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Review article

Role of microbial inoculants as bio fertilizers for improving crop productivity: A review

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ABSTRACT

The world's population is increasing and is anticipated to spread 10 billion by 2050, and the issue of food security is becoming a global concern. To maintain global food security, it is essential to increase crop productivity under changing climatic conditions. Conventional agricultural practices frequently use artificial/chemical fertilizers to enhance crop productivity, but these have numerous negative effects on the environment and people's health. To address these issues, researchers have been concentrating on substitute crop fertilization methods for many years, and biofertilizers as a crucial part of agricultural practices are quickly gaining popularity all over the globe. Biofertilizers are living formulations made of indigenous plant growth-promoting rhizobacteria (PGPR) which are substantial, environment-friendly, and economical biofertilizers for amassing crop productivity by enhancing plant development either directly or indirectly, and are the renewable source of plant nutrients and sustainable agronomy. The review aims to provide a comprehensive overview of the current knowledge on microbial inoculants as biofertilizers, including their types, mechanisms of action, effects on crop productivity, challenges, and limitations associated with the use of microbial inoculants. In this review, we focused on the application of biofertilizers to agricultural fields in plant growth development by performing several activities like nitrogen fixation, siderophore production, phytohormone production, nutrient solubilization, and facilitating easy uptake by crop plants. Further, we discussed the indirect mechanism of PGPRs, in developing induced system resistance against pest and diseases, and as a biocontrol agent for phytopathogens. This review article presents a brief outline of the ideas and uses of microbial inoculants in improving crop productivity as well as a discussion of the challenges and limitations to use microbial inoculants.

Abbreviations: PGPR, Plant growth-promoting rhizobacteria; BNF, Biological nitrogen fixation; SNF, Symbiotic nitrogen fixation; KSB, Potassium solubilizing bacteria; PSB, Phosphate solubilizing bacteria; ACC, Aminocyclopropane-1-carboxylase; IAA, Indole acetic acid; ABA, Abscisic acid; ISR, Induced system resistance; DMDS, Dimethyl disulfide; HCN, Hydrogen cyanide.

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1. Introduction

Microorganisms in the soil play a crucial role in soil biodiversity and coordinated nutrient management. They are essential to the growth and evolution of plants. Recent years have seen the use of chemical fertilizers in agriculture, making the nation more self-sufficient in food production, but at the expense of the ecosystem and the well-being of all living things. The excessive use of these fertilizers in agriculture is expensive and has several negative impacts on soil fertility. To satisfy our agricultural requirements, beneficial microorganisms are better alternatives to conventional farming methods. Biofertilizers are safer than chemical fertilizers because they cause less environmental harm, have more focused activity, and are more efficient when used in lesser amounts. Additionally, they have the capacity to multiply while being concurrently regulated by the plant and local microbes. Additionally, microbial inoculants have quicker decomposition processes and are less likely to cause pathogens and pests to develop resilience [1].

Bioinoculants do not show any detrimental impact on the soil's plant and animal life as they are ecofriendly, highly efficient, and can be utilized as bio pesticides that do not affect any harmful influence on plant products. The plant requires mineral nutrients which can only be provided when chemical fertilizers are used directly or indirectly, along with organic manure and biofertilizers to increase the organic carbon in soil and uphold sustainability in a field and horticultural crops [2]. Microbial inoculants are described as organisms that are introduced into an environment for a particular purpose, such as biocontrol or promoting plant growth, such as bacteria, fungi, and other microorganisms [3]. The term bio-fertilizer refers to a wide range of products that contain living or dormant microorganisms, including bacteria, fungi, actinomycetes, and algae. Upon application, these microorganisms help to fix atmospheric nitrogen or solubilize/mobilize soil nutrients in addition to secreting substances that promote plant growth [4]. Now a day, biofertilizers and bio pesticides are currently available as substitutes for conventional inorganic fertilizers and synthetic pesticides respectively along with a variety of other products.

The market for biofertilizers, which was valued at USD 1.57 billion in 2018, is anticipated to expand at a compound annual growth rate of 12.1% between 2022 and 2027 [5]. Currently, there are a large number of small and fewer big companies operating across various geographical regions, creating a highly fragmented market. Currently, the market for biofertilizers is dominated by many small companies because it is largely unregulated; however, if regulations are implemented, as has happened in the market for biopesticides globally, it is possible that the market will become more consolidated [6].

