

Microbial Inoculants: Effective Biofertilizers for Improving Crop Productivity



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Abstract

In 2025, the world's population is expected to reach 10 billion, making food security a global concern. Improving agricultural production in response to changing climatic circumstances is crucial for maintaining global food security. Conventional farming operations commonly employ artificial/chemical fertilizers to increase crop output, but these have several detrimental environmental and human health consequences. Researchers have long focused on alternative crop fertilization methods, and biofertilizers are becoming increasingly common in agriculture worldwide. Biofertilizers, made from indigenous plant growth-promoting rhizobacteria, are a cost-effective and environmentally friendly way to enhance crop productivity. This article provides an overview of microbial inoculants as biofertilizers, covering their types, modes of action, crop productivity impacts, problems, and limitations. This article focuses on the use of biofertilizers in agriculture to promote plant growth through nitrogen fixation, phytohormone production, siderophore generation, nutrient solubilization, and easy uptake by crop plants. This review article discusses how microbial inoculants might improve agricultural productivity and their challenges and limitations.

Keywords: Microbial inoculants; Biofertilizers; Crop productivity; Nitrogen fixation; Phytohormones; Nutrient solubilization

Introduction

Soil microorganisms are required for both effective nutrient control and soil biodiversity. They are necessary for plant development and growth. In recent years, chemical fertilizers have been employed in agriculture to increase food production and independence for the country, but at the expense of the environment and the health of all living beings. Overusing these fertilizers in farming is costly and has many negative consequences for soil fertility. Beneficial microorganisms offer alternatives to traditional farming approaches for addressing our agricultural needs. Biofertilizers are safer compared to chemical fertilizers, they are more concentrated have fewer negative environmental effects, and function better in smaller quantities. Furthermore, microbial inoculants degrade faster and are less likely to cause resistance to diseases and pests [1]. Because bioinoculants are ecologically friendly but exceptionally powerful and may be used as biopesticides without harming plant products, they have no adverse effects on soil-dwelling animals and plant life. The plant needs mineral nutrients, which can only be obtained through the direct or indirect application of chemical fertilizers in conjunction

with organic manure and biofertilizers to boost the content of organic soil and ensure sustainability in fields and horticultural crops [2]. Organisms like bacteria, fungi, and other microbes are microbial inoculants that are introduced into an environment to achieve a specific aim, such as biocontrol or plant development [3]. The word "bio-fertilizer" refers to a wide range of products that contain active or dormant microorganisms such as bacteria, fungi, actinomycetes, and algae. Some bacteria secrete compounds that enhance plant growth, these bacteria help fix atmospheric nitrogen and solubilize or mobilize soil nutrients upon application [4]. In addition to numerous other products, biofertilizers, and biopesticides are now available as alternatives to standard synthetic pesticides, inorganic fertilizers, and inorganic fertilizers, respectively. From 2022 to 2027, the biofertilizer market is predicted to rise at a compound yearly 12.1% growth rate, from 1.57 billion in 2018 [5]. The market is tremendously fragmented because of the vast number of small and large businesses operating in various locations. Because it is now mostly unregulated, the biofertilizer market is dominated by numerous small businesses; however, if rules are enforced, as has occurred in the global market

for biopesticides, the market may become more concentrated [6]. Furthermore, because they occur naturally in the rhizosphere, are non-pathogenic, environmentally friendly, and directly increase plant yield, PGPRs are a distinct class of microbes that influence plant defense mechanisms and provide host resistance to further pathogen attack via an incredibly diverse mechanism. As a result, they are regarded as more effective biocontrol agents than traditional chemical fertilizers [7]. PGPRs can directly or indirectly influence plant development and stimulate the development of plant growth by releasing mineral nutrients into soils, controlling or inhibiting phytopathogens, producing various plant growth regulators, improving bioremediation and soil structure by separating toxic heavy metals, and reducing chemical compounds such as fungicides and pesticides [8-10]. In addition to the mentioned roles, PGPRs also contribute to various defense mechanisms in plants by synthesizing volatiles, biosurfactants, antibiotics, siderophores, and enzymes that degrade cell walls and raise systemic resistance (ISR). PGPRs comprise an extensive range of symbiotic and non-symbiotic bacterial species from the genera *Azotobacter*, *Klebsiella*, *Azospirillum*, *Bacillus*, *Serratia*, and *Enterobacter* [11]. Many researchers are continuously working to better understand the diversity, importance, and functions

that biofertilizers play in improving agricultural sustainability. Plant age, species, soil conditions, growth phases, and soil types all influence the impacts of PGPRs [12]. Enhancing plant nutrient absorption is an important function of PGPR that is suitable for crop development [13,14]. PGPRs resist the loss of plant development caused by a variety of stresses [15], consisting of heavy metals stress [16], waterlogging stress [17], salt stress [18,19], drought stress [20], and other unfavorable environmental conditions. PGPR inoculation reduces plant stress, which improves growth, fitness, nutrient uptake, and production. PGPRs are thus necessary for continuous, advantageous agricultural reasons, such as increasing soil fertility and crop yields in tough conditions. In recent decades, PGPRs have been increasingly used for safe and secure agriculture around the world. The lack of superior bioinoculants is the biggest obstacle to farmer's success. *Azolla*, *Azotobacter*, *Acetobacter*, *Bacillus thuriengensis*, *Trichoderma*, and *Azospirillum* must be carefully considered before being employed in grain and vegetable crops. These biofertilizers are used in conjunction with chemical fertilizers and organic manures to increase soil organic carbon content and ensure crop viability [2] (Figure 1).

