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REVIEW ARTICLE

A Sustainable Agriculture Method Using Biofertilizers: An Eco-Friendly Approach

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Abstract

Biofertilizers symbolize a promising and eco-friendly approach to increasing agricultural productivity while reducing the hazardous environmental impact of chemical fertilizers. Biofertilizers are compounds containing living microorganisms or their byproducts that, when applied to soil, enhance nutrient uptake and promote plant growth. These biological agents include nitrogen-fixing bacteria, mycorrhizal fungi, and phosphate-solubilizing microorganisms. Biofertilizers are well recognized for their composition, cost-effectiveness, and environment-friendly nature. These are safe substitutes for hazardous synthetic fertilizers. They contribute to soil health and biodiversity conservation by enriching the soil with beneficial microorganisms. This review provides an overview of biofertilizers, their significance in modern agriculture, and their potential to promote sustainable farming practices.

Keywords

biofertilizer; soil microbes; sustainable agriculture; mycorrhizal fungi

Introduction

The demand for food is rising as a result of the growing world population. According to FAO projections, there will be a 60% rise in the overall demand for agricultural goods by 2030 (1). In the 21st century, meeting this need will require increasing agricultural output while reducing contamination and pollution of the environment (2). Overuse of chemical fertilizers has led to several drawbacks, such as high prices, contaminated soil, problems with water retention, disturbance of soil fertility, and interference with soil nutrients and biogeochemical cycles (3). It is essential to switch from chemical fertilizers to biofertilizers to solve these problems.

"Biofertilizer" is a phrase that combines the terms "bio," which refers to living things, and "fertilizer," which refers to materials, either natural or artificial, that are used to encourage plant development. Biofertilizers are biological products that contain living microorganisms that aid in plant development in many ways. These mechanisms include increasing nutrient availability, root area, root biomass, and the plant's capacity to absorb nutrients. These organic fertilizers increase the amount of nutrients that plants absorb; they are derived from living creatures, including plants and animals as well as microbial cells that contain nutrients. The biofertilizers can be used either dry or solid, usually after being mixed with appropriate carriers like lignite, peat, humus, clay minerals, or wheat bran. The biofertilizers' shelf life is extended and their handling is made easier by several carriers. To turn atmospheric nitrogen into ammonia, which plants may use, biofertilizers rely on certain microbes. Through several mechanisms, including phosphate solubilization, fixation of nitrogen, phosphate mobilization, and improving plant nutrient absorption, they supply nutrients. The low cost, kindness toward the environment, ease of application, enhanced soil production, and biological diversity are some advantages of biofertilizers. They also help prevent plant diseases and get rid of dangerous pollutants that might harm crops. Because of these advantages, biofertilizers are crucial for promoting sustainable agriculture. The first investigation on legume-*Rhizobium* symbiosis for use in commercial biofertilizer production was carried out in India (4). Biofertilizers not only increase crop output and soil fertility, but they also offer defense against illnesses and insect pests. It has been demonstrated that using biofertilizers strengthens roots, lengthens plant life, eliminates harmful substances, boosts seedling survival rates, and reduces flowering time (5).

Plants require 17 fundamental elements for optimal growth and development, of which phosphorus (P), nitrogen (N), and potassium (K) are the 3 macronutrients. Nitrogen-fixing bacteria and cyanobacteria are frequently utilized as biofertilizers; on the other hand, phosphate-solubilizing bacteria are combined with molds and fungi to increase phosphate availability (6). The Indian government has taken steps to enhance the potential of the current biofertilizers by mixing them with chemical fertilizers and giving them to farmers. Utilizing biofertilizers significantly enhances the microbial condition of the soil, which in turn activates the native soil microbiota. As a result, there is an improvement in the organic matter breakdown process and nutritional accessibility. Crop output may be increased by inoculants that introduce a diverse microbial population to the soil. Organic inoculants in the soil can mobilize nutrients and change them into forms that are beneficial through processes including nitrogen fixation, the creation of growth-promoting chemicals, and the solubilization of zinc and phosphorus.

In addition to being sprayed on leaves, biofertilizers can also be applied directly to the soil, seeds, roots, and other plant parts. This aids in the mobilization of nutrients in the target plants by enhancing microbial activity. Therefore, when soil fertility is increased, crops grow healthier and yield more. The process by which biofertilizers fix nitrogen from the atmosphere, solubilize nutrients from plants like phosphates and potash, synthesize components that promote development, and keep a steady 2:1 C: N ratio is known as biological nitrogen fixation (BNF) (7). Based on their characteristics and functions, biofertilizers may be divided into 5 main groups: rhizobacteria that promote plant development, P-mobilizing biofertilizers, nitrogen-fixing biofertilizers, P-solubilizing biofertilizers and biofertilizers for micronutrients. Potash mobilizers such as *Frateuriaaurentia*, sulphur solubilizers such as *Thiobacillus* sp., and manganese solubilizers such as fungal cultures of *Penicillium citrinum* are among the recent findings that are being explored for commercial applications. The importance of biofertilizers and their vital function in sustainable agriculture are emphasized in this study. It highlights the advantages of applying biofertilizers in place of chemical fertilizers in agricultural practices. Based on their composition and roles, such as nitrogen-fixing, P-solubilizing, P-mobilizing, and rhizobacteria that promote plant development and micronutrient-based biofertilizers.

History of biofertilizers

The commercial history of biofertilizers began with the introduction of 'Nitragin' by Nobbe and Hiltner in 1895. This product involved a laboratory culture of Rhizobia, marking a significant step in the development of biofertilizers. Subsequently, researchers discovered other microorganisms like *Azotobacter* and blue-green algae that could be utilized as biofertilizers. In India, the exploration of biofertilizers commenced in 1920 under the guidance of N.V. Joshi. The isolation of *Rhizobium* from various leguminous crops was a pioneering achievement and it laid the foundation for extensive research by scientists such as Gangulee, Sarkaria, and Madhok. Their work delved into the philosophy of nodule bacteria and its inoculation methods to enhance crop productivity (8). The following table outlines the key milestones in the history of biofertilizers in India (Table 1).

Need for Biofertilizers

The extensive use of chemical fertilizers has given rise to various environmental concerns, including soil pollution, water basin contamination and depletion of essential microorganisms, increased susceptibility of crops to diseases, and a decline in soil fertility. The high demand for fertilizers far exceeds their availability and the use of fossil fuels in their production contributes to rising costs. One of the primary reasons for the reduction in soil fertility is the widening gap between the removal of nutrients by crops and the supply of nutrients. On the other hand, long-term usage of biofertilizers provides a more accessible, economical, efficient, and ecologically friendly option, especially for marginal and small-scale farmers. Looking ahead, it's estimated that by 2030, to achieve the targeted food grain production of 321 million tonnes, we will require approximately 28.8 million tonnes of nutrients. However, the available supply is projected to be only 21.6 million tonnes, resulting in a deficiency of approximately 7.2 million tonnes". Biofertilizers are essential for enhancing plant growth as they contain microorganisms crucial for nutrient absorption from the soil. Each crop has specific nutrient requirements and the selection of an appropriate biofertilizer is imperative. Proper classification of biofertilizers is essential as different crop species demand precise nutrient levels. Categorization can be based on the type of microorganism contained or the biofertilizer's function, ensuring that the right biofertilizer is chosen to improve crop yield and quality (Table 2).