In addition, PGPRs are a special category of microbes that persuade plant defense mechanism and provide resistance to host through the extremely diverse mechanism for further pathogen attack, and considered more beneficial biocontrol agents (BCAs) than typical chemical fertilizers as they are non-pathogenic, naturally inhabitant of the rhizosphere, environment friendly, and enhancing plant yield directly. According to Gupta et al. [7], PGPRs can influence plant development either directly or indirectly and induce plant growth by deploying mineral nutrients in soils, regulating or inhibiting plants from phytopathogens, generating different plant growth regulators, ameliorating soil structure and bioremediating the soil through separation of noxious heavy metals and lowering chemical compounds such as pesticides, fungicides [8–10]. Besides, above mentioned functions of PGPRs, it also plays different defense actions in plants by producing antibiotics, siderophores, bio-surfactants and volatiles, and enzymes that vitiate cell wall and brought systemic resistance (ISR). Saharan and Nehra [11] suggested that a broad range of non-symbiotic and symbiotic bacterial species belonging to

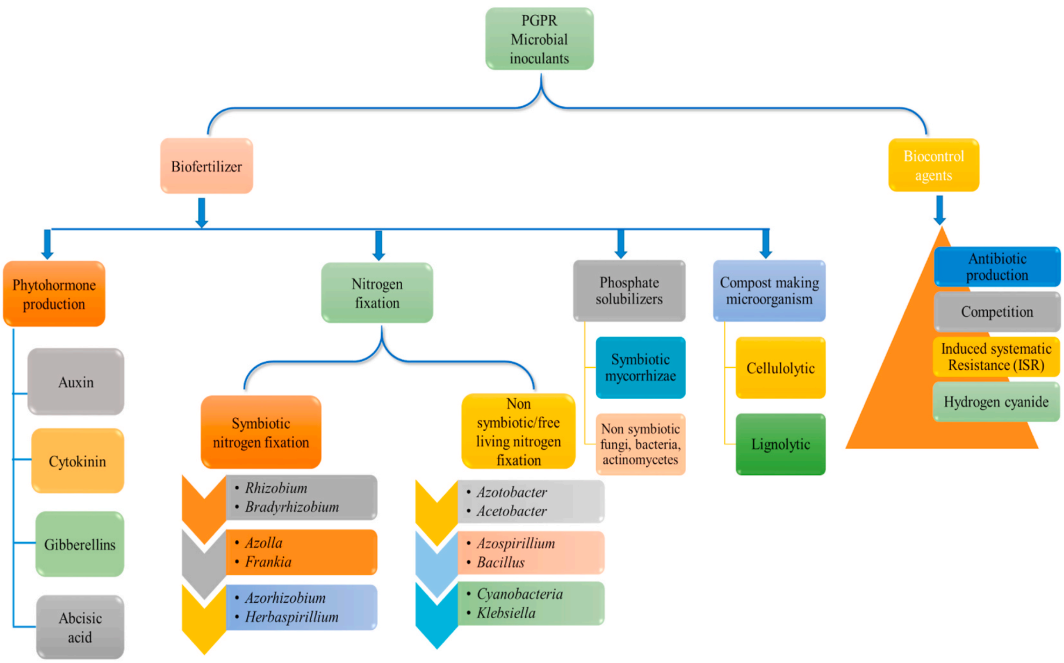

Fig. 1. Schematic Illustration of PGPRs microbial inoculants.

the genus *Klebsiella, Azotobacter, Azospirillum, Bacillus, Enterobacter,* and *Serratia* were considered as PGPRs. Many researchers are still working on knowing the diversity and significance of biofertilizers and their functions in the improvement of agricultural sustainability. The effects of PGPRs are due to plant age, plant species, soil factors, different stages of growth and various form of soil [12]. Kumar et al. [13,14] reported that PGPR's role in enhancing nutrient uptake for plants is an essential activity and appropriate for crop development. PGPRs overcome the reduction in plant growth generated by different forms of stresses [15] including, heavy metals stress [16], water logging stress [17], salt stress [18,19] drought stress [20], and various supplementary hostile environmental situations.