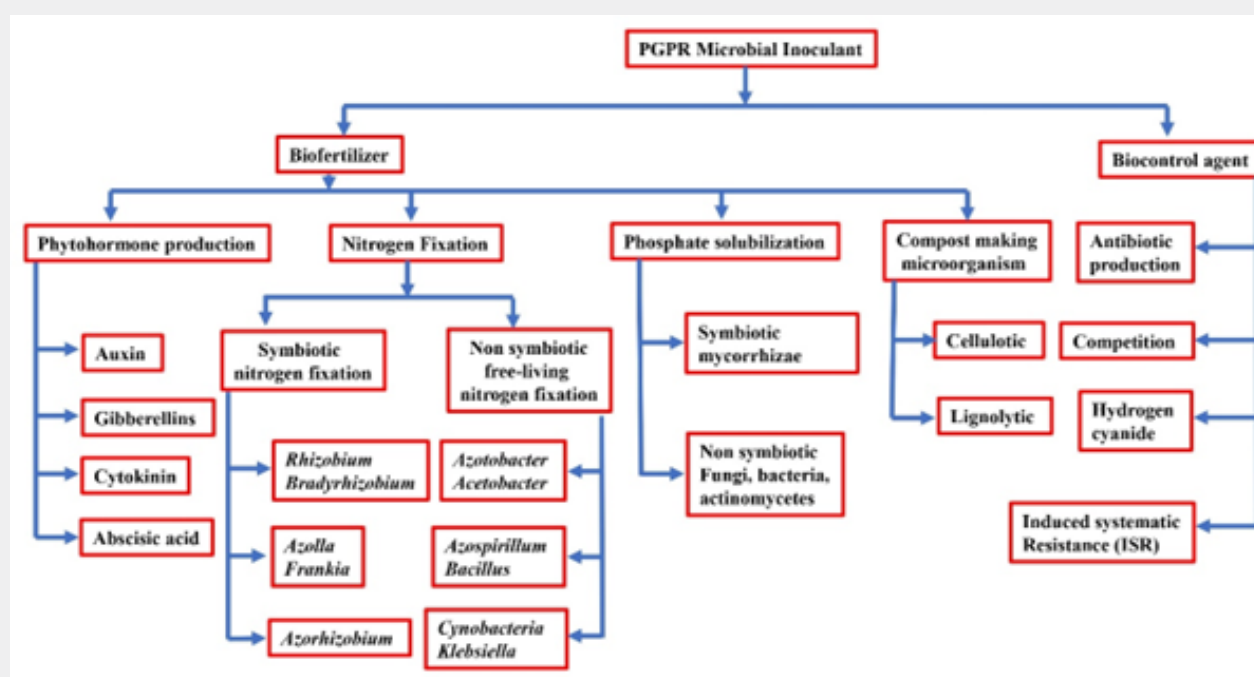


Figure 1: An illustration of the numerous microbial inoculants, or PGPRs, and their crucial role in crop promotion.

The goal of this paper is to provide an overview of the value of biofertilizers using microbial inoculants and how they improve crop output. This review offers an in-depth investigation of the Bio inoculants have both direct and indirect methods, including symbiotic and non-symbiotic biological nitrogen fixation,

production of phytohormones, solubilization of nutrients (phosphate and potassium), production of siderophores, and biocontrol of phytopathogens, chitinases, HCN, and other antifungal properties, to boost crop yield.

Action Mechanism of PGPR

PGPR: Direct mechanism

Biological nitrogen fixation (BNF)

Nitrogen is the main nutrient for the growth of plants and is regarded as the fourth most important component of dry biomass in plants. It has an important function in membrane lipids, enzymes, structural proteins, and genetic material [21]. The majority of nitrogen seems to be unavailable to plants and animals in gaseous form. The application of nitrogen-fixing

bacteria (PGPRs) to plant yield results in disease control, growth promotion, and nitrogen retention [22]. BNF is a technology that uses microbes such as actinomycetes, eubacteria, and blue-green algae to help convert atmospheric nitrogen into ammonia via a reduction cycle.

Each kind is converted by a unique process in various crops and is shown in Table 1 & 2. Naturally, biological nitrogen fixation—the method by which bacteria fix 70% of the nitrogen—and physical and chemical processes fix another 30% of the nitrogen [2].

Table 1: Biological nitrogen fixation can be classified as either free-living or associative.