Table 1. History of biofertilizers in India

In 1895, Commercial history of biofertilizers began with the launch of ‘Nitragin’ by Nobbe and Hiltner.
In 1920, The first study on legume Rhizobium symbiosis was started by N.V Joshi and the first commercial production was started in early 1956.
Now, *Rhizobium* and blue-green algae (BGA) can be considered as established biofertilizers while *Azolla*, *Azospirillum*
In 1934, Documented production of rhizobium biofertilizer was done by M.R. Madhok.
In 1939, the Discovery of nitrogen fixation by Blue Green Algae (BGA) in rice fields by P.K.Dey.
In 1956, the First commercial production of biofertilizers was done.
In 1957, the Solubilization of phosphate by microorganisms was first studied by Sen and Pal.
In 1958, the Standardised quality of legume inoculant was first attempted by A.Sankaran.
In 1960, the Isolation of the first non-symbiotic Nitrogen-fixing organism *Derxiagummosa* in the world by P.K. Dey and R.Bhattacharya.
In 1964, Demand for biofertilizers for soybeans increased in Madhya Pradesh.
In 1968, ICAR set up an all-India pulse improvement project and a Soybean project where *Rhizobium* got priority.
In 1969, the Use of Indian peat as the carrier was reported by V.Iswaran.
In 1976, the Indian Standards Specification for *Rhizobium* was done.
In 1977, the Use of Indian Standards Institution (ISI) marked *Rhizobium*.
In 1979, the All India Coordinated project was initiated on Biological nitrogen fixation.
Again in 1979, Use of one more inoculant as ISI mark i.e.*Azotobacter*.
In 1983, Setting up of the National Project on Development and Use of Biofertilizer by the Ministry of Agriculture, Govt. of India.
In 1985, the First National Productivity Award on biofertilizer.
In 1988, the National Facility Centre for Biological Nitrogen-Fixation was set up at Indian Agricultural Research Institute.
In 1990 – 2000, towards the end of the 20th century commercial production of *Azotobacter*, *Azospirillum,* and Blue-green algae started.
In 2002, As per the Fertilizers Control Order (FCO), 4 biofertilizers namely *Rhizobium*, phosphate solubilizing bacteria, *Azotobacter,* and *Azospirillum* were approved for commercial production, and in 2010 mycorrhizal biofertilizers were added to the list.
In 2006, the Ministry of Agriculture and Farmers Welfare in collaboration with NABARD provided credit credit-linked subsidy scheme for compost and biofertilizer manufacturing units.
In 2011, MGM-3 media was prepared to develop three biofertilizers namely *Azospirillum*, PSB, and PGPR together in one place for farmers.
From 2012 onwards, *Acetobacter* was added to the FCO list and recently in 2019 phosphate solubilizing fungal biofertilizer was also added.
In 2014-18, Government schemes aimed at promoting the setting up of manufacturing units of biofertilizers such as soil health management schemes to give subsidies to farmers to set up production units.
From 2020 onwards, Indian states in the southern zone produced more than half of the total production of solid Carrier biofertilizers followed by Western, northern, and eastern zones respectively Indian Institute of Farming Research Systems estimated that India will need about 730 million tons of organic waste to replace 25% of inorganic chemical fertilizers by 2050.
In 2021, Fermented organic manure along with liquid organic fermented manure was added to the FCO-certified list and an amendment was made to FCO rules by the Union Ministry of Agriculture and Farmers Welfare to include a wider range of biostimulants under it.
In 2023, the Government of India published a report titled “The State of biofertilizers and organic fertilizers in India” according to which production of Carrier-based biofertilizers increased and almost doubled in the financial year 2018-19 to 2021-22.

Table 2. Classification of biofertilizers and mode of action

Biofertilizers	Mechanism	Groups	Examples	References
Phosphorus solubilizing	The nitrogen content of the soil will rise as a result of removing atmospheric nitrogen and making it available to the plants.	Free-living	*Nostoc*, *Klebsiella*, *Stigonema*, *Desulfovibrio*, *Rhodospirillum*	(9)
		Symbiotic	*Rhizobium*, *Frankia*, *Anabaena azollae*and*Trichodesmium*	
		Associative symbiotic	*Azospirillum*spp., *Herbaspirillum*spp., *Alcaligenes*, *Enterobacter*, *Azoarcus*spp. *Acetobacter diazotrophicus*	
Nitrogen-fixing	By capturing atmospheric nitrogen and making it available to the plants, soil nitrogen content will be increased.	Bacteria	*Bacillus circulans*, *B. subtilis*, *Pseudomonas striata*, *Penicillium* spp.,*B. polymyxa*, *Microccocus*, *Agrobacterium*, *Aereobacter* and *Flavobacterium*	(10)
		Fungi	*Penicillium* spp., *Aspergillus awamori* and *Trichoderma*	
	Transfer soil phosphorus to the root cortex. These are bio -fertilizers with a broad scope	Mycorrhiza	*Arbuscular mycorrhiza*, *Glomus* spp.,*Gigaspora*spp., *Acaulospora*spp., *Scutellospora*spp. and *Sclerocystis*spp.	(11)
Potassium solubilizing	By creating organic acids that break down silicates and aid in the removal of metal ions, you can solubilize potassium (silicates) and make it available to plants.	Bacteria	*Bacillus mucilaginosus*, *B. circulanscan*, *B. edaphicus* and *Arthrobacter* spp.	
		Fungi	*Aspergillus niger*	(12)
Plant growth Promoting	Create hormones that enhance crop output, nutrient availability, and root growth.	Plant growth-promoting rhizobacteria	*Pseudomonas* spp. *Agrobacterium*, *Pseudomonas fluorescens*, *Arthrobacter*, *Erwinia*, *Bacillus*, *Rhizobium*, *Enterobacter*, *Streptomyces* and *Xanthomonas*	(13)
Micronutrient	Oxidizing sulphur creates sulphates that plants can use.	Sulfur oxidizing	*Thiobacillus* spp.	
	Zinc should be made soluble through oxidoreductive systems, acidification, chelated ligands, and protonation.	Zinc solubilizing	Mycorrhiza, *Pseudomonas* spp., *Bacillus* spp.	(14)

Plant growth-promoting rhizobacteria (PGPRs)

A class of rhizosphere bacteria known as Plant Growth-Promoting Rhizobacteria (PGPR) has been identified for its capacity to promote plant development through several processes, such as nitrogen fixation, phosphate solubilization, and phosphate mobilization. PGPRs are useful as biofertilizers because they colonize plant roots and promote plant growth (15). These advantageous bacteria help plants develop better and provide resistance to biotic and abiotic stress. Auxins, IAA, ethylene, gibberellins, and other growth-regulating hormones are also increased in soil when PGPRs are used (16). Because they offer a sustainable substitute for conventional pesticides, fertilizers, and other additives, PGPRs have a lot of potential applications in agriculture. These microbes greatly influence the overall form and well-being of plants by producing chemicals that promote growth. Considering their capacity for colonization and their mode of action in the rhizosphere, PGPRs have the potential to be highly significant in governing sustainable agriculture.

PGPR directly influences plant growth through mechanisms such as providing plants with compounds synthesized by the bacteria, including phytohormones, or aiding in the uptake of specific nutrients from the environment (Fig. 1). Plants gain indirectly from PGPR because it shields them against the damaging impacts of one or more phytopathogenic organisms. This can be accomplished by making compounds that are hostile to pathogens or by making plants resistant to them. The interactions between PGPR and plants have great commercial potential and show promise for sustainable agriculture. Research into the application of these PGPR has been conducted in various crops, including maize, wheat, oats, barley, peas, tomatoes, potatoes, and cucumbers. PGPR encompasses members of different genera, including *Agrobacterium*, *Alcaligenes*, *Azotobacter*, *Bacillus*, *Frankia*, *Xanthomonas*, and *Enterobacter*, among others (17). These diverse microorganisms contribute to