PGPRs inoculation soothes plant stress by promoting useful impacts on plant fitness, growth, increasing the production and assimilation of nutrients. Therefore, it is necessary to use PGPRs for ongoing, beneficial agricultural reasons to improve crop yields and soil fertility in challenging conditions. Over the last few decades, PGPRs are increasingly being used for secure and safe agriculture worldwide. The main obstacle to the farmers' success is a lack of high quality bioinoculants available to them. *Azotobacter, Azolla, Acetobacter, Trichoderma, Bacillus thuriengensis,* and *Azospirillum* need to receive the proper attention given to them and their use in different cereal and vegetable crops. To boost the soil's organic carbon and keep the sustainability of field and horticultural crops, these biofertilizers should be combined with organic manures and chemical fertilizers [2]. The schematic representation of different types of PGPRs or microbial inoculants and their significant contribution in crop improvements are documented in Fig. 1.

The aim of this review is to summarize the importance of microbial inoculants used as biofertilizers, and their mechanism to enhance crop productivity. This review highlights a detailed study of direct and indirect mechanisms of bio inoculants, including biological nitrogen fixation (symbiotic and non-symbiotic), phytohormone production, nutrient solubilization (phosphate and potassium), siderophore production etc., and biocontrol of phytopathogen, chitinases, HCN, and others antifungal properties, as biofertilizer to increase crop yield.

2. Mode of actions or mechanism of PGPRs

2.1. Direct mechanism of PGPRs

2.1.1. Biological nitrogen fixation (BNF)

The primary nutrient for plant growth is nitrogen, considered the fourth significant component of plant dry biomass. It is an important part of genetic material, membranous lipids, and amino acids (enzymatic and structural proteins) [21]. It was described that most nitrogen is inaccessible to animals and plants in gaseous form. Nitrogen fixing PGPRs inoculation on plant yield leads to disease management, growth elevating functions, and retaining the nitrogen level [22]. BNF is a process that converts air elemental nitrogen into ammonia through a reduction cycle with the aid of microbes, some of which are eubacteria, actinomycetes, and blue-green algae. (Table-1). Asymbiotic or free-living nitrogen fixation and symbiotic or associative nitrogen fixation are the broad category of biological nitrogen fixation and are converted by a different mechanism in different crops, and have been presented in Table-1 and 2. The volume of free nitrogen available in the atmosphere is about 4×10^{21} g N, of which nearly 2.5×10^{11} kg NH_3 is fixed yearly by microorganisms [23]. Naturally, in total, 70% of the nitrogen is fixed by microbes referred to as biological nitrogen fixation, and 30% by chemical and physical processes [2]. Table 2 shows the amount of atmospheric nitrogen fixed by different microbial inoculants.

2.1.1.1. Symbiotic nitrogen fixation (SNF). Symbiotic nitrogen fixation (SNF) is a mutualistic association between plants and microbes. The symbiotic nitrogen fixing microbes have the capability of fixing atmospheric nitrogen symbiotically and provided access to all types of plants. Mutualistic relationships begin once the plant starts to secrete flavonoids and iso-flavonoids in its rhizosphere, where it

Table 1
Showing different types of nitrogen fixing microorganisms in various crops.

S. No.	Free living/non-symbiotic/symbiotic	Crops	Reference (s)	Free living/non-symbiotic/ symbiotic	Crops	Reference (s)
1.	*Azotobacter, Azospirillum Azospirilliun* sp., *Pseudomonas* sp.,	Potato	[34]	*B. subtilis, B. lichenoformis P. agglomerans, B. cereus*	chickpea	[45] [46]
2.	*Herbaspirillum* sp., *Bacillus sps. Pasteurella multicida, K. pneumonia, K. oxycota Acetobacter*	Sugarcane,	[35] [36]	*Bacillus* sp. *Klebsiella* sp. *B. majavensis, P. aeruginosa,*	Maize	[47] [48]
3.	*Azospirillum brasilense Pseudomonas* sp. *P. mosselii Stenotrophomonas maltophilia, Chryseobacterium*	Wheat	[37] [38] [39]	*Bacillus, Pseudomonas* sp.	Sorghum and chilli	[49]
4.	*Pseudomonas* sp, *S. marcescens Anabaena, Azolla K. pneumonia, B. subtilis, Microbacterium*	Rice	[40] [41]	*Mesorhizobium Sinorhizobium Azorhizobium*	Lotus Alfaalfa *Sesbania*	-
5.	*Rhizobium* sp. *Bradyrhizobium*	Beans, Peas, Green gram (*Vigna radiate*)	[42] [27]	*Cyanobacteria*	Moss	–
6.	*Rhizobium japonicum Bradyrhizobium*	Soybean (*Glycine max*)	[43] [44]	*Frankia*	Actinorhizal plants	–

