural productivity. There are various types of abiotic and biotic stress factors like soil salinity, drought, wind, improper temperature, heavy metals, waterlogging, and different weeds and phytopathogens like bacteria, viruses, fungi, and nematodes which attack plants, reducing crop productivity and quality. There is a shift toward the use of biofertilizers due to all these facts, which provide nutrition through natural processes like zinc, potassium and phosphorus solubilization, nitrogen fixation, production of hormones, siderophore, various hydrolytic enzymes and protect the plant from different plant pathogens and stress conditions. They provide the nutrition in adequate amount that is sufficient for healthy crop development to fulfill the demand of the increasing population worldwide, eco-friendly and economically convenient. This review will focus on biofertilizers and their mechanisms of action, role in crop productivity and in biotic/abiotic stress tolerance.

**Keywords:** Abiotic Stress, Biotic Stress, Biofertilizers, Crop Productivity, Plant-Root Interaction

### Introduction

The world population will reach 9 billion by 2050 in accordance with Food and Agricultural Organization; as a result, there should be an enhancement in crop yield to meet the food demand. Soil is an important source of food production in human lifespan. In the last decades, due to the increase in agricultural practices such as pesticides and chemical fertilizers it has been degraded at a universal scale and causes lower fertility due to loss in biodiversity, water retention, and disturbance in biogeochemical cycles. Soil health and plant productivity are severely influenced by numerous interactions among plant, soil, and microorganisms. Soil microbes cooperate with one another and also with plant roots in numerous means providing a wide variety of essential acts which are valuable for sustaining the ecological balance in soil. Plant microbial interactions are positive if they improve plant survival, nutritional status, and crop productivity and they are negative if they reduce plant growth. The application of biofertilizers can be a probable approach to improve soil microbial status that stimulates the natural soil microbiota therefore influencing nutrient accessibility and decomposition of organic matter. It was observed that the supply of biofertilizers in apricot modifies the microbial composition and degradation process which could be efficient in nutrient cycles in soil under field conditions. The capability of biofertilizers to form a high-level microbial diversity in soil may outcome better crop productivity for sustainable agriculture.

Nutrients are required by every living creature in this world. A total of 17 essential plant nutrients are mandatory for the proper development of plants. These 17 nutrients are divided into three classes based on the amount required such as major nutrients (carbon, hydrogen, oxygen, nitrogen, phosphorus, and potassium), minor nutrients such as sulfur, calcium, and magnesium, and micronutrients (nickel, zinc, molybdenum, manganese, iron, copper, chlorine, and boron). The plant takes up oxygen, hydrogen, and carbon from air and water, but the other nutrients are taken from soils in inorganic forms. Biofertilizer or biological fertilizer is a material that contains living or dormant microorganisms that colonize the rhizosphere or present inside the plants and directly or indirectly promotes the growth of plants by supplying nutrition. Microorganisms present in soil used as biofertilizers can mobilize the nutrient from soil and convert them into a usable form from unusable form through biological processes like nitrogen fixation, phosphorus solubilization, zinc solubilization, siderophores production, and producing plant growth-

promoting substances. Biofertilizers are applied to seed, root, soil, or by the foliar spray to enhance the microbial activity through their multiplication which then mobilizes the nutrients to target plants which remarkably improved the soil fertility and sooner increases the crop health and production.

Biotic stress is responsible to damage plants by pathogenic organisms like bacteria, fungi, viruses, parasites, and insects and by other harmful plants. They lead to declining the crop productivity by causing diseases such as vascular wilts, leaf spots, cankers, nutrient deficiency, systematic damage, chlorosis, stunting and reduce plant

vigor, ultimately causing the death of the plants. The indirect mechanisms include the induction of acquired systematic resistance, plant pathogen molecular patterns (PAMPs) which in turn trigger the immunity and plant resistance proteins. Microorganisms solubilize the phosphorus and zinc, fixing the nitrogen and other macro- and micronutrients which promote the growth of the plants under biotic stress condition by providing nutrition. They also enhance the stress resistance in plants by expressing the gene of phytohormones and stress-related metabolite. When pathogen attacks, the plant produces various compounds within the tissues that lead to the activation of defense mechanisms inside the plants such as induced systematic resistance, peroxidases, phenylalanine ammonia-lyase, polyphenol oxidase, and hypersensitivity.