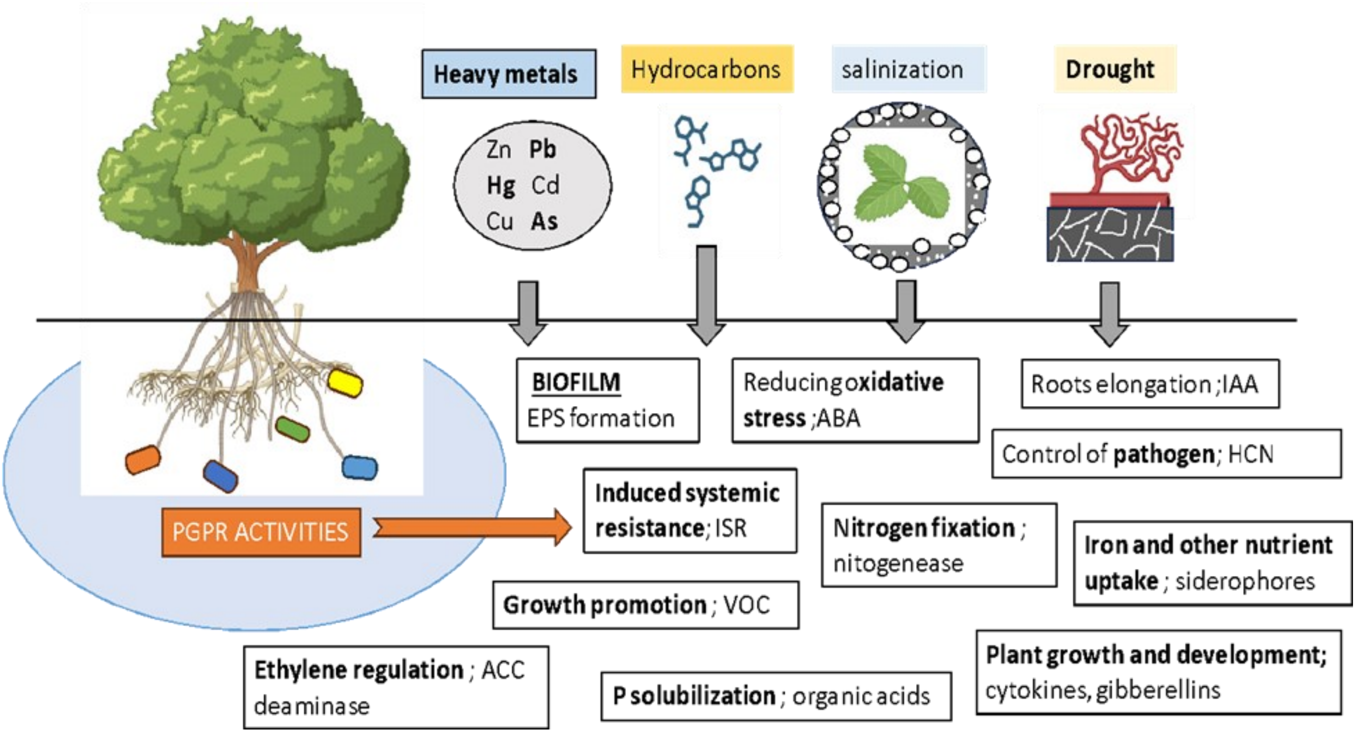

Fig. 1. Effect of PGPR activity on plant growth and crop improvement.

the enhancement of plant growth and the management of plant health in agricultural systems.

Potential role of biofertilizers for crop improvement

Biofertilizers play a vital role in enhancing crop improvement through various mechanisms and their potential contributions include the use of beneficial soil microorganisms, either inoculants or symbionts, effectively supporting crop productivity. These microorganisms can establish mutualistic relationships with plants, providing them with essential nutrients and growth-promoting factors. Biofertilizers produce plant hormones like indole acetic acid (IAA), gibberellins (GA), and cytokinins (CK) which stimulate plant growth, root development, and overall crop vigour. Inoculants in biofertilizers can solubilize essential nutrients, making them more accessible to plants. This increases nutrient availability and facilitates better nutrient uptake by crops. Biofertilizers can also enhance the photosynthetic efficiency of plants, leading to increased biomass production (18). This, in turn, results in improved crop yields and quality. The application of biofertilizers can further boost a plant's ability to tolerate various stress factors, such as drought, salinity, and temperature extremes. Additionally, these can enhance a plant's resistance to diseases, contributing to healthier and more robust crops. Biofertilizers promote improved root architecture, which is essential for enhanced nutrient absorption and overall plant growth. This includes the development of increased root hair density, elevated nitrate reductase activity, and the formation of root nodules. Certain strains of biofertilizers, such as *Azospirillium*, *Phosphobacter*, *Azotobacter*, and *Rhizobacter*, are adept at fixing atmospheric nitrogen and converting it into forms that plants can use (Table 3). This ability contributes significantly to nitrogen cycling in the soil, ensuring a steady supply of accessible nitrogen to support crop growth. In summary, biofertilizers have the potential to significantly improve crop performance and yield by enhancing nutrient availability, stimulating plant growth, and increasing resistance to stress and diseases. Their positive effects on root architecture and nitrogen cycling further underscore their importance in sustainable agriculture. The proper application of biofertilizers to soil is very important and the mode of application for bio-fertilizers can vary and several methods can be employed to introduce them into the soil. Dry bio-fertilizers can be mixed with seeds before planting. This method ensures that the bio-fertilizers are close to the germinating seeds. Further, bio-fertilizers can be applied to the soil in a powdered form. These are evenly distributed on the soil surface and then incorporated into the soil during cultivation. Another, most extensively used method is the sprinkle method which involves adding a small amount of water to the seed hopper and then incorporating the bio-fertilizers. The mixture is then applied to the soil in a sprinkle-like manner (19). Bio-fertilizers can also be mixed with water to create a suspended solution and this slurry is then added to the seeds before planting. This ensures even distribution of bio-fertilizers. The bio-fertilizers are combined with an adhesive and applied to the seeds. The adhesive-coated bio-fertilizer adheres to the seeds, allowing for controlled release in the soil. In slurry, the seeds and bio-fertilizers are mixed and an adhesive that may contain lime-like materials is applied to coat the seeds. This coating ensures that the bio-fertilizers adhere to the seeds. These methods allow for the effective and controlled application of bio-fertilizers, promoting their interaction with the soil and plant roots to enhance

Table 3. Biofertilizers used for specific crops

Biofertilizer	Function	Crops	References
Rhizobium (symbiotic)	Increases yield up to 10-30 %, Maintains soil fertility, Fixes 200-300 kg N/ha/year	pea, pulses, legumes, black gram, wheat, bajra, maize	(20)
Azospirillum	Increases water and mineral, Uptake and enhances root, Growth, Fixes 20-160 kg N/ha.year, Increases crop yield	rice, sugarcane, millet, wheat, bajra, sorghum	(21)
Azolla	Fixes 30-60kg N/ha/year	rice	(22)
Azotobacter	Used as green manure, Supplies 20-40 kg N/ha/year, Promotes growth substances such as IAA, and gibberellic acid, Maintains soil fertility, Increases yields upto 10-15%	mustard, sunflower, sugarcane, papaya, banana, coconut	(23)
Blue-green algae	Fixes 20-40 kg N/ha/year, Promote growth substances, Such as IAA,	rice	(24)
Arbuscular mycorrhizal Fungi (Symbiotic)	Increase nutrient absorption, area for nutrient access, Fix phosphate, Increase crop yield	soybean, wheat, corn	(25)
Bacillus spp.	Solubilize the phosphate and fix the nitrogen in the soil, Synthesis of growth hormones, Increase crop yield	many vegetables and fruits	(26)
Pseudomonas	Production of siderophores and Plant hormones, Fixes phosphate, Increases crop yields	potato, sugar	(27)

nutrient availability and plant growth while minimizing environmental impacts.

Role of biofertilizers in biotic stress management

Abiotic and biotic stresses are significant factors that limit crop productivity. Various scientific approaches have been extensively employed to mitigate the impact of these stresses on crops, with Plant Growth-Promoting Rhizobacteria (PGPRs) playing a pivotal role as bio-protectors. Natural outbreaks of plant diseases have necessitated the adoption of sustainable agricultural practices with reduced agrochemical usage. The ecology and the agriculture industry have been seriously threatened by the long-standing use of chemicals. Prolonged pesticide use not only jeopardizes soil and plant health but also leads to substantial crop losses.

Table 4. Role of biofertilizers in biotic stress tolerance

Biofertilizers	Host Plant	Pathogen	Response	Reference
Aureobasidium pullulans	Crops	*Botrytis cinerea, Alternaria alternata*	Volatile organic acid production is increased and pathogen development is inhibited	(28)
Bacillus safensis	*Vaccinium*	*Botrytis cinerea*	Enhanced the synthesis of chitinase, hydrolytic, and proteases and shields plants against disease	(29)
Bacillus subtilis	*Atractylodesmacrocephala*	*Ceratobasidium* sp.	Reduce pathogen expansion and increase plant growth	(30)
Pseudomonas aeruginosa	Cruciferous vegetables	*Xanthomonas campestris*	Produces chitinase to protect plants from pathogens	(31)
Trichoderma koningii	*Nicotiana tabacum*	Tobacco Mosaic Virus	Increased proline content, pathogen-related enzymes, and pathogen growth inhibition	(32)
Aureobasidium pullulans	Olive trees	*Colletotrichum acutatum*	Increased production of volatile fatty acids and improves seed germination	(33)
Pseudomonas spp.	*Gossypium*	*Fusarium* spp.	Impede pathogen growth by producing HCN and enzymes	(34)
P.putida	*Solanum tuberosum*	*Phytophthora infestans*	Increased production of HCN against pathogens	(35)
Trichoderma harzianum	*Zea mays*	*Curvularialunata*	Utilises platelet-activating factor and JA signaling to defend plants from pathogens.	(36)
Bacillus subtilis	*Solanum lycopersicum*	*Fusarium oxysporum*	Increased plant growth and suppression of the growth of pathogens	(37)