Table 2
Showing various inoculants' contributions to the amount of biological N_2 fixation.

S. No.	State	Aerobic/anaerobic	Bacteria	Crop	Amount of N_2 fixed Kg/ha/year	Reference(s)
1.	Free living	Aerobic	*Azotobacter*		10–20	[2]
			Azotobacter	Dry land crops	20–25	[4]
		Anaerobic	*Clostridia*		2–5	
		Facultative	*Klebsiella*		5–10	
2.	Symbiotic	Legumes	*Rhizobia*		50–500	[2]
			Rhizobium strains	Groundnut, soybean	50–200	[4]
		Non-legumes	*Azospirillum*		5–20	
			Acetobacter		150	
			Anabaena	rice	600	[41,50]
3.	Blue green algae		*Anabaena*		20–25	[2]
			Azolla		70–100	
			Azolla	rice	30–100	[4]

is identified by *Rhizobium* [24]. *Rhizobium, Sinorhizobium, Bradyrhizobium,* and *Mesorhizobium* are a few examples of bacteria living symbiotically with leguminous plants, *Frankia* with non-leguminous plants and shrubs [25]. Out of these symbiotic nitrogen fixing bacteria, *Rhizobium* is the leading cause of legume crops' symbiotic nitrogen fixation. Besides bacteria, some small fern is also working as symbiotic nitrogen fixers. For example, *Azolla* is a small, free-floating aquatic fern that collaborates with cyanobacteria (*Anabaena*) to fix atmospheric nitrogen. The appropriate environment, phytohormones, and nutrients are provided by *Azolla* to *Anabaena* in the interchange of fixed nitrogen. In *Anabaena,* the phenomenon of nitrogen fixation happens in heterocyst cell. *Azolla* contributes primarily to rice cultivation by fertilizing the soil with nitrogen and incorporating biomass. Actinomycetes, for example, *Frankia* can produce root nodules for the actinorhizal plants. *Frankia* can be nodulated by certain other genera, such as *Allocasuarina*, *Myrica*, *Eleagnus*, *Coriaria* and *Casuarina.* They are monocot plants with a promising future in agricultural and land reclamation. N is fixed by *Azotobacter* and *Bacillus* species, and they also help in the growth and development of maize plants and forest crops [26]. Inoculation of *Bradyrhizobium japonicum* enhanced plant growth, nodulation, and N fixation in soybean [27].

2.1.1.2. Nonsymbiotic or free living nitrogen fixation. Free-living nitrogen fixers are found in the root zone of plants and obtain food and nutrient from plants, and in favor of return fixed nitrogen under a free-living state. Non-symbiotic nitrogen fixation is also accomplished by diazotrophs that stimulate the development of non-leguminous plants such as rice and radish. Certain other rhizopheric bacteria that fall under the genus *Azotobacter, Burkholderia, Azoarcus, Azospirillum, Gluconacetobacter, Diazotrophicus, Pseudomonas, Enterobacter* and *Cyanobacteria* (*Anabaena, Nostoc*) that also act as non-symbiotic nitrogen fixers [28,29]. Mukherjee et al. [30] suggested that *Azotobacter chroococcum* can be utilized as a biofertilizer because of its capacity to fix 10 mgN/g of in-vitro-supplied carbon source. According to Galindo et al. [31] *A. brasilense* lowers N fertilization, enhances plant nutrition, and boosts plant biomass and wheat grain yield.