Free-living/Non-symbiotic/Symbiotic	Crops	Ref.
<i>Azotobacter</i> , <i>Azospirillum</i> , <i>Azospirillum</i> sp., <i>Pseudomonas</i> sp.	Potato	[33]
<i>Herbaspirillum</i> sp., <i>Bacillus</i> sp.	Sugarcane	[34]
<i>Pasteurella multocida</i> , <i>K. pneumonia</i> , <i>K. oxytoca</i> , <i>Acetobacter</i>		
<i>Azospirillum brasilense</i>	Wheat	[36]
<i>Pseudomonas</i> sp., <i>P. mosselii</i>		[37]
<i>Stenotrophomonas maltophilia</i> , <i>Chryseobacterium</i>		[38]
<i>Pseudomonas</i> sp., <i>S. marcescens</i>	Rice	[39]
<i>Anabaena</i> , <i>Azolla</i> , <i>K. pneumonia</i> , <i>B. subtilis</i> , <i>Microbacterium</i>		[40]
<i>Rhizobium</i> sp.	Beans, Peas,	[41]
<i>Bradyrhizobium</i>	Green gram (<i>Vigna radiata</i>)	[26]
<i>Rhizobium japonicum</i>	Soybean (<i>Glycine max</i>)	[42]
<i>Bradyrhizobium</i>		[43]
<i>B. subtilis</i> , <i>B. licheniformis</i>	Chickpea	[44]
<i>P. agglomerans</i> , <i>B. cereus</i>		[45]
<i>Bacillus</i> sp., <i>Klebsiella</i> sp.	Maize	[46]
<i>B. majavensis</i> , <i>P. aeruginosa</i> ,		[47]
<i>Bacillus</i> , <i>Pseudomonas</i> sp.	Sorghum and chilli	[48]
<i>Frankia</i>	Actinorhizal plants	

Table 2: Displays the amount of nitrogen fixed by various microbial inoculants.

State	Aerobic/ Anaerobic	Bacteria	Crop	Amount of N ₂ fixed Kg/ha/year	Ref.
Free-living	Aerobic	<i>Azotobacter</i>		10 to 20	[2]
		<i>Azotobacter</i>	Dryland Crops	20 -25	[4]
	Anaerobic	<i>Clostridia</i>		2 to 5	
	Facultative	<i>Klebsiella</i>		5 to 10	
Symbiotic	Legumes	<i>Rhizobia</i>		50-500	[2]
		<i>Rhizobium strain</i>	Groundnut, Soybean	50-200	[4]
	Non-legumes	<i>Azospirillum</i>		5 to 20	
		<i>Acetobacter</i>		150	
		<i>Anabaena</i>	Rice	600	[40,49]
		<i>Anabaena</i>		20 - 25	[2]
Blue-Green Algae		<i>Azolla</i>		70-100	
		<i>Azolla</i>	Rice	30-100	[4]

Symbiotic nitrogen fixation (SNF)

The mutualistic association between bacteria and plants is known as symbiotic nitrogen fixation (SNF). Symbiotic nitrogen-fixing bacteria may access all types of plants and fix atmospheric nitrogen in a symbiotic manner. When a plant starts producing iso-flavonoids and flavonoids in its rhizosphere, *Rhizobium* sees this as the start of a mutualistic relationship [23]. *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, and *Mesorhizobium* are examples of bacteria that coexist with leguminous plants symbiotically, while *Frankia* coexists symbiotically with shrubs and non-leguminous plants [24]. *Rhizobium* is the most common symbiotic nitrogen-fixing bacteria in legume crops. In addition to bacteria, certain small ferns act as symbiotic nitrogen fixers. As an example, the tiny, free-floating aquatic fern *Azolla* interacts with cyanobacteria (*Anabaena*) to fix nitrogen from the atmosphere. In exchange for fixed nitrogen, *Azolla* provides *Anabaena* with optimal circumstances, nutrition, and phytohormones. The nitrogen-fixing phenomenon occurs in *Anabaena*'s heterocyst cells. *Azolla* mostly aids rice growing by incorporating biomass and nitrogen fertilizer into the soil. Actinorhizal plants can acquire root nodules from actinomycetes such as *Frankia*. Some genera, such as *Myrica*, *Allocasuarina*, *Eleagnus*, *Coriaria*, and *Casuarina*, can nodulate *Frankia*. These plants are monocots with an assurance future in agriculture and reclaimed land. *Bacillus* and *Azotobacter* species fix nitrogen, which stimulates the growth and development of forest crops and maize plants [25]. *Bradyrhizobium japonicum* inoculation enhanced soybean plant growth, and nitrogen fixation [26].