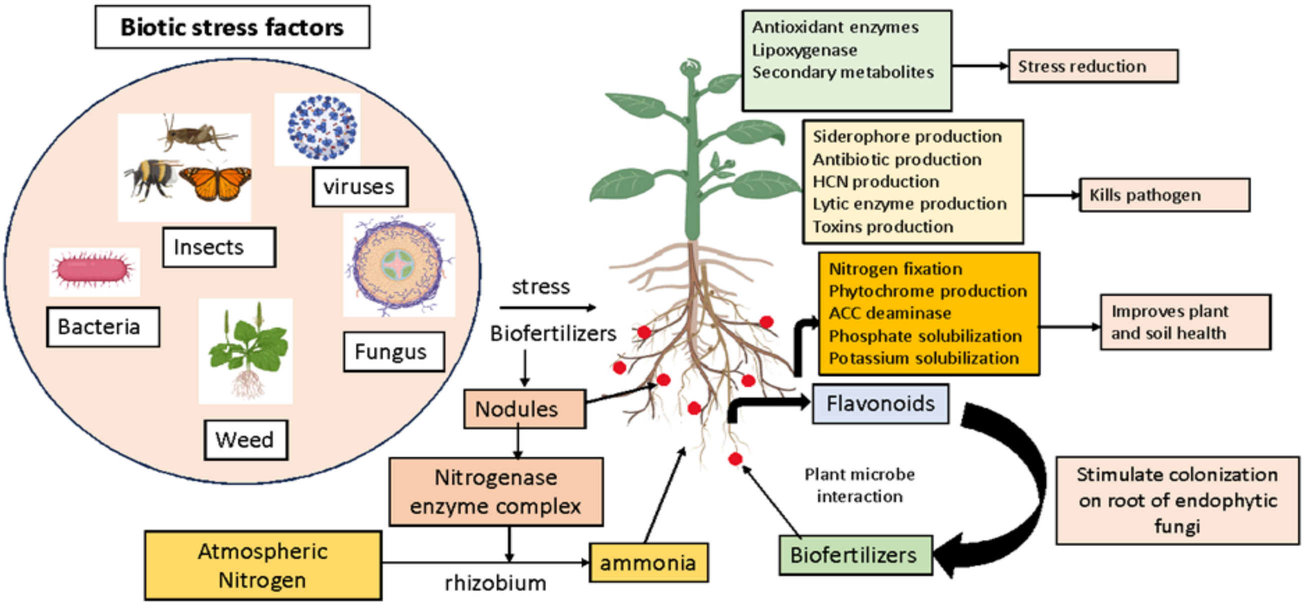

Fig. 2. Biofertilizers promoting biotic stress management in plants.

Hence, there is a pressing need for effective and environmentally friendly strategies for managing phytopathogens, including the use of biofertilizers (Table 4).

Using endophytes as possible biofertilizers is one promising strategy to shield crop plants against a variety of bacterial and fungal diseases (Fig. 2). Plant diseases are biologically controlled by the use of beneficial bacteria, including *Streptomyces*, *Pantoea* spp., *Pseudomonas* spp., *Bacillus* spp., and numerous fungal species (20,38). *Bacillus thuringiensis* (Bt), which generates endotoxins used as biopesticides and as a source of genes for creating transgenic plants resistant to insects, is one of the most effective biopesticides on the market today (39). As a safe alternative to harmful chemicals like fertilizers, herbicides, pesticides, and insecticides, biofertilizers in the form of potential biocontrol agents have gained attention for managing phytopathogens, including bacteria, fungi, viruses, aphids, and nematodes. Endophytes are widely found in nearly all plant species, ranging from small non-vascular plants to large conifers like *Pinus radiata,* and exhibit a hyperdiverse range of biodiversity (40). Examples of recognized endophytes include *Burkholderia*, *Stenotrophomonas*, *Rhizobium*, *Microbacterium*and *Bacillus* spp. Plants are equipped with antioxidant enzymes such as peroxidase (POD), polyphenol oxidase, phenylalanine ammonia-lyase (PAL), lipoxygenase, and chitinase, among others, to protect against stress conditions (41). Endophytes contribute to enhancing plant immunity when facing pathogen infections by priming systemic acquired resistance (SAR) and induced systemic resistance (ISR) through various phytohormones (42,43). Many endophytes that establish symbiotic relationships with host plants produce and accumulate pathogenesis-related proteins with antibacterial properties. *Bacillus* strains produce secondary metabolites such as surfactin, fengycin, and bacillibactin and express defense-related genes like SOD and PAL to counteract diseases like *Verticillium* wilt caused by *Verticillium dahliae* (44).

Bacillus atrophaeus is known to produce volatile dimethyl disulfide and antioxidant enzymes, effectively preventing the growth of *Meloidogyne incognita* (45). *Bacillus cereus*, as reported by (46), produces antioxidant enzymes that inhibit the growth of *Pseudomonas syringae*. *Pseudomonas fluorescence* has been found to regulate genes related to iron absorption and provide defense against phytopathogens (47). *Acrophialophorajodhpurensis*, on the other hand, produces enzymes such as peroxidase, chitinase, and phenylalanine, which protect tomato plants from *Rhizoctonia solani*, the causative agent of crown root disease (48). In a similar vein, *Trichoderma atroviride* produces glutamate and glyoxylate aminotransferase, offering protection to plants against *Botrytis cinerea* (49).

To defend against viruses, pests, and herbivores, secondary metabolites play a pivotal role. Many endosymbionts associated with various plants influence defense systems by secreting a range of compounds (50). Innate immunity and defensive signaling are facilitated by secondary plant metabolites, including steroids, alkaloids, phenolics, flavonoids, and terpenoids (51). Endophyte-derived volatile organic compounds (VOCs) can modulate the plant's microbiome and exhibit antibacterial properties. For instance, a combination of VOCs produced by the fungal endophyte *Phomopsis* sp. inhibits various fungi, including Ascomycetes and Deuteromycetes (52). Additionally, 3VOCs from the endophytic fungi *Sarocladiumbravhiariae* HND5—caryophyllene, 2-methoxy-4-vinylphenol, and 3,4-dimethoxystyrol—have demonstrated antifungal activity against *Fusarium oxysporum* (53).

One notable example of secondary metabolites produced by endophytic fungi is the alkaloid produced by *Epichloe* sp. in several grass species. According to (54), *Epichloefestucae*invades agricultural forage grasses and protects against herbivorous insects. *Streptomyces hydrogenans* metabolites can serve as safe bio control agents against *Meloidogyne incognita* and as plant growth stimulants for *Solanum lycopersicum* (55). *Bacillus velezensis* stands out as a potential pesticide due to its robust biocontrol capabilities and its ability to enhance host defense against the fungus *Magnaporthe oryzae*, responsible for causing rice blast disease (56). *Trichoderma asperellum*, in an isolated form, has been shown to enhance tomato seedling resistance to *A. alternata* leaf spot (57). *Trichoderma* species exhibit the ability to restrict the mycelial growth of pathogenic fungi and have biocontrol potential against *V. dahliae*, which is known to infect olive trees and cause wilting (36). Additionally, *Trichoderma* sp. has been demonstrated to effectively suppress *Sclerosporagraminicola*, the causative agent of pearl millet downy mildew disease, and induce systemic resistance (58).

Certain endophytes are capable of controlling systemic acquired resistance (SAR) mediated by salicylic acid to manage stress effectively. SAR offers broad-spectrum effectiveness against various infections and long-term stress management (59). It typically involves the accumulation of pathogenesis-related proteins (PR) and proteins related to pathogenicity. In one study, the *Paenibacillus* strain (PB2) was used to suppress pathogenesis-related proteins (PR1) induced by *Mycosphaerellagraminicola* (60), which is considered a marker of SAR. By utilizing the salicylic acid/ethylene pathways, the application of *Bacillus aryabhattai* enhanced the plant's long-lasting defensive response against pathogens (61).

Trichoderma harzianum has been found to increase the transcripts of JA marker genes in plants, enhancing their resistance to *Nezara viridula* feeding invasion (62). In the context of *Solanum lycopersicum*, *Bacillus subtilis,* and *Pseudomonas fluorescens* have been shown to reduce systemic biotic stress against *Sclerotium rolfsii*. In another instance, the endophytic strain *B. aryabhattai* (HKEB) drove *A. thaliana* to express defence-related genes such as protein (PR1) and phytoalexin-deficient 3 and enhanced gene expression linked to the jasmonic and salicylic acid pathways (63). In a greenhouse trial, *Trichoderma* spp. demonstrated antagonistic action against phytopathogens like *B. cinerea*, *Fusarium solani,* and *Rhizoctonia solani*, making them valuable biocontrol agents (64).

Role of biofertilizers in Abiotic stress management

The increased emergence of abiotic stresses in crops, which significantly decreases global production, is frequently attributed to climate change. Abiotic stress has a range of physiological, biochemical, and morphological effects on plants, which eventually impact the important plant produce's economic yield.