Climatic change is one of the major factors for enhancing abiotic stress on crops which results in reduced crop productivity. Climatic-related abiotic stresses included drought, waterlogging, excessive heat, and soil-related abiotic stresses are fertility, heavy metals, and salinity; all these are responsible for the poor yields of crops around the whole globe. There is less water available to plants during drought conditions, and biofertilizers have the potential to produce cytokinin, gibberellins, abscisic acid, and IAA, which cause the plant to increase its growth, root length, total surface area, and the formation of root hairs and lateral roots, which increases water absorption from water-deficient soil. Pollutants released from industry without any further operation if released in the environment then they cause the accumulation of heavy metals such as copper, lead, nickel, zinc, etc which have detrimental effects on the plants and animals. These heavy metals are removed from the environment by micro- and macro-nutrient solubilizing and mineralizing microorganisms. Heat stress causes cellular changes like production of reactive oxygen species, reduction in cell turgidity, reduction in water uptake, reduction in growth of plants, ultimately leading to death of plant by showing initial symptoms like leaf senescence, damages to chloroplast, wilting of plant, and chlorosis, whereas low temperature causes the inactivation of protein and reduces the cell membrane fluidity leading to increases in photosynthesis, imbalance of water transport. All these temperature-related stresses coped up by plants after the accumulation of the hydrophilic and osmolytes protein.

Literature review:

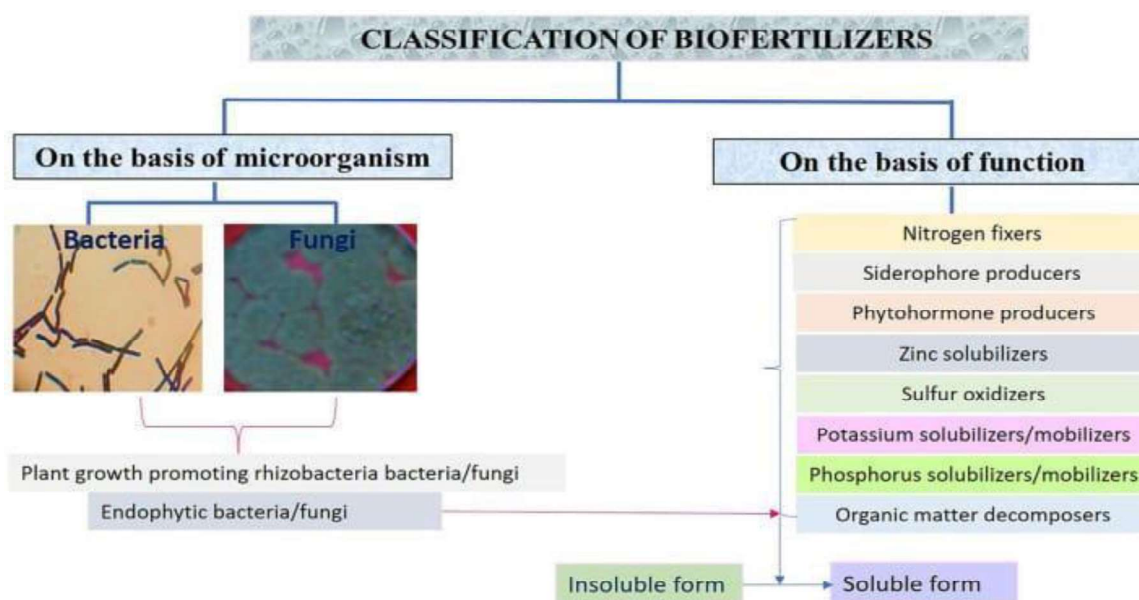
- biofertilizers — microbial inoculants such as rhizobia, Azotobacter, Bacillus, Pseudomonas, arbuscular mycorrhizal fungi (AMF) and microalgae — in sustaining crop productivity while reducing chemical inputs. Reviews and meta-analyses report consistent yield and nutrient-use efficiency improvements when biofertilizers are integrated into cropping systems, and they document substantial potential for reducing synthetic N and P fertilizer requirements (Chaudhary, 2022; Santos, 2024).
- Mechanistically, recent work has clarified how biofertilizers confer both nutritional and stress-protective benefits. Key mechanisms include biological nitrogen fixation, solubilization/mobilization of phosphorus and potassium, production of siderophores, secretion of phytohormones (e.g., IAA), synthesis of ACC-deaminase (which lowers stress ethylene), antioxidant enzyme induction, and production of lytic compounds that suppress pathogens. These multifunctional traits enable microbes to improve nutrient availability and strengthen plant resilience to abiotic stresses (drought, salinity, temperature extremes, heavy metals) and biotic stresses (pathogens, nematodes). The importance of ISR (induced systemic resistance) and microbe-triggered modulation of plant signalling pathways has been emphasised in several recent reviews (de Andrade et al., 2023; Chaudhary, 2022; Salwan et al., 2023).
- Applied studies from 2020–2024 provide crop-level evidence: inoculation with PGPR and AMF improved drought tolerance through enhanced root growth and osmotic adjustment, while certain Bacillus and Pseudomonas strains reduced salt injury by maintaining K<sup>+</sup>/Na<sup>+</sup> balance and producing osmoprotectants. Field and pot trials also demonstrate reduction of heavy-metal uptake via microbial biosorption and immobilization mechanisms. Such applied reports underscore that targeted biofertilizer use can measurably enhance yield stability under stress conditions (Samantaray et al., 2024; Zhao, 2024).
- Despite promising results, contemporary literature repeatedly flags limitations and research gaps. These include variable field efficacy due to soil, climate and crop interactions; inconsistent regulatory frameworks and quality standards across regions; scale-up challenges for low-cost, high-viability products; and the need for long-term ecological assessments of introduced strains. Several authors call for standardized efficacy testing, genomic-guided strain selection, and integrated management packages (biofertilizer + organic amendments + best agronomy) to achieve reliable outcomes at scale (Chaudhary, 2022; Santos, 2024; Zhao, 2024).

#### **Biofertilizers:**

Biofertilizer refers to the use of microorganisms to meet nutritional needs, whereas in other countries, the term microbial bioinoculant is used. Biofertilizers are bio-based organic fertilizers that either could be from plant or animal sources or from living or dormant microbial cells that have the potential to improve the bioavailability and bioaccessibility of nutrient uptake in plants. biofertilizers are properly defined as “the preparations containing live

microbes that help in enhancing soil fertility by fixing atmospheric nitrogen, solubilizing phosphorus or decomposing organic wastes or by elevating plant growth through the production of growth hormones with their biological activities. Biofertilizers are generally applied in solid or dry forms, which are prepared after packing on suitable carriers such as clay minerals, rice bran, peat, lignite, wheat bran, humus, and wood charcoal. Carriers increase the shelf life and enable the easy handling of microbial inoculants. The benefits of biofertilizers include low cost, enhanced nutrient availability, improved soil fertility, protect plants from soil-borne pathogens, sustainable agricultural production, enhanced biotic and abiotic stress tolerance, promote phytohormone production, improve soil health, causing less environmental pollution, and its continued use improves the fertility of soil considerably. Based on the source and raw material, global biofertilizer is marketed under two major categories like organic residue-based biofertilizer and microorganisms-based biofertilizer. Green manure, crop residues, treated sewage sludge, and farmyard manure are generally organic-based biofertilizers. While on the contrary, microorganism-based biofertilizers contain beneficial microorganisms like bacteria, fungi, and algae. Directly or indirectly, these biofertilizers mediate the performance of plant growth. Direct mechanisms that act upon plants directly include nitrogen fixation, phosphate solubilization, micronutrient solubilization, and the production of phytohormones. The indirect mechanism generally protects the plant from the deleterious effect of the pathogens by releasing lytic enzymes, antibiotics, siderophores, and cyanide production.