Associative nitrogen fixing bacteria are *Herbaspirillum, Acetobacter, Azospirillum* and *diazotrophicus* which are accompanied by plant root cells of the gramineae family. *Azospirillum* is aerobic, non-nodulating, gram-negative, associative nitrogen-fixing bacteria living with C4 plants, such as maize, bajra, sugarcane, sorghum, and cereals like rice, barley, wheat [32]. The inoculation of *Azospirillum* showed marked results in maize, sorghum, wheat, and other grass seedlings. According to Montanez et al. [33], bacteria can provide up to 25% of rice and corn's overall nitrogen needs.

2.1.2. Siderophores production

Siderophores are small organic molecules that carry out antibiosis by supplying iron (Fe) to crops, consequently making pathogens impoverished of iron [51]. Iron is a necessary mineral nutrient for plant development and growth and is needed as a protein cofactor used in metabolic phenomena like respiration and photosynthesis [52]. Mathiyazhagan et al. [53] reported that iron deficiency suppresses pathogen growth by obstructing main processes including sporulation and nucleic acid synthesis. PGPRs have evolved numerous iron absorption approaches to remain alive and adapted to their environment to solve this challenge and supply iron to the plant. The generation of siderophores is one of these strategies. Bacterial species such as *Pseudomonas* use the siderophores formed by other rhizosphere microbes to complete their iron requirements. Gouda et al. [54] reported that *Pseudomonas putida* has the ability to utilize heterologous siderophores made by other microbes present in the root area to increase the iron level existent in the natural environment. Sarwar et al. [55] reported that application of siderophore-producing *Bacillus* sp. enhances the plant growth of groundnut. The production of siderophore and antioxidant enzymes by *Pseudomonas koreensis* in maize plants prevented the development of plant pathogens [56]. The available literature has confirmed that fluorescent *Pseudomonas* sp. generates two major types of siderophores viz pseudobactins [57] and pyochellins [58]. According to Battu and Reddy [59] siderophores are considered growth promoters of plants and biocontrolling agents of fungal diseases cognate with other crops. Therefore, it is crucial to clarify the role of siderophores produced by *Pseudomonas strain B324* in preventing the pathogen *Pythium* which causes root rot disease in wheat [60]. Table-3 summarized a few examples of siderophore producing bacteria that have been linked in various plants.

Schippers et al. [61] reported that *Pseudomonads* produce another form of siderophore namely pyoverdine. It was observed by Loper and Henkels [62] that mutant strains of *Pseudomonads* produce less amount of pyoverdine and caused less repression of the

Table 3
Instances of siderophore producing, phosphate, and potassium solubilizing bacteria in different crops.

S. No	Mechanism /function	Plant growth-promoting rhizobacteria (PGPRs)	Crop	Reference
1.	Phosphate solubilization	*Bacillus* sp., *Pseudomonas* sp., *Serratia* sp	*Solanum tuberosum* (potato)	[99]
		Azospirillum, P. putida, Stenotrophomonas maltophilia, chryseobacterium	*Triticum aestivum* L. (wheat)	[100] [39]
		Bacillus sp., *Klebsiella* sp., *Pseudomonas* sp.	*Cicer arietinum* (chickpea)	[101]
		Herbaspirillum spp., *Bacillus* spp.	*Vigna unguiculata* (cowpea)	[35]
		B. safensis, B. simplex, Lysinibacillus fusiformis, B. pumilus	*Glycine* max (soybean)	[102]
		S. marcescens, Pseudomonas sp.	*Oryza sativa* (rice)	[103]
		P. brassicacerum, Acinetobacter calcoaceticus, P. marginalis	*Solanum lycopersicum* (tomato)	[104]
2.	Potassium solubilization	*Pseudomonas* sp., *Acinetobacter* sp., *bacillus sp.*	*Phaseolus vulgaris* (common bean)	[105]
		B. subtilis, K. oxycota	*Zea mays* (maize)	[106]
		Rhizobium sp.	*Vica faba* (faba bean)	[107]
		Bacillus, Pseudomonas sp.	*Sorghum bicolr (sorghum)*	[49]
		B. circulans	*Citrus sinensis* (orange)	[108]
		Pseudomonas sp., *Rhizobium, Mesorhizobium, Bacillus, Azotobacter* sp.	Leguminous and non-leguminous plants	[109]
3.	Siderophore production	*Bacillus* sp. *KB129, KB133*	*Sorghum bicolr (sorghum)*	[110]
		V. paradox RAA3	*Triticum aestivum* L *(wheat)*	[111]
		Azotobacter sp. *Az63, Az69 and Az70*	*Zea mays (maize)*	[112]
		Rhizobacteria sp.	*pulses*	[113]
		Bacillus amyloliquefaciens ROH14	*pepper*	[114]
		Bacillus amyloliquefaciens FZB42	*Arabidosis*	[115]