Drought Stress: One of the main abiotic stresses that cause plants to lack water, which causes economic loss in the agricultural sector, is drought stress. By lowering cellular water content, inadequate water availability interferes with normal plant development and therefore reduces photosynthetic rates, germination, and agricultural output (37). Under stressful circumstances, the use of beneficial biofertilizers, such as rhizospheric and endophytic bacteria, has been shown to improve plant growth and development. To reduce the impact of

Table 5. Role of biofertilizers in abiotic stress tolerance

Biofertilizers	Host Plant	Pathogen	Response	Reference
Aureobasidium pullulans	Crops	*Botrytis cinerea, Alternaria alternata*	Volatile organic acid production is increased and pathogen development is inhibited	(65)
Bacillus safensis	*Vaccinium*	*Botrytis cinerea*	Enhanced the synthesis of chitinase, hydrolytic, and proteases and shields plants against disease	(28)
Bacillus subtilis	*Atractylodesmacrocephala*	*Ceratobasidium* sp.	Reduce pathogen expansion and increase plant growth	(29)
Pseudomonas aeruginosa	Cruciferous vegetables	*Xanthomonas campestris*	Produces chitinase to protect plants from pathogens	(30)
Trichoderma koningii	*Nicotiana tabacum*	Tobacco Mosaic Virus	Increased proline content, pathogen-related enzymes, and pathogen growth inhibition	(31)
Aureobasidium pullulans	Olive trees	*Colletotrichum acutatum*	Increased production of volatile fatty acids and improves seed germination	(32)
Pseudomonas spp.	*Gossypium*	*Fusarium* spp.	Impede pathogen growth by producing HCN and enzymes	(33)
P.putida	*Solanum tuberosum*	*Phytophthora infestans*	Increased production of HCN against pathogens	(34)
Trichoderma harzianum	*Zea mays*	*Curvularialunata*	Utilises platelet-activating factor and JA signaling to defend plants from pathogens.	(35)
Bacillus subtilis	*Solanum lycopersicum*	*Fusarium oxysporum*	Increased plant growth and suppression of the growth of pathogens	(36)

drought stress, biofertilizers that generate growth hormones such as IAA and cytokinins have been used (66). For instance, *Pseudomonas putida* inoculation can increase the synthesis of abscisic acid, salicylic acid, and flavonoids, which shield the soybean plant from stress caused by drought (67).

Salinity Stress: The accumulated salt in soil from farming is a notable example of salinity stress, another abiotic stressor. Plants under salinity stress are affected physiologically, morphologically, and molecularly, which includes the toxicity of ions, osmotic stress, and decreased rates of transpiration, photosynthesis, and CO_2 fixation. Furthermore, salinity stress negatively affects microbial diversity and nutritional availability (68). By enhancing the physicochemical characteristics of the soil, bioinoculants are extremely helpful in reducing the negative impacts of soil salinity, which has eventually enhanced crop productivity (69).

Temperature Stress: Temperature stress, attributed to global warming, poses a significant risk to plant growth and development. Elevated temperatures, both heat and cold, have profound effects on plants (70). Heat stress can lead to disturbances in homeostasis, protein degradation, delayed seed germination, seed damage, and reduced agricultural production (18). Cold stress, on the other hand, results in dehydration due to ice formation, leading to protein denaturation, leaf lesions, leaf yellowing, and rotting. Cold stress can also affect seed germination and crop yields (71). Several microbial applications have been effective in alleviating the damaging effects of heat stress in various plants by producing phytohormones, forming biofilms, and enhancing heat shock proteins (72,73).

Heavy Metal Stress: Excessive use of inorganic chemical fertilizers in agriculture can lead to the accumulation of toxic metals like nickel, manganese, cadmium, iron, and zinc in the soil (74). While these metals are beneficial to plants at low concentrations, higher levels can induce stress by reducing plant growth, photosynthesis, nutrient uptake, membrane integrity, and enzyme activities, in addition to causing oxidative stress (75). Reactive oxygen species (ROS) generation, which has negative effects on vital macromolecules, occurs under both favorable and unfavorable conditions (Fig. 3). Inoculation of rhizobium can enhance chlorophyll content and promote plant growth in lentils in nickel-contaminated soil (76) (Table 5). Similarly, *Bradyrhizobium* inoculation has been shown to increase IAA and siderophore production while improving the shoot weight of *Lolium multiflorum* in cadmium-contaminated soil (8). The inoculation of *Talaromycespinophilus* in *Triticum aestivum* plants has been found to stimulate plant growth by producing gibberellic acid under heavy metal stress (77).

Application of Biofertilizers

Application of Biofertilizers in Crop Production:

Biofertilizers play a crucial role in enriching the soil environment with a variety of micro and macronutrients through nitrogen fixation, phosphate, and potassium solubilization or mineralization, the release of substances that regulate plant growth, the production of antibiotics and the decomposition of organic matter in the soil (78). By introducing artificially cultured beneficial microorganisms, it is possible to gradually restore the lost biological activity in the soil, often caused by excessive chemical fertilizer use. In contrast to hazardous chemical fertilizers, biofertilizers are more environmentally friendly and support sustainable agriculture. Biofertilizers contain microbes that directly supply atmospheric nitrogen to plants, which plays a vital role in the nitrogen cycle, reducing nitrogen dioxide emissions associated with nitrogen fertilizer use.

Enhancement of Soil Fertility:

The presence of *A. brasilense*, in combination with nitrogen fertilizers, has been shown to increase grain yield by up to 29% compared to nitrogen fertilizer alone. Observations of *Rhizobium* strain interactions with plant-

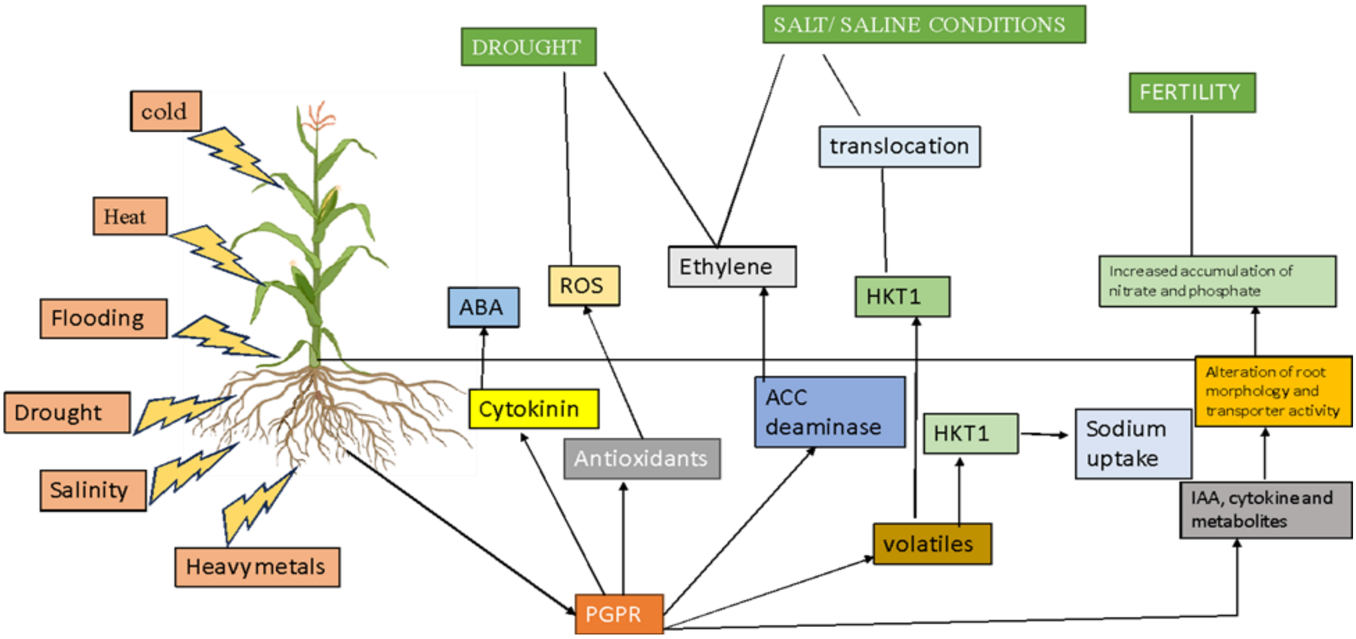

Fig. 3. Biofertilizers promoting abiotic stress management in plants.

microbe relationships, plant development, and grain yield complexity highlight the potential of adding rhizobia secondary metabolites to biofertilizers. In another instance, maize plants injected with a P-solubilizing *Pseudomonas fluorescence* strain exhibited faster growth and higher rates of arbuscular mycorrhizal fungi (AMF) infection compared to uninoculated control plants (79).