Figure 1:



### Types of biofertilizers and their role in crop production and soil health maintenance

Biofertilizers are classified based on microorganisms such as bacteria and fungi and function of the biofertilizers

#### ➤ Nitrogen-fixing biofertilizers

Nitrogen is the vital macro-nutrient essential by plants because it improves the growth of the shoot system, helps in reproduction, is a constituent of chlorophyll responsible for the deep green color, and also increases the size of the grains. Although the nitrogen content in the atmosphere is 78% by a mass fraction, dinitrogen contains triple bonds and is an unavailable form of nitrogen present in the air for the plants. Dinitrogen should be first converted into soluble non-toxic form ammonia by the diazotrophs through the biological process of nitrogen fixations. This ammonia is then converted to the nitrite and nitrate by the ammonia-oxidizing bacteria and by nitrifying bacteria, respectively. The unused nitrate is converted to the atmospheric nitrogen in the deeper soil horizons through the process of denitrification which will then escape to the atmosphere as dinitrogen gas. This is the typical path of the nitrogen cycle

#### ➤ Symbiotic nitrogen-fixing microbes

In the process of symbiosis, macro-symbiont is the plant and microsymbionts are the prokaryotic bacteria. Rhizobium and legume symbiosis is one of the most studied mutualistic relationships between plant root nodules and nitrogen-fixing microorganisms. Mutualistic relationships are initiated when the plant began to secrete the flavonoids and iso-flavonoids in its rhizosphere, where it is recognized by Rhizobium. It started to do infection by differentiating root hairs, developing infection thread up to the root hair cell where

infectious thread releases all its bacteria in the cytoplasmic region. Then, bacterial cell are terminally differentiated into the bacteroides, and the further development of bacteroides leads to the formation of symbiosome which is the site of nitrogen fixation. This atmospheric nitrogen fixation inside the nodule is carried out by the nitrogenase enzyme. Examples include Rhizobium associated with leguminous plants, Frankia (actinomycetes) associated with non-leguminous plants. Azolla and the blue-green alga Anabaena azollae, and association of cyanobacteria with gymnosperms. Fixation of N helps to improve the soil fertility and crop productivity.

➤ **Free-living nitrogen-fixing bacteria**

Mostly Azotobacter is studied because it is a free-living, non-symbiotic, and phototropic bacterium. Azotobacter chroococcum can be used as a biofertilizer because it has the potential to fix 10 mgN/g of carbon source supplied in-vitro. Plant hormones such as indole acetic acids, gibberellic acids, naphthalene acetic acid, and vitamin B complex are produced by Azotobacter. It inhibits the root pathogens while promoting root growth, helps in mineral uptake, and improves soil fertility.

➤ **Nitrogen-fixing bacteria**

Spirillum was found associated with the roots of the grain which were also capable of fixing nitrogen. Azospirillum is gram-negative, non-nodulating, aerobic-associative nitrogen-fixing bacteria with plants having a C4 dicarboxylic pathway of photosynthesis, such as sugarcane, maize, sorghum, bajra, and cereals like wheat, rice, barley. They also produce cytokinin, gibberellins, and indole acetic acid, which aid in the uptake of N, P, and K and promote the growth of roots.

➤ **Phosphorus-solubilizing biofertilizers**

Phosphorus is the second macro-nutrient that is responsible for limiting the growth of plants. It is an important constituent of organic and nucleic acids and is responsible for the synthesis of ATP and several amino acids. P helps in the nodulation process, amino acid synthesis, and proteins in leguminous plants. Soluble form of phosphorus is phosphate anion (orthophosphate), and their uptake is facilitated by rhizospheric microbes which help in plant nutrition. There are different microbes which can solubilize the remaining unavailable form of P into available form via organic acid production by bacteria which lowers the pH of the soil, leads to the dissolution of the phosphate compounds, and makes them available for the plant's nutrition.