Free-living or nonsymbiotic nitrogen fixation

Plants' root zones include free-living nitrogen fixers, which feed on and absorb nutrients. *Diazotrophs* also help in non-symbiotic nitrogen fixation by stimulating the growth of non-leguminous plants like radish and rice. *Enterobacter*, *Azotobacter*, *Burkholderia*, *Diazotrophicus*, *Pseudomonas*, *Gluconacetobacter*, and *Cyanobacteria* (*Nostoc*, *Anabaena*) are examples of rhizospheric bacteria that do not fix nitrogen symbiotically [27,28]. *Azotobacter chroococcum* can fix 10mgN/g of carbon source *in vitro*, indicating that it can be employed as a biofertilizer [29]. *A. brasilense* decreases N fertilization, improves plant nutrition, increases plant biomass, and boosts wheat grain output [30]. *Acetobacter*, *Herbaspirillum*, *Diazotrophicus*, and *Azospirillum*, are nitrogen-fixing bacteria that thrive with C4 plants such as bajra, maize, sorghum, sugarcane, and cereals including rice, barley, and wheat [31]. *Azospirillum* inoculation yielded notable outcomes in sorghum, wheat, maize, and other grass seedlings. The total nitrogen requirement of rice and corn is about 25% which is contributed by bacteria [32].

Production of Siderophores

Antibiosis is carried out by small organic molecules known as siderophores, which provide crops with iron (Fe), depriving

pathogens of iron [50]. One of the important mineral elements is iron for the growth and development of plants and it serves as a cofactor for proteins involved in metabolic activities such as respiration and photosynthesis [51]. Iron deficiency reduces pathogen growth by blocking essential activities such as sporulation and nucleic acid synthesis [52]. *Pseudomonas putida* can increase the quantity of iron in the natural environment by utilizing heterologous siderophores produced by other microbes available in the root zone [53]. Using *Bacillus* sp. that produces siderophores stimulates groundnut plant growth [54]. *Pseudomonas koreensis* prevented the spread of plant diseases by generating siderophores and antioxidant enzymes in maize plants [55]. Siderophores are believed to be plant growth promoters and biocontrol agents for fungal diseases associated with other crops [56]. To clarify the significance of *Pseudomonas* strain B324 which produces siderophores in fighting *Pythium*, the pathogen that causes wheat root rot disease, is therefore critical [57]. Table 3 shows some examples of siderophore-producing bacteria associated with various plants. *Pseudomonas* produces a new similar siderophore called pyoverdine [58]. Mutant *Pseudomonas* strains produced less pyoverdine and suppressed the fungal pathogen less than their original strains did [59]. As a result, it has been proven that the synthesis of siderophores is an important biological regulatory mechanism. When plants exposed to additional metals such as nickel and cadmium, the ferric siderophore complex is important for iron absorption [60]. PGPRs are valuable assets because they create siderophores that feed plants with the necessary quantity of iron. However, further research is required to discover whether PGPRs can create siderophores. Bacteria also reduce phytopathogens by producing siderophores. The majority of the iron in the rhizosphere is held together by siderophores, which act as iron chelators. Researchers have concentrated on creating microbial inoculants to protect plants from pathogen-caused illnesses.

Solubilization of nutrient

Potassium solubilization

Potassium (K) is the 3rd most significant macronutrient for plants. Insoluble rock made mostly of silicate minerals has greater than 90% potassium. It plays a role in protein synthesis, food intake, regulating opening and closing of stomata, enhancing product quality, and providing adaptability to harsh environmental conditions [61]. It is required for enzyme activation, protein biosynthesis, and photosynthesis. Lack of potassium concentration causes several major problems for plants throughout development, including slow growth, bare roots, and reduced yield and seed production [62]. To maintain crop output, potassium prominence, and plant absorption in the soil should be preserved [63]. The solubilization of potassium rock by PGPRs via the formation and release of organic acids has been extensively researched [64-66]. PGPRs, such as *Paenibacillus* sp., *B. edaphicus*, and *Ferrooxidans* sp., can easily detect potassium levels in soil by

solubilizing and releasing potassium components from potassium-containing minerals [67]. Using potassium-solubilizing PGPRs to increase agricultural nutrients can reduce the application of synthetic fertilizers while promoting sustainable agricultural output [68,69]. Biofertilizers as items containing dormant spores and live microbes or the inoculum they carry that benefit plants, particularly the soil, seed, and root [70]. Potassium solubilizing bacteria to plant seeds typically resulted in a significant improvement in seedling vigor, productivity, potassium uptake, and plant growth [64,71]. The formation of organic acids directly enhances K dissolution via indirect or ligand-mediated mechanism

by creating a compound in solution with reaction products. This is the way KSB distributes potassium to plants. Using Potassium solubilizing bacteria as a biofertilizer can contribute to enhancing environmentally sustainable agricultural output by reducing the need for chemical fertilizers while enhancing plant growth and yield [72]. These technologies are increasingly indispensable in today's agricultural operations. Biofertilizers will make a stronger argument in the upcoming years as farming techniques change and environmental dangers added with chemical fertilizers become more apparent.

Table 3: Some examples of rhizobacteria that solubilize potassium and improve K absorption in various crops.