For Cereal Crops:

Biofertilizers, through the activities of nitrogen-fixing bacteria like *Azotobacter* and *Azospirillum* and phosphate-solubilizing bacteria like *Bacillus* and *Pseudomonas* spp., are particularly valuable for cereal crops. These plant growth-promoting rhizobacteria (PGPR) fulfill the phosphate and nitrogen requirements of cereals while enhancing soil fertility. By reducing the reliance on synthetic fertilizers and promoting eco-friendly agricultural practices, biofertilizers have the potential to maintain crop productivity while decreasing environmental risks (80).

Role of Biofertilizer in Photosynthesis:

Photosynthesis is a critical process in plant growth and high rates of photosynthesis lead to improved plant growth. Some strains of Rhizobia have been found to increase leaf surface area, enhance photosynthesis rates, and improve stomatal function and water use efficiency (79). Leaves are the primary photosynthetic organs in plants and having a higher number of leaves is crucial for plant growth. Increased leaf numbers activate root growth, improve water uptake, enhance mineral accumulation, and ultimately boost plant yield (81).

Increase in Plant and Crop Growth:

Microbial fertilizers have demonstrated their capacity to improve plant development through direct or indirect increases in nitrogen uptake. By generating growth-regulating hormones, strengthening root systems, and boosting the capacity of plants to absorb nutrients, bacteria that promote plant growth play a critical role (82). Biofertilizers significantly boost plant growth metrics such as plant length, number of branches, length of roots and shoots, and accumulation of dry matter in plant organs. Consequently, this leads to higher crop production and general plant health.

Future perspective

Excessive use of chemical fertilizers by farmers in intensive agriculture has led to the accumulation of excess nutrients, particularly phosphorus (P), in soils. As a result, a critical research objective should be the development of effective and sustainable biofertilizers for crop plants. This approach can significantly reduce the reliance on inorganic fertilizers and mitigate the emergence of new pollution problems. To address this challenge, interdisciplinary collaboration between soil microbiologists, agronomists, plant breeders, plant pathologists, nutritionists, and economists is crucial. The key research priorities include the selection of efficient and economical multi-purpose biofertilizers for diverse crops. Identifying biofertilizers that are both effective and cost-efficient for various crops is essential. Further, scaling up biofertilizer production technology and formulation optimization, which bring biofertilizer production to an industrial scale, and refining formulation processes are vital. The establishment of a quality control system for inoculant manufacturing and field application ensures the quality of plant-microorganism symbiosis and investigating the benefits of biofertilizer use requires a robust quality control system for both manufacturing and field application. Microbial persistence of biofertilizers in soil under challenging conditions, like extreme soil environmental conditions, is a critical area of research. Sharing technological expertise on an industrial scale to develop the best biofertilizer formulations is essential for widespread adoption. Implementing a "Bio-Fertilizer Act" and enforcing stringent regulations for quality control in markets and during application is necessary to ensure the efficacy and safety of biofertilizers.

Conclusion

In summary, biofertilizers or fertilizers based on microbes are extremely beneficial for improving crop quality. The use of biofertilizers has two main considerations. First off, these make a big difference in the productivity of agriculture and the nutritional value of human food. Biofertilizers are an eco-friendly and sustainable option since they are safe for people, animals, and plants, in addition to the environment. Second, biofertilizers are essential to maintaining agriculture's sustainable growth. Plant health and crop output are improved by giving vital nutrients, including nitrogen (N), phosphorus (P), and potassium (K), to plants in the rhizosphere, along with other minerals and vitamins. Furthermore, biofertilizers protect soil from adverse environmental conditions and enhance soil health. The use of several microbial agents, such as plant growth-promoting rhizobacteria (PGPR), highlights the diverse benefits of using biofertilizers.

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Authors' contributions

HS and SK conceptualized the study. P, RC, MK, KT, SN, AR, MJ, AP, and IR conducted literature surveys. HS and SK prepared the final manuscript. All authors contributed equally to revising the manuscript and approved the final draft of the manuscript

Compliance with ethical standards

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References

1. Mia MB, Shamsuddin Z. Rhizobium as a crop enhancer and biofertilizer for increased cereal production. Afr J Biotechnol. 2010;9:6001-6009.
2. Berg G. Plant-microbe interactions promoting plant growth and health: Perspectives for controlled use of microorganisms in agriculture. Appl Microbiol Biotechnol. 2009;84:11-18.
3. Sprent JI, Sprent P. Nitrogen fixing organisms: Pure and applied aspects. Nitrogen Fixing Org. 1990;19:288.
4. Rana R, Kapoor R, Pooja. Biofertilizers and their role in agriculture. Popular Kheti. 2013;1:56-61.
5. Youssef M, Eissa M. Biofertilizers and their role in management of plant parasitic nematodes. A review. J Biotechnol Pharm Res. 2014;5:1-6.
6. Umesha S, Singh PK, Singh RP. Microbial biotechnology and sustainable agriculture. In: Biotechnology for Sustainable Agriculture. Elsevier: Amsterdam, The Netherlands. 2018; pp. 185-205.
7. Agri U, Chaudhary P, Sharma A, Kukreti B. Physiological response of maize plants and its rhizospheric microbiome under the influence of potential bioinoculants and nano chitosan. Plant Soil. 2022;474:451-468.
8. Wani SP, Lee KK. Population dynamics of nitrogen-fixing bacteria associated with pearl millet (P.americanum L.). In: Biotechnology of Nitrogen Fixation in the Tropics. University of Pertanian, Malaysia. 2013;21-30.
9. Pandey J, Singh A. Opportunities and constraints in organic farming: An Indian perspective. J Sci Res. 2012;56:47-72.
10. Board N. The complete technology book on biofertilizer and organic farming. National Institute of Industrial Research. Delhi, India; 2004.
11. Choudhury A, Kennedy I. Prospects and potentials for systems of biological nitrogen fixation in sustainable rice production. Biol Fertil Soils. 2004;39:219-227.
12. Chang CH, Yang SS. Thermo-tolerant phosphate-solubilizing microbes for multi-functional biofertilizer preparation. Bioresour Technol. 2009;100:1648-58.
13. Etesami H, Emami S, Alikhani HA. Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth and future prospects. A review. J Soil Sci Plant Nutr. 2017;17:897-911.
14. Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E et al. Plant growth promoting rhizobacteria: Context, mechanisms of action and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci. 2018;9:1473.
15. Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA, Mehnaz S. Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. Front Microbiol. 2017;8:2593.
16. Beneduzi A, Ambrosini A, Passaglia LMP. Plant growth promoting rhizobacteria (PGPR): Their potential as antagonists and biocontrol agents. Genet Mol Biol. 2012;35:1044-1051. https://doi.org/10.1590/S1415-47572012000600020.
17. Tahir HAS, Gu Q, Wu HJ, Raza, W, Hanif A, Wu LM et al. Plant growth promotion by volatile organic compounds produced by Bacillus subtilis SYST2. Front Microbiol. 2017;8:11. https://doi.org/10.3389/fmicb.2017.00171.
18. Yadav AN, Verma, P, Kumar S, Kumar V, Kumar M, Kumari S. Actinobacteria from rhizosphere in new and future developments in microbial biotechnology and bioengineering. 2018; https://doi.org/10.1016/B978-0-444-63994-3.00002-3.
19. Abadi VAM, Sepehri M, Khatabi B, Rezaei, M. Alleviation of zinc deficiency in wheat inoculated with root endophytic fungus Piriformospora indica and Rhizobacterium, Pseudomonas putida. Rhizosphere. 2021;17:100311. https://doi.org/10.1016/j.rhisph.2021.100311.
20. Kohl J, Kolnaar R, Ravensberg WJ. Mode of action of microbial biological control agents against plant diseases: Relevance beyond efficacy. Front Plant Sci. 2019;10:845. https://doi.org/10.3389/fpls.2019.00845.
21. Brahmaprakash G, Sahu PK. Biofertilizers for sustainability. J Indian Inst Sci. 2012;92:37-62.
22. Pathak D, Kumar M, Rani K. Biofertilizer application in horticultural crops. In: Microorganisms for Green Revolution. Springer: Berlin/Heidelberg, Germany. 2017; pp. 215-227.
23. Thomas L, Singh I. Microbial biofertilizers: Types and applications. In: Biofertilizers for Sustainable Agriculture and Environment. Springer: Berlin/Heidelberg, Germany. 2019; pp. 1-19.
24. Singh JS, Kumar A, Rai AN, Singh DP. Cyanobacteria: Apreciousbio-resource in agriculture, ecosystem and environmental sustainability. Front Microbiol. 2016;7:529.
25. Kobae Y. Dynamic phosphate uptake in arbuscular mycorrhizal roots under field conditions. Front Environ Sci. 2019;6:159. https://doi.org/10.3389/fenvs.2018.00159.
26. Hashem MA, Nur-A-Tomal MS, Mondal NR, Rahman MA. Hair burning and liming in tanneries is a source of pollution by arsenic, lead, zinc, manganese and iron. Environ Chem Lett. 2017;15: pp. 501-06. https://doi.org/10.1007/s10311-017-0634-2.
27. Kloepper JW, Leong J, Teintze M, Schroth MN. Enhanced plant growth by siderophores produced by plant growth-promoting rhizobacteria. Nature. 1980;286:885-886.
28. Don Y, Schmidtke SM, Gambetta LM. Aureobasidium pullulans volatilome identified by a novel, quantitative approach employing SPME-GC-MS, suppressed Botrytis cinerea, and Alternaria alternata in vitro. Sci Rep 2020;10:4498. https://doi.org/10.1038/s41598-020-61471-8.
29. Hassan EA, Yasser S, Mostafa A, Mohamed H, Nivien AN. Biosafe management of Botrytis grey mold of strawberry fruit by novel bioagents. Plants. 2021;12:2737. https://doi.org/10.3390/plants10122737.
30. You WJ, Ge CH, Jiang ZC, Chen MM, Li W, Shao YZ. Screening of a broad-spectrum antagonist-Bacillus siamensis and its possible mechanisms to control postharvest disease in tropical fruits. Biol Control. 2021;157:104584. https://doi.org/10.1016/j.biocontrol.2021.104584.
31. Mishra S, Arora NK. Evaluation of rhizospheric Pseudomonas and Bacillus as biocontrol tools for Xanthomonas campestris pv campestris. World J Microbiol Biotechnol. 2012;28:693-702. https://doi.org/10.1007/s11274-011-0 865-5.
32. Taha RS, Seleiman MF, Shami A, Alhammad BA, Mahdi AHA. Integrated application of selenium and silicon enhances growth and anatomical structure, antioxidant defense system, and yield of wheat grown in salt-stressed soil. Plants. 2021;10:1040. https://doi.org/10.3390/plants1006 1040.
33. Sdiri et al. Biocontrol ability and production of volatile organic compounds as a potential mechanism of action of olive endophytes against Colletotrichum acutatum. Microorganisms. 2022;10(3):571. https://doi.org/10.3390/microorganisms10030571.
34. Zain M, Yasmin S, Hafeez FY. Isolation and characterization of plant growth promoting antagonistic bacteria from cotton and sugarcane plants for suppression of phytopathogenic Fusarium species. Iran J Biotechnol. 2019;17:e1974. https://doi.org/10.21859/ijb.1974.
35. Anand A, Chinchilla D, Tan C, Mene-Saffrane L, Haridon F, Weisskopf L. Contribution of hydrogen cyanide to the antagonistic activity of Pseudomonas strains against