➤ **Phosphorus-mobilizing biofertilizers**

They are beneficial bacteria that effectively mobilize the soluble phosphorus and mineralization of the organic phosphorus compound, both are unavailable form of phosphorus. Bacillus, Pseudomonas, and Rhizobium are representative phosphorus-mobilizing microorganisms (PMB). Three different mechanisms have been reported for this process. First, PMB is releasing the phosphatases enzyme. Second, PMB is producing organic acids. The last one added PMB may interact symbiotically with the other fungal mycorrhiza which mobilizes the soluble phosphorus from distant places where plant roots cannot reach by absorbing soluble phosphate by hyphae. One of the major advantages of Arbuscular mycorrhiza is transporting both inorganic and organic forms of phosphorus to plants.

➤ **Sulfur-solubilizing biofertilizers**

➤ **Sulfur helps in chlorophyll formation, activation of a certain enzyme, amino acid formation, vitamin formation** and promotes nodulation, vital for the development of all plants. Sulfur solubilizers are also known as sulfur-oxidizing bacteria because they are transforming the most insoluble form of sulfur that is hydrogen sulfide (H<sub>2</sub>S) into an available form of sulfur known as sulfate (SO<sub>4</sub><sup>-2</sup>), and the reverse of this process is known assimilatory sulfate reduction which is mediated by sulfate-reducing bacteria. Sulfur transformation in the soil is primarily due to the microbial activity through the processes of mineralization, immobilization, oxidation, and reduction.

➤ **Zinc-solubilizing biofertilizers**

Zinc is required during protein synthesis, DNA-protein interaction, growth hormone production, seed development, production of chlorophyll and protects plants from stress conditions. Insoluble forms of zinc are mostly ZnO, Zn<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>, ZnCO<sub>3</sub>, and metallic Zn. The usable form of zinc by the plant is divalent cations. Zinc-solubilizing fertilizers contain the zinc solubilization bacteria which produce the organic acids to solubilize the insoluble zinc to Zn<sup>+2</sup>, thereby enhancing zinc uptake in plants.

➤ **Phytohormone-producing biofertilizers**

Plant hormone or phytohormone plays a substantial role in plant development, secreted by both plants and microorganisms. Plant hormone production is an important feature of the beneficial microbes which is producing the indole-3-acetic acids, gibberellins, cytokinin, etc. Auxin helped in the differentiation and division of plant cells. Cytokinin prevents the premature leaf senescence of plants. Abscisic acid is also identified as hormone which is produced by plants during stress conditions. Gibberellins are involved in seed germination, shoot elongation, flowering, and fruiting. These hormones are generally secreted by microorganisms under environmental stress conditions to protect the plants by modulating the phytohormone level inside the host plants.

➤ **Organic matter decomposer biofertilizers**

Soil organic matter is a mixture of living organisms consisting of bacteria, fungi, and insects, and the non-living part which includes fresh organic residues or waste, the dead and decaying matter of living organisms is generally known as humus. In organic matter generally, cellulose, lignin, hemicellulose, chitin, and lipids are present which are degraded by microbes such as bacteria, actinomycetes, and fungi. The organic-matter-degrading organisms break down the SOM into simpler or inorganic from which they derive energy and carbon for their growth. Examples of bacteria include *Bacillus subtilis* and *Pseudomonas fluorescens* and of fungi include ectomycorrhizal fungi. *Trichoderma* spp. involved in the degradation of litter at a faster rate releases antimicrobial compounds, improves the physicochemical properties of soil, and improves microbial diversity.

➤ **Endophytic bacteria as biofertilizers**

Mutualistic microorganisms that employ the whole or part of their life cycle inside the plant tissues are known as endophytes. Endophytes are of interest because they improve the nutritional requirements of the non-leguminous and leguminous plants by nitrogen fixation, phosphate solubilization, or by siderophore production. These bacteria have the potential to suppress pathogenic effects by activating the plant defense system.