Function	Plant - Growth Promoting Rhizobacteria (PGPR)	Crops	Ref.
Phosphate solubilization	<i>Bacillus</i> sp., <i>Pseudomonas</i> sp., <i>Serratia</i> sp.	<i>Solanum tuberosum</i>	[90]
	<i>Azospirillum</i> , <i>P. putida</i> ,	<i>Triticum aestivum</i> L.	[91]
	<i>Stenotrophomonas maltophilia</i> , <i>chryseobacterium</i>		[38]
	<i>Bacillus</i> sp., <i>Klebsiella</i> sp., <i>Pseudomonas</i> sp.	<i>Cicer arietinum</i>	[92]
	<i>Herbaspirillum</i> sp., <i>Bacillus</i> sp.	<i>Vigna unguiculata</i>	[34]
	<i>B. safensis</i> , <i>B. simplex</i> , <i>Lysinibacillus fusiformis</i> , <i>B. pumilus</i>	<i>Glycine max</i>	[93]
	<i>S. marcescens</i> , <i>Pseudomonas</i> sp.	<i>Oryza sativa</i>	[94]
	<i>P. brassicacerum</i> , <i>Acinetovacter calcoaceticus</i> , <i>P. marginalis</i>	<i>Solanum lycopersicum</i>	[95]
Phosphate solubilization	<i>Pseudomonas</i> sp., <i>Acinetovacter</i> sp., <i>Bacillus</i> sp.	<i>Phaseolus vulgaris</i>	[96]
	<i>B. subtilis</i> , <i>K. oxycota</i>	<i>Zea mays</i>	[97]
	<i>Rhizobium</i> sp.	<i>Vica faba</i>	[98]
	<i>Bacillus</i> , <i>Pseudomonas</i> sp.	<i>Sorghum bicolor</i>	[48]
	<i>B. circulans</i>	<i>Citrus sinensis</i>	[99]
	<i>Pseudomonas</i> sp., <i>Rhizobium</i> , <i>Mesorhizobium</i> , <i>Bacillus</i> , <i>Azotobacter</i> sp.	Leguminous and non-leguminous plant	[100]
Siderophore production	<i>Bacillus</i> sp. KB129, KB133	<i>Sorghum bicolor</i>	[101]
	<i>V. paradox</i> RAA3	<i>Triticum aestivum</i> L.	[102]
	<i>Azotobacter</i> sp. Az63, Az69 and Az70	<i>Zea mays</i>	[103]
	<i>Rhizobacteria</i> sp.	pulses	[104]
	<i>Bacillus amyloliquefaciens</i> ROH14	pepper	[105]
	<i>Bacillus amyloliquefaciens</i> FZB42	<i>Arabidosis</i>	[106]

Phosphate Solubilization

Phosphorus [73] is the 2nd most important element for plants, and it can be absorbed only in monobasic ions or dibasic ions [53,74]. Plants cannot absorb 95-99% of the P in the soil because it is frozen, insoluble, or precipitated. As a result, crops can only consume a tiny percentage of total soil P, and rarely enough [75,76]. It has been proven that a wide spectrum of microorganisms contributes to the biogeochemical cycling of Phosphate in the rhizospheric zone. As a result, inoculants based on Phosphate solubilizing microorganisms (PSM) are expected to become popular in the commercial market soon [77,78]. Researchers are interested in employing a variety of PGPRs as plant inoculants due

to their capacity to solubilize Phosphate [53,79]. These species are commonly mentioned as possible P biofertilizers since many agricultural soils have an intrinsic P shortage [37]. Heterotrophic bacteria known as PSBs were chosen because of their ability to release organic ions with a low molecular weight that acidify the medium, consequently, phosphate compounds that are only slightly soluble in produced media are dissolved [80]. Although PSB produces many enzymes that aid in phosphate solubilization, acidification is frequently used to accelerate this process [39,78]. PSB strains from many taxa, including *Pseudomonas*, *Burkholderia*, and *Bacillus*, have been isolated [81]. A recent study discovered a positive association between *Pseudomonas*

sp. Phosphate solubilizing capabilities and organic acid synthesis [82]. *Bacillus subtilis* protects plants from environmental stress and promotes safflower development [83]. NanoPhos was used in field circumstances to increase the population of bacteria and soil enzymes resulting in higher maize production [84]. *Xanthomonas*, *Chryseobacterium* [88], *Pantoea*, *Klebsiella*, *Enterobacter* [87], *Pseudomonas* sp. [89], and 18 microbial inoculants as biofertilizers. *Azotobacter* [85], *Bacillus*, *Rhodococcus*, *Serratia*, *Arthrobacter*, *Gordonia*, *Delftia Phyllobacterium*, sp. [86], *Pantoea*, *Klebsiella*, *Enterobacter* [87], *Xanthomonas*, *Chryseobacterium* [88], and *Pseudomonas* sp. [89].

Phytohormone production

Phytohormones, produced by plants and microorganisms both, have a profound impact on plant growth and development [107]. Plant hormone production refers to the positive phenomenon in which beneficial microorganisms produce ethylene, abscisic acid, gibberellins, cytokinin, and indole-3-acetic acid. Microbes create and transport plant hormones, which are organic compounds capable of causing morphological, physiological, and biochemical effects in plants at extremely low concentrations. These hormones function as signaling molecules, promoting nodulation, increasing nutrient intake, and stimulating root growth [108]. The five main groups of plant hormones are auxin, gibberellins, cytokinins, abscisic acid, and 1-aminocyclopropane-1-carboxylase (ACC). Polyamines and brassinosteroids are also produced in the tissues of growing plants. Plants naturally create phytohormones. Numerous articles have confirmed soil microbes' ability to produce phytohormones, which stimulate plant growth and development [109].