Phytophthora infestans. Microorganisms. 2020;8:1144. https://doi.org/10.3390/microorganisms8081144.

36. Yu Z, Wang Z, Zhang Y, Wang Y, Liu Z. Biocontrol and growth-promoting effect of Trichoderma asperellum TaspHu1 isolate from Juglans mandshurica rhizosphere soil. Microbiol Res. 2021;242:e126596. https://doi.org/10.1016/j.micres.2020.126596.
37. Sundaramoorthy S, Balabaskar P. Biocontrol efficacy of Trichoderma spp. against wilt of tomato caused by Fusarium oxysporum f. sp. lycopersici. J Appl Biol Biotechnol. 2013;1:36-40.
38. Chaudhary A, Parveen H, Chaudhary P, Khatoon H, Bhatt P, et al. Rhizospheric microbes and their mechanism. Microbial Technology for Sustainable Environment.eds (Singapore: Springer). 2021; https://doi.org/10.1007/978-981-16-3840-46.
39. Sujayanand GK, Akram M, Konda A, Nigam A, Bhat S, Dubey J et al. Distribution and toxicity of Bacillus thuringiensis (Berliner) strains from different crop rhizosphere in Indo-Gangetic plains against polyphagous lepidopteran pests. Int J Trop Insect Sci. 2021;41:2713-2731. https://doi.org/10.1007/s42690-021-00451-5.
40. Liu H, Carvalhais LC, Crawford M, Singh E, Dennis PG, Pieterse CM, et al. Inner plant values: Diversity, colonization, and benefits from endophytic bacteria. Front Microbiol. 2017;8:2552. https://doi.org/10.3389/fmicb.2017.02552.
41. Kandel SL, Joubert PM, Doty SL. Bacterial endophyte colonization and distribution within plants. Microorganisms. 2017;5:77. https://doi.org/10.3390/microorganisms5040077.
42. Cataldo E, Fucile M, Mattii GB. Biostimulants in viticulture: A sustainable approach against biotic and abiotic stresses. Plants. 2022;11:162. https://doi.org/10.3390/plants11020162.
43. Romera FJ, García MJ, Lucena C, Martínez-Medina A, Aparicio MA, Ramos J et al. Induced systemic resistance (ISR) and Fe deficiency responses in dicot plants. Front Plant Sci. 2019;10:287. https://doi.org/10.3389/fpls.2019.00287.
44. Oukala N, Aissat K, Pastor V. Bacterial endophytes: The hidden actor in plant immune responses against biotic stress. Plants. 2021;10:1012. https://doi.org/10.3390/plants10051012.
45. Hasan N, Farzand A, Heng Z, Khan IU, Moosa A, Zubair M et al. Antagonistic potential of novel endophytic Bacillus strains and mediation of plant defense against Verticillium wilt in upland cotton. Plants. 2020;9:1438. https://doi.org/10.3390/plants9111438.
46. Ayaz M, Ali Q, Farzand A, Khan A, Ling H, Gao X. Nematicidal volatiles from Bacillus atrophaeus GBSC56 promote growth and stimulate induced systemic resistance in tomato against Meloidogyne incognita. Int J Mol Sci. 2021;22:5049. https://doi.org/10.3390/ijms22095049.
47. Nie P, Chen C, Yin Q, Jiang C, Guo J, Zhao H, et al. Function of miR825 and miR825 as negative regulators in Bacillus cereus AR156-elicited systemic resistance to Botrytis cinerea in Arabidopsis thaliana. Int J Mol Sci. 2019;20:5032. https://doi.org/10.3390/ijms20205032.
48. Desrut A, Moumen B, Thibault F, Le Hir R, Coutos-Thevenot P, Vriet C. Beneficial rhizobacteriaPseudomonas simiae WCS417 induce major transcriptional changes in plant sugar transport. J Exp Bot. 2020;71:7301-7315. https://doi.org/10.1093/jxb/eraa396.
49. Daroodi Z, Taheri PS. Direct antagonistic activity and tomato resistance induction of the endophytic fungus Acrophialophorajodhpurensis against Rhizoctonia solani. Biol Control. 2021;160:104696. https://doi.org/10.1016/j.biocontrol.2021.104696.
50. Gonzalez-Lopez MDC, Jijon-Moreno S, Dautt-Castro M, OvandoVazquez C, Ziv T, Horwitz BA et al. Secretome analysis of Arabidopsis-Trichoderma atroviride interaction unveils new roles for the plant glutamate: glyoxylate aminotransferase GGAT1 in plant growth induced by the fungus and resistance against Botrytis cinerea. Int J Mol Sci. 2021;22:6804. https://doi.org/10.3390/ijms22136804.
51. Divekar PA, Narayana S, Divekar BA, Kumar R, Gadratagi BG, Ray A et al. Plant secondary metabolites as defense tools against herbivores for sustainable crop protection. Int J Mol Sci. 2022;23:2690. https://doi.org/10.3390/ijms23052690.
52. Pang Z, Chen J, Wang T, Gao C, Li Z, Guo L et al. Linking plant secondary metabolites and plant microbiomes: A review. Front Plant Sci. 2021;12:621276. https://doi.org/10.3389/fpls.2021.621276.
53. Hummadi EH, Cetin Y, Demirbek M, Kardar NM, Khan S, Coates CJ et al. Antimicrobial volatiles of the insect pathogen Metarhizium brunneum. J Fungi. 2022;22:326. https://doi.org/10.3390/jof8040326.
54. Yang Y, Chen Y, Cai J, Liu X, Huang G. Antifungal activity of volatile compounds generated by endophytic fungiSarocladiumbrachiariae HND5 against Fusarium oxysporum f. sp. cubense. PLoS ONE. 2021;16:e0260747. https://doi.org/10.1371/journal.pone.0260747.
55. Hennessy LM, Popay AJ, Glare TR. Olfactory responses of Argentine stem weevil to herbivory and endophyte-colonisation in perennial ryegrass. J Pest Sci. 2022;95:263-77. https://doi.org/10.1007/s10340-021-01375-2.
56. Sharma N, Khanna K, Manhas RK, Bhardwaj R, Ohri P, Alkahtani J et al. Insights into the role of Streptomyces hydrogenans as the plant growth promoter, photosynthetic pigment enhancer, and biocontrol agent against Meloidogyne incognita in Solanum lycopersicum seedlings. Plants. 2020;9:1109. https://doi.org/10.3390/plants9091109.
57. Chen Z, Zhao L, Dong Y, Chen W, Li C, Gao X et al. The antagonistic mechanism of Bacillus velezensis ZW10 against rice blast disease: Evaluation of ZW10 as a potential biopesticide. PLoS ONE. 2021;16:e0256807. https://doi.org/10.1371/journal.pone.0256807.
58. Reghmit A, Benzina-tihar F, Escudero FJL, Halouane-Sahir F, Oukali Z, Bensmail S et al. Trichoderma spp. isolates from the rhizosphere of healthy olive trees in Northern Algeria and their biocontrol potentials against the olive wilt pathogen, Verticillium dahliae. Org Agric. 2021;11:639-57. https://doi.org/10.1007/s13165-021-00371-1.
59. Nandini B, Puttaswamy H, Saini RK, Prakash HS, Geetha N. Trichovariability in rhizosphere soil samples and their biocontrol potential against downy mildew pathogen in pearl millet. Sci Rep. 2021;11:9517. https://doi.org/10.1038/s41598-021-89061-2.
60. Xia Y, Liu J, Chen C, Mo X, Tan Q, He Y et al. The multifunctions and future prospects of endophytes and their metabolites in plant disease management. Microorganisms. 2022;10:1072. https://doi.org/10.3390/microorganisms10051072.
61. Samain E, Aussenac T, Selim S. The effect of plant genotype, growth stage and Mycosphaerellagraminicola strains on the efficiency and durability of wheat-induced resistance by Paenibacillus sp. strain B2. Front Plant Sci. 2019;10:587. https://doi.org/10.3389/fpls.2019.00587.
62. Portieles R, Xu H, Yue Q, Zhao L, Zhang D, Du L et al. Heat-killed endophytic bacterium induces robust plant defense responses against important pathogens. Sci Rep. 2021;11:12182. https://doi.org/10.1038/s41598-021-91837-5.
63. Alınc T, Cusumano A, Peri E, Torta L, Colazza S. Trichoderma harzianum strain T22 modulates direct defense of tomato plants in response to Nezaraviridula feeding activity. J Chem Ecol. 2021;47:455-462. https://doi.org/10.1007/s10886-021-01260-3.