➤ **Plant growth-promoting rhizobacteria**

PGPR is used as biofertilizers; it represents the variation of soil bacteria that live in association with the rhizosphere, rhizoplane associated to root surface, and endophytes present inside the intercellular places. PGPRs are soil bacteria which increase the growth and enhance the tolerance of plants toward stress conditions. There are diverse mechanisms shown by PGPR which support the plant growth such as N<sub>2</sub> fixation, macro- and micronutrient mineralization, secretion of exopolysaccharides, phytohormone production, siderophore, hydrogen cyanide to prevent the growth of phytopathogens, antibiotics, etc. *Rhizobium lupini* increased alfalfa growth and enhanced nutrient uptake efficiency. Application of biofertilizers such as *Pseudomonas taiwanensis*, *Bacillus* spp., and *Pantoea agglomerans* improved the maize growth, yield, and soil health parameters.

**Role of biofertilizers in biotic stress management**

The outbreak of plant diseases in nature necessitates sustainable agriculture with minimum use of agrochemicals. For a long time, the use of chemicals has posed a significant risk to the environment and the agricultural sector. Long-term use of pesticides, on the other hand, harms both plant/soil health and eventually leads to significant crop loss. Thus, effective and eco-friendly phytopathogen control strategies such as biofertilizers are required. The exploitation of potential biofertilizers as endophytes could be useful to improve crop plants from various bacterial and fungal diseases. Biological control of plant diseases occurs via destruction of pathogens via beneficial microbes such as *Bacillus* spp., *Pseudomonas* spp., *Streptomyces*, *Pantoea* spp., and several fungal spp. Such endosymbiont group of biocontrol agents being friendly, they not only colonize internal plant tissue but also protect host plant throughout its life cycle without causing any apparent damage.

Biofertilizers in the form of potential biocontrol agents represent a safe alternative to harmful chemicals like fertilizers, herbicides, pesticides, and insecticides. Consequently, the use of biofertilizers is receiving special attention for the management of phytopathogens that are comprised of bacteria, fungi, virus, aphids, and nematodes. Their ubiquitous nature and the ability to reside within plant tissues make them unique, showing multidimensional interactions within the host plant.

**Role of biofertilizers in biotic stress tolerance**

Category	Example	Role	Mechanism of Action
Nitrogen Fixers	Rhizobium, Azotobacter, Azospirillum	Protect plants from pathogen attacks and improve immunity Enhance nitrogen supply, trigger induced systemic resistance	Enhance nitrogen supply, trigger induced systemic resistance
Zinc Solubilizers	Bacillus, Pseudomonas	Reduce fungal and bacterial infection.	Increase zinc availability, enhance plant defense enzyme activity.
Sulfur Oxidizers	Thiobacillus	Suppress soil-borne fungal pathogens.	Produce sulfuric acid and other compounds toxic to pathogens
Phosphorus	Bacillus megaterium, Pseudomonas striata	Suppress root pathogens and nematodes.	Release organic acids and enzymes, improve P nutrition and root defense
Organic Matter	Trichoderma, Aspergillus	Control soil-borne diseases.	Produce antibiotics, lytic enzymes, and compete with pathogens