Auxin production

Auxins naturally produce growth hormones. Auxins appear in a variety of forms, but the most frequent one that generates spontaneously is indole-3-acetic acid. participating in regulating plant development. IAA stimulated the growth of lateral roots, apical dominance, cell elongation, differentiation, blooming, fruit set, and ripening [110,111]. Plants use oxidative deamination or decarboxylation processes to convert tryptophan into IAA [112]. *Bacillus*, *Klebsiella*, *Pseudomonas*, *Rhizobium*, *Enterobacter*, *Bradyrhizobium*, *Agrobacterium*, and Indole-3-pyruvic acid, for example, can synthesize phytohormones via the indole-3-acetamide and indole-3-acetic acid aldehyde pathways [113-115]. *Cylindrospermum*, *Nostoc*, *Anabeana*, *Gloeotheca*, *Calothrix*, *Gloeotheca*, *Plectonema*, *Chlorogloeopsis*, and *Gloeotheca* have all been proven to produce IAA.

Gibberellins production

Tetracyclic diterpenoid compounds that is Gibberellins, have a role in a variety of plant physiological and developmental processes [116]. More than 136 gibberellins are widely distributed in nature [117], with GA3 being the most regularly used and GA1 being the most active. Geranyl diphosphate can be turned into

gibberellins by a variety of methods. GAs activates maximum biological activity, such as fruit growth and floral induction in plants, stem elongation, production of amylolytic enzymes, and seed germination by breaking seed dormancy [118]. Gibberellin synthesis is required for stem growth; low or non-existent gibberellin levels lead plants to grow to a minimum height. Gibberellins are produced by the fungus *Gibberella fujikuroi* as well as the plants themselves. Nonetheless, several studies have shown that PGPRs, such as *Xanthomonas*, *Pseudomonas*, *Agrobacterium*, *Micrococcus*, *Rhizobium* *Bacillus*, *Azospirillum*, and *Clostridium*, produce gibberellins [119-122].

Cytokinin production

Adenine derivatives known as cytokinins regulate cytokinesis in plant tissues [123]. A variety of bacteria, primarily streptomycetes and *Azospirillum*, *Bacillus*, *Pseudomonas putida*, *Pseudomonas fluorescens*, and *Bradyrhizobium* have been shown to produce cytokinin, primarily zeatin [122,124-126]. Plant cytokines increase cell proliferation, root hair growth, and elongation inhibit lateral root, and control root meristem differentiation [127]. Furthermore, cytokinins have a role in influencing plants, delaying leaf aging, and boosting mitotic cell division in shoots and roots [128]. Bacterial inoculation that produces cytokinin promotes plant shoot growth while decreasing the root-to-shoot ratio [129]. *A. chroococcum*, a cytokinin-producing bacterium, was introduced into a maize plant to enhance growth conditions [130].

Abscisic acid (ABA) production

Abscisic acid (ABA), often known as the stress hormone, is primarily involved in plant development and response to environmental stresses such as high salt, temperature, and drought [131]. ABA production enhances water tolerance and drought in plants. Bacteria like *A. brasilense* may increase the amount of ABA generated by plants during water stress and drought by closing stomata and thereby lowering water loss [132]. Furthermore, this causes the formation of lateral roots.

Aminocyclopropane-1- carboxylate (ACC) deaminase production

At very low quantities, ethylene is an important growth hormone that controls plant growth and development [133]. It is also known as a stress hormone because it is produced in both biotic and abiotic stress conditions [28]. At lower doses, it promotes plant growth, but at higher concentrations, it has been demonstrated to be harmful. Ethylene promotes senescence, fruit ripening, and the abscission of numerous plant components by inhibiting auxin transport and stopping root extension [134,135]. Certain PGPRs, such as *Rhizobium*, *Enterobacter*, *Azospirillum brasilense*, *Pseudomonas*, *Achromobacter*, *Agrobacterium*, *Azospirillum*, *Alcaligenes*, *Serratia*, *Ralstonia*, *Burkholderia* spp., and others, create ACC directly as a precursor to ethylene. These PGPRs can break down ACC while also promoting plant development by reducing ethylene levels and increasing plant

tolerance to harsh conditions [136-138]. Microbes depend upon ACC deaminase hydrolysis to obtain ammonia and α -ketobutyrate, both of which are carbon and nitrogen sources for their growth

[139]. Microorganisms that exhibit ACC deaminase activity are expected to have higher growth and productivity, making them potential sources of biofertilizers [140] (Table 4).

Table 4: Lists the many types of phytohormones that PGPRs create in a variety of crops.