fungal pathogen as compared to their parental strains. Thus, it is proved that the production of siderophore is one of the essential process of biological control. The siderophores are categorized into 3 groups hydroxamate, phenol/catechol, and hydroxycarboxylic acid based on their chemical role that is taking part in iron chelation. Over 500 siderophores are identified till now, and out of these a chemical configuration of 270 has been identified [63]. Beneduzi et al. [64] recorded that ferric siderophore complex plays significant activity in iron absorption when plants are exposed to other metals, including cadmium and nickel. PGPRs are a major asset because of generating siderophores that provide the necessary amount of iron to plants. However, further research on the ability of PGPRs to generate siderophores is yet to be explored.

Besides, siderophore production is another mechanism of microbes to control phytopathogens. Most of the iron in the rhizospheric region is bound by siderophores, which operate as iron-chelators. This prevents bacteria and fungi from growing there by using the iron for their purposes [65]. Thus attention has been paid by researchers to develop microbial inoculants that protect plants from diseases caused by pathogens.

2.1.3. Nutrient solubilization

2.1.3.1. Potassium solubilization. The third most important macronutrient that plants need is potassium (K). More than 90% of potassium is found in the form of silicate minerals and insoluble rock. It is particularly involved in the control of stomatal opening and closure, protein synthesis, nutrient uptake, increasing the quality of products, and providing resistance to stressful environmental conditions [66]. It is a crucial component of protein synthesis, enzyme activation, and photosynthesis, making it the third necessary nutrient for plants. The deficiency of potassium causes many major problems in the development of plants [67] and bore underdeveloped roots, slow growth, and lower seed and yield production due to lack of proper potassium content. Kumar and Dubey [68] suggested that it is necessary to discover the source of potassium to conserve potassium eminence and plant absorption in the soil to support crop production. Comprehensive research has been done on potassium rock's solubilization through PGPRs by generating and releasing organic acids [69–71]. Liu et al. [72] reported that PGPRs such as *B. edaphicus, Acidothiobacillus* sp, *Burkholderia* sp, *Ferrooxidans* sp., and *Paenibacillus* sp can solubilize and release potassium elements from potassium containing minerals in the soil so that plants can easily assess that. The application of potassium solubilizing PGPRs as biofertilizers to boost agricultural nutrients can therefore inhibit the utilization of chemical fertilizers and encourage sustainable agricultural production [40,73,74]. According to Macik et al. [75], biofertilizers are substances containing living microorganisms or their inocula and dormant spores that have positive effects on plants, particularly on the seed, root, or soil [76]. Inoculation of seeds of various plants with potassium solubilizing bacteria (KSB) generally exhibited a pronounced increase in seedling vigor, germination rate, plant growth, productivity, and plant potassium uptaking under both greenhouse as well as field conditions [69,77]. Production of organic acids is a significant phenomenon that either directly increases K dissolution through proton or ligand-mediated mechanism or indirectly does so by forming complexes in solution with reaction products. This is one of the mechanisms used by KSB to make K available to plants. As a result, using KSB as a biofertilizer can help promote environmentally sustainable agricultural production by reducing the usage of chemical fertilizers while also increasing plant growth and output [78]. These technologies are becoming essential in the farming practices of today. In the coming years, the changing plan of agricultural practices and environmental threats linked with chemical fertilizers demands a greater position for biofertilizers. Some examples of potassium solubilizing rhizobacteria and improved K uptake in various crops have been presented in Table-3.