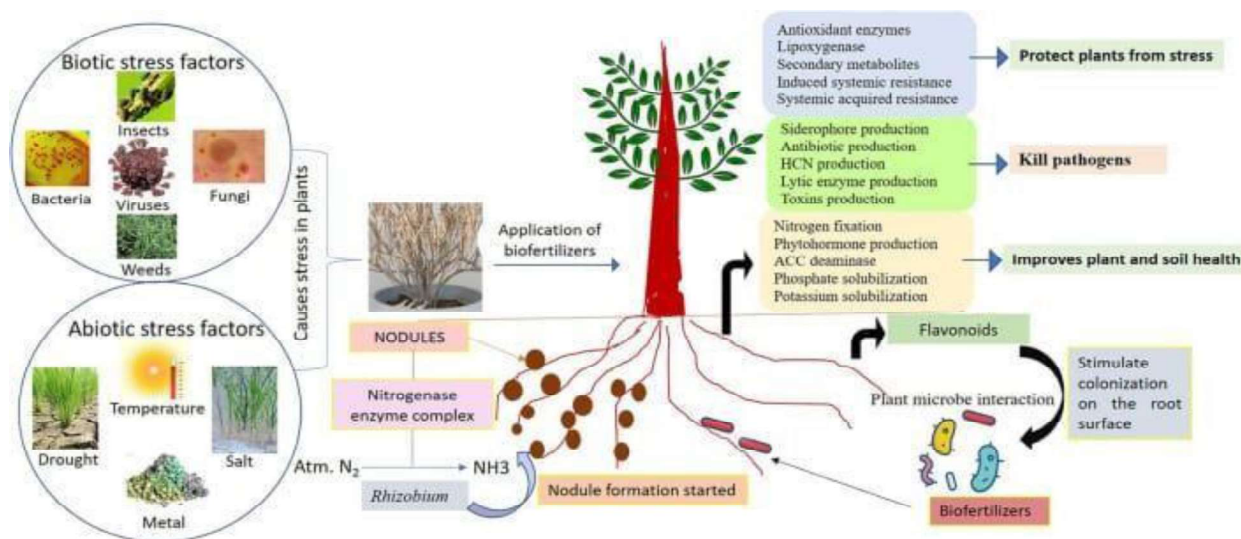
(Source – Primary data)

**Role of biofertilizers in abiotic stress management**

Climate change is one of the major reasons for the increasing abiotic stresses on the crops, which results in reducing the world's agriculture productivity. Abiotic stresses like drought, salinity, waterlogging, and excessive heat are responsible for the poor yield of crops. In recent years, the abiotic stress has increased so fast, because of the fluctuation of climates or climate change, and it has caused an unusual rise in the weather conditions and incidents, which is responsible for the substantial losses of crops around the globe. These abiotic stresses induce several physiological, biochemical, and morphological changes in plant that finally affect the economic yield of crop plants, and it was reported that the yield loss from abiotic stress is about 51–82%, which if continues will affect the goal of sustainable food production.

Biofertilizers as endophytes are found to have diverse associations with its host plant such as symbiotic, parasitic, and mutualistic and colonize plant tissues without causing any disease, thus benefiting for plants. Endophytes may benefit from mutualistic associations as they obtain nutrients from the hosts, and they spread by host seed transmission. They are also able to enhance the nutrients uptake like nitrogen, magnesium, zinc, and phosphorus from soil and provide to the host plant for better growth and survival. It is well-identified that plant biofertilizers play a significant role in supporting the growth of crops under different abiotic stresses.

Figure 02



Role of biofertilizers for maintenance of crop productivity and soil health

**Role of biofertilizers in abiotic stress tolerance**

Abiotic stress factor	biofertilizers	Mechanism of action	Benefit to plants
Drought	Azospirillum, bacillus subtilis	Enhance root growth, improve water uptake	Improves drought tolerance, better water-use efficiency
Salinity stress	Azotobacter, mycorrhizal fungi	Osmolyte production, ion homeostasis regulation, exopolysaccharide secretion	Reduces salt toxicity, maintains plant growth
Temperature	Azospirillum	Production of heat- shock proteins, antioxidants, and protective metabolites	Protects cells from oxidative damage, stabilizes enzymes
Soil nutrient deficiency	Rhizobium, azotobacter	Nitrogen fixation, phosphate & potassium solubilization, phytohormone production	Enhances soil fertility and nutrient availability
Oxidative stress	Bacillus, pseudomonas	Antioxidant enzyme production (SOD, CAT, peroxidases), secondary metabolites	Protects plant cells from ROS (reactive oxygen species) damage

(Source – Primary data)