PGPR	Phytohormones	Plant	Ref.
<i>Achromobacter xylosoxidans</i> , <i>Enterobacter cloacae</i>	ACC deminase, IAA	Maize	[143]
25 <i>Acinetobacter</i> sp. ALEB16	Abscisic acid	<i>Atractylodes lancea</i>	[150]
<i>Azospirillum</i> sp.	Cytokinin production	<i>Mimosa pudica</i>	[147]
<i>Bacillus</i>	Cytokinin production	Cucumber	[148]
<i>Bacillus</i>	Gibberellin production	Pepper	[153]
<i>Bacillus amyloliquefaciens</i> QST713	IAA, EPS	Alfalfa (<i>Medicago sativa</i> L.)	[146]
<i>Bacillus circulans</i>	ACC deminase	Mustard	[142]
<i>Bacillus</i> sp.	Gibberellin production	Alder	[151]
<i>Bacillus</i> sp.	ACC deminase, IAA, EPS	Rice	[144]
<i>Bacillus subtilis</i>	IAA	Edible tubercle	[114]
<i>Herbaspirillum seropediacae</i>	IAA	<i>Ocimum sanctum</i>	[17]
<i>Pseudomonas</i> BA-8	Cytokinin production	Strawberry	[149]
<i>Pseudomonas putida</i>	ACC deminase	Tomato	[141]
<i>Pseudomonas putida</i>	IAA	Canola	[145]
<i>Sphingomonas</i>	Gibberellin production	Tomato	[152]

PGPR: Indirect mechanism

ISR: Induced system resistance

Plants have a wide range of active defensive mechanisms that are activated in response to plant diseases. These diseases affect plant health and pose a long-term risk to ecosystem sustainability and food production. Plants have an ISR, which protects them from many diseases and biotic stressors [154]. ISR in plants is mostly induced by *Pseudomonas* sp. via pathways regulated by jasmonic acid and ethylene [155-158]. *P. fluorescence* was found to significantly reduce the pathogenicity of phytopathogens such as viruses, fungi, and bacteria while also inducing self-response (ISR) in a variety of plants, including tobacco, radish, and *Arabidopsis*, via jasmonic acid/ethylene (JA/ET) signaling pathways [159]. According to reports, a different type of plant hormones has been demonstrated to facilitate ISR induction by producing elicitors, which are microorganism-derived compounds [160,161]. Cell wall constituents such as chitin, flagellin, lipopolysaccharides, and others are examples of microbial elicitors [162], volatile organic compounds (VOC) such as alcohols, phenolic compounds, terpenoids, sulfides, and ketones [161], and metabolites such as antibiotics and siderophores [163]. These elicitors work together to regulate plant diseases and trigger the immune system response (ISR) to a variety of pathogens. Occasionally, elicitors generate ISR by interfering with phytohormones required for the plant signaling system, triggering the defense response [164]. Other *Bacillus* species, including *B. pumilus*, *B. amyloliquefaciens*, *B. subtilis*, *B.*

cereus, and *B. mycoides*, as well as *Pseudomonas* isolates, have also been shown to produce resistance to a variety of disorders [165]. Dimethyl disulfide (DMDS) produced by *B. cereus* has been shown to activate immunological responses (ISRs) in a variety of pathogenic fungi [166]. Inoculating arabidopsis plants with *P. simiae* leads them to produce the phenolic compound coumarin scopoletin, which acts as an elicitor to reduce soil-borne illnesses [167]. Furthermore, it has been demonstrated that PGPRs may change the physiology and morphology of plant roots in response to pathogen invasion by secreting phytohormones such as auxin, JA, NO, and cytokinins that protect the plant from infection [168-170]. Microbes can boost plant ISR by many processes, such as producing chitinase, β -1,3-glucanase, phenylalanine ammonia-lyase, peroxidases [171].

Biocontrol of Phytopathogen

Disease development and Pathogen attacks are the leading causes of diminishing crop yield and food product contamination in agricultural plants. Several chemical components, such as insecticides, are used to protect agricultural yield against disease [172]. On the other side, prolonged usage of these pesticides has increased disease resistance and jeopardized the ecology. Thus, biological control is intended to tackle the pathogen onslaught instead of insecticides. Because of their enormous impact on plant health and ability to suppress diseases and illnesses, rhizobacteria are used as biofertilizers, promote plant development, and may operate as phytopathogen biological agents. Disease assaults

are prevented by a range of strategies that use non-toxic and ecologically friendly microorganisms in crop fields. PGPRs from the following genera can function as biocontrol agents: *Enterobacter*, *Beijerinckia*, *Derxia*, *Bacillus*, *Gluconacetobacter*, *Rhodococcus*, *Klebsiella*, *Acinetobacter*, *Azotobacter*, *Azoarcus*, *Pseudomonas*, and *Azospirillum*, and others [173]. Antibiotic production is the most generally recognized technique by which PGPRs resist infections' damaging effects on plants. Antibiotics derived from *Streptomyces*, *Stenotrophomonas*, *Bacillus*, *Pseudomonas*, and such as amphisin, pyrrolnitrin, hydrogen cyanide (HCN), tropolone, kanosamine, and others, have antifungal, antibacterial, and antiviral properties and protect plants from diseases and foreign pathogens [174].