64. Sanchez-Montesinos B, Santos M, Moreno-Gavíra A, Marín-Rodulfo T, Gea FJ, Dianez F. Biological control of fungal diseases by Trichoderma aggressivum f. europaeum and its compatibility with fungicides. J Fungi. 2021;24:7. https://doi.org/10.3390/jof7080598.

65. Lata R, Chowdhury S, Gond SK, White JF. Induction of abiotic stress tolerance in plants by endophytic microbes. Lett Appl Microbiol. 2018;66:268-76. https://doi.org/10.1111/lam.12855.

66. Fasusi OA, Cruz C, Babalola OO. Agricultural sustainability: Microbial biofertilizers in rhizosphere management. Agriculture. 2021;11:163. https://doi.org/10.3390/agriculture11020163.

67. Kang SM, Radhakrishnan R, Khan AL, Kim MJ, Park JM, Kim BR. Gibberellin-secreting rhizobacterium, Pseudomonas putida H-2-3 modulates the hormonal and stress physiology of soybean to improve the plant growth under saline and drought conditions. Plant Physiol Biochem. 2014;84:115-24. https://doi.org/10.1016/j.plaphy.2014.09.001.

68. Luo J, Zhang Z, Hou Y, Diao F, Hao B, Bao Z, et al. Exploring microbial resource of different rhizocompartments of dominant plants along the salinity gradient around the hypersaline lake Ejinur. Front Microbiol. 2021;12:698479. https://doi.org/10.3389/fmicb.2021.698479.

69. Jiménez-Mejía R, Medina-Estrada RI, Carballar-Hernández S, Orozco-Mosqueda M, Santoyo G et al. Teamwork to survive in hostile soils: Use of plant growth-promoting bacteria to ameliorate soil salinity stress in crops. Microorganisms. 2020;10:150. https://doi.org/10.3390/microorganisms10010150.

70. Imran QM, Falak N, Hussain A, Mun BG, Yun BW. Abiotic stress in plants; stress perception to molecular response and role of biotechnological tools in stress resistance. Agronomy. 2021;11:1579. https://doi.org/10.3390/agronomy11081579.

71. Wu Y, Huang W, Tian Q, Liu J, Xia X, Yang X et al. Comparative transcriptomic analysis reveals the cold acclimation during chilling stress in sensitive and resistant passion fruit (Passiflora edulis) cultivars. Peer J.2021;9:e10977. https://doi.org/10.7717/peerj.10977.

72. Issa A, Esmaeel Q, Sanchez L, Courteaux B, Guise JF, Gibon Y. Impacts of Paraburkholderiaphytofirmans strain PsJN on tomato (Lycopersicon esculentum L.) under high temperature. Front Plant Sci. 2018;9:1397. https://doi.org/10.3389/fpls.2018.01397.

73. Sarkar J, Chakraborty B, Chakraborty U. Plant growth promoting rhizobacteria protect wheat plants against temperature stress through antioxidant signalling and reducing chloroplast and membrane injury. J Plant Growth Regul. 2018;37:1396-1412. https://doi.org/10.1007/s00344-018-9789-8.

74. Ghori NH, Ghori T, Hayat MQ, Imadi SR, Gul A, Altay V et al. Heavy metal stress and responses in plants. Int J Environ Sci Technol. 2019;16:1807-1828. https://doi.org/10.1007/s13762-019-02215-8.

75. Ahmad P, Tripathi DK, Deshmukh R, Pratap SV, Corpas FJ. Revisiting the role of ROS and RNS in plants under changing environment. Environ Experi Botany. 2019;161:1-398. https://doi.org/10.1016/j.envexpbot.2019.02.017.

76. Guo J, Chi J. Effect of Cd-tolerant plant growth promoting Rhizobium on plant growth and Cd uptake by Lolium multiflorum Lam. and Glycine max (L.) Merr. in Cd-contaminated soil. Plant Soil. 2014;375:205-14. https://doi.org/10.1007/s11104-013-1952-1.

77. El-Shahir AA, Noha A, ElT, Omar MA, Arafat AH, Abdel L et al. The effect of endophytic Talaromycespinophilus on growth, absorption, and accumulation of heavy metals of Triticum aestivum grown on sandy soil amended by sewage sludge. Plants. 2021;10:2659. https://doi.org/10.3390/plants10122659.

78. Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N. Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance, and crop productivity. Microb Cell Fact. 2014;13:1-10. https://doi.org/10.1186/1475-2859-13-66.

79. Krey T, Vassilev N, Baum C, Eichler-Löbermann B. Effects of long -term phosphorus application and plant-growth-promoting rhizobacteria on maize phosphorus nutrition under field conditions. Eur J Soil Biol. 2013;55:124-30. https://doi.org/10.1016/j.ejsobi.2012.12.007.

80. Malusa E, Vassilev N. A contribution to set a legal framework for biofertilizers. Appl Microbiol Biotechnol. 2012;98:6599-607. https://doi.org/10.1007/s00253-014-5828-y.

81. Olanrewaju OS, Glick BR, Babalola OO. Mechanisms of action of plant growth promoting bacteria. World J Microbiol Biotechnol. 2017;33:0. https://doi.org/10.1007/s11274-017-2364-9

82. Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, et al. Biofertilizers: A potential approach for sustainable agriculture development. Environ Sci Pollut Res. 2017;24:3315-3335.