- **Drought stress**  
Drought is one of the most critical abiotic stresses that reduces water availability, photosynthesis, and crop productivity. Plants under drought stress often produce high amounts of ethylene, a stress hormone that inhibits growth. Biofertilizers such as Azospirillum and Bacillus subtilis help plants by producing ACC deaminase, an enzyme that lowers ethylene levels, thus reducing stress effects. Mycorrhizal fungi also play a key role by increasing root surface area, which enhances water absorption from deeper soil layers. Additionally, some microorganisms produce exopolysaccharides (EPS) that improve soil structure and water retention. As a result, biofertilizers improve water-use efficiency, root development, and overall plant tolerance to drought.
- **Salt Stress (Salinity):**  
Salinity stress occurs due to excessive accumulation of salts in soil, mainly sodium (Na<sup>+</sup>) and chloride (Cl<sup>-</sup>) ions, which cause osmotic stress and ion toxicity in plants. This leads to leaf burn, nutrient imbalance, and stunted growth. Biofertilizers such as Pseudomonas fluorescens, Azotobacter, and arbuscular mycorrhizal fungi help plants overcome salinity by producing osmoprotectants and antioxidants that protect plant cells. They also regulate ion uptake by reducing sodium absorption and maintaining a healthy potassium/sodium ratio. Some bacteria produce exopolysaccharides that bind salt ions, reducing their harmful effect on roots. These mechanisms allow plants to maintain chlorophyll content, photosynthetic efficiency, and normal growth under saline conditions.
- **Temperature Stress:**  
Extreme temperatures negatively affect plant metabolism, enzyme activity, and cell membrane stability. High temperatures can denature proteins and reduce grain filling, while low temperatures slow down metabolic processes and damage tissues. Biofertilizers such as Azospirillum, Pseudomonas, and certain cyanobacteria help plants withstand temperature fluctuations by producing heat-shock proteins, antioxidants, and protective secondary metabolites. These compounds reduce oxidative damage and stabilize cellular structures. Through these protective mechanisms, biofertilizers enhance plant resilience against both heat and cold stress, ensuring better survival and productivity in adverse climates.
- **Heavy Metal Stress:**  
Heavy metal contamination of soil due to industrial activities and fertilizers is a major challenge for agriculture, as metals like cadmium (Cd), lead (Pb), and zinc (Zn) are toxic to plants. They inhibit enzyme activity, reduce nutrient uptake, and lead to poor plant growth. Biofertilizers such as Pseudomonas putida, Rhizobium, and mycorrhizal fungi mitigate this stress by producing siderophores, organic acids, and chelating agents that bind heavy metals and reduce their availability to plants. Some microorganisms also immobilize or transform metals into less toxic forms through biosorption.

and bioaccumulation. This reduces heavy metal toxicity, improves nutrient absorption, and enhances plant tolerance in contaminated soils.

➤ **Soil Nutrient Deficiency:**

Nutrient deficiency is another abiotic stress that reduces crop yield and soil fertility. Biofertilizers such as Rhizobium, Azotobacter, phosphate solubilizing bacteria (PSB), and potassium solubilizers play a crucial role in nutrient cycling. They fix atmospheric nitrogen, solubilize insoluble phosphorus and potassium, and release phytohormones that stimulate root growth. This ensures continuous nutrient availability in the soil, strengthens plants, and reduces stress caused by poor soil fertility.

**Conclusion:**

Agriculture systems have to face the task of food production, stress management, and dependency on agrochemicals. The presence of pest and pathogen in crops causes decrease in crop yield and heavy crop losses every year. The occurrence of abiotic stresses due to the change in climatic conditions leads to difficult challenge to crop production worldwide. Different effective approaches should be employed to reduce crop output loss and control diseases. Hence, the necessity to implement the eco-friendly approaches such as biofertilizers is of great importance for sustainable agriculture. The application of biofertilizers not only improves plant health parameters but also enhances the crop productivity, soil health and protects from stress environment. More research has been focused on physiological and molecular aspects under different conditions with different crops using biofertilizers under field conditions.

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