Chitinase

PGPRs also suppress phytopathogens by enzymatic synthesis. PGPRs, such as *S. marcescens*, *P. stutzeri*, *Paenibacillus* sp., and *S. plymuthica*, produce enzymes such chitinase, lipase, protease, and

others that hydrolyze fungal pathogens' chitin, cellulose, proteins, and hemicellulose [175,176].

Hydrogen cyanide (HCN)

Hydrogen cyanide, released by microorganisms such as *Rhizobium*, *Pseudomonas*, *Bacillus*, and kills pathogens and protects plants from illnesses [177]. According to El-Rahman et al. [178], *Rhizobacteria* create hydrogen chloride (HCN), which inhibits the growth of *Meloidogyne incognita* and *Agrobacterium tumefaciens*. Thus, phytohormone-producing bacteria (PGPRs) are critical microorganisms with a major impact on crop improvement and plant growth development. They provide a variety of tasks, including phytohormone generation, nitrogen fixation, potassium and phosphate solubilization, phytohormone management, siderophore production, and increased soil structure (Figure 2).

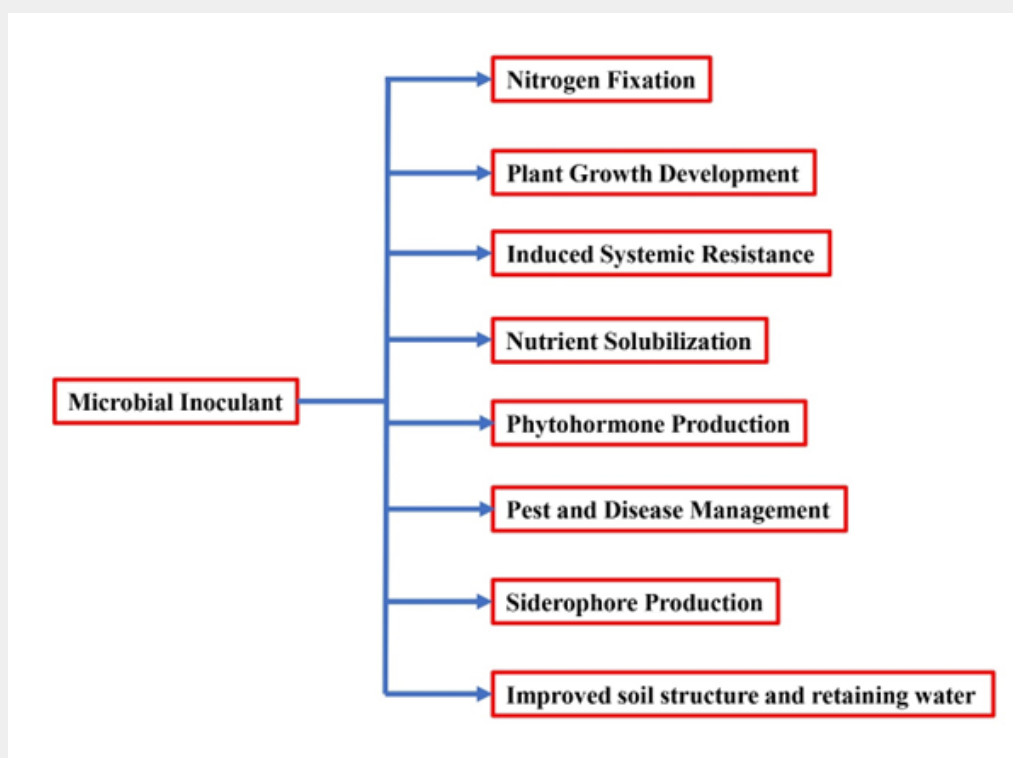


Figure 2: Previously documented significant contribution of microbial inoculants to increased crop production and productivity.

Conclusion

While Chemical fertilizers and insecticides are beneficial for disease management and crop production, their continued use is hazardous to human health, the soil environment, and plant life. Using beneficial bacteria as biocontrol agents and biofertilizers is a low-cost and environmentally benign answer

to the challenge of sustainable agriculture. Biofertilizers may replace chemical fertilizers and pesticides while increasing crop output, hence their usage in agriculture should be encouraged. Farmers should be educated on the advantages of employing PGPRs as biofertilizers, with an emphasis on commercialization. Consequently, we finalized that PGPRs are extremely beneficial to

agriculture and that employing biofertilizers in agricultural fields is the superior substitute to chemical fertilizers, which negatively impact fauna, flora, and soil health. Microbial inoculants have a bright future as biofertilizers since they provide various benefits over typical chemical fertilizers. Growing knowledge of the harmful environmental effects of conventional farming systems has necessitated the adoption of more sustainable agricultural practices. Furthermore, by reducing dependency on chemical fertilizers and improving soil health, microbial inoculants as biofertilizers can promote sustainable agriculture.

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