2.1.3.2. Phosphate solubilization. The second-most important plant element is phosphorus [79] which can only be absorbed as monobasic or dibasic ions [54,80]. 95–99% of soil P exists in insoluble, frozen, or precipitated forms that are not available for the plant. As a result, only a small amount of the total soil P is useable by crops and is rarely enough [81,82]. Numerous microorganisms have been demonstrated to contribute to the biogeochemical cycling of inorganic and organic P in the plant rhizosphere, and inoculants based on P-solubilizing microorganisms are anticipated to expand quickly on the commercial market in the future [83,84]. Due to their capacity to solubilize P, many PGPRs have caught the interest of researchers for use as plant inoculants [54,85]. Due to the intrinsic P deficiency in many agricultural soils, these organisms are frequently suggested as potential P biofertilizers [38]. P-solubilizing bacteria (PSB) are referred heterotrophic bacteria chosen for their ability to solubilize phosphate compounds that are only weakly soluble in manufactured media by secreting low molecular weight organic ions, which acidify the medium [86].

According to reports, PSB can increase the solubility of precipitated inorganic P ions by acidifying the rhizosphere, which helps desorb inorganic P and complex organic P compounds from clay particles in soil. The solubilization of P is widely advanced to occur by acidification, despite the fact that PSB secrete a variety of enzymes and metabolites that do so [40,84]. It has been possible to extract PSB strains from a variety of genera, including *Pseudomonas, Bacillus, and Burkholderia* [87]. Although many strains have been demonstrated to solubilize P in numerous in vitro tests and pot trials [88], only a small number of PSB have been made available for purchase commercially to date [89]. For instance, recent research by Zeng et al. [90] effectively showed a positive correlation between the production of organic acids and *Pseudomonas frederiksbergensis's* P solubilizing activities. According to Zhang et al. [91] *Bacillus subtilis* shields plants from environmental stress and improves safflower growth. Under field circumstances, NanoPhos with phosphate-solubilizing bacteria increased the population of soil enzymes and bacteria, which improved maize production [92]. The commonly known P-solubilizers include *Pseudomonas*, 18 microbial inoculants as biofertilizer *Azotobacter* [93], 314 *Bacillus*, *Rhodococcus, Arthrobacter, Serratia, Gordonia, Phyllobacterium, Delftia* sp. [94], *Pantoea, Klebsiella, Enterobacter* [95], *Xanthomonas, Chryseobacterium* [96], *Rhizobium leguminosarum bv. Trifolii* [97], *Pseodomonas* sp. [98].

2.1.4. Phytohormone production

Plant hormones are important and secreted by both plants and microorganisms that play a significant role in plant growth and development [116]. Plant hormone production is the beneficial phenomenon of valuable microbes which is producing indole-3-acetic acids, cytokinin, gibberellins, ethylene, and abscisic acid [117]. Our earth supports abundant microbes capable of employing useful effects on plant growth and development. Microbes produce and transport plant hormones are the organic constituents having the capability of inducing physiological, morphological, and biochemical activities of plants even at minute concentrations. These hormones act as signaling molecules and show the direct impact, as they induce root growth, enhance nutrient uptake, and increase nodulation [118]. These are mainly five different types of plant hormones viz; auxin, gibberellins, abscisic acid, cytokinins, and 1-Aminocyclopropane-1-carboxylase (ACC). Some plants also produce brassinosteroids and polyamines in their young tissues. Phytohormones are endogenous in the origin of plants. Numerous reports confirmed that soil microbes can produce phytohormones and can improve the development and growth of plants [119].

2.1.4.1. Auxin production. Auxins are naturally forming growth hormones. There are various types of auxins, and the most prevalent auxin that occurs naturally is indole-3-acetic acid. Involving in the regulation of plant growth. Indole acetic acid (IAA) induced lateral root formation, cell elongation and differentiation, apical dominance, and also induced flowering, fruit setting as well as ripening [120, 121]. Plants themselves synthesize IAA from tryptophan via involving the oxidative deamination mechanism or decarboxylation mechanism [122]. However, some microbes such as *Azospirillum, Rhizobium, Bradyrhizobium, Enterobacter, Agrobacterium, Pseudomonas, Xanthomonas, Bacillus,* and *Klebsiella* are also capable of synthesizing phytohormones via indole-3-pyruvic acid, indole-3-acetic acid aldehyde pathway and through indole-3-acetamide formation [123–125]. The ability of IAA production was found in cyanobacteria such as *Anabeana, Nostoc, Calothrix, Gloeothece, Chlorogloeopsis, Plectonema,* and *Cylindrospermum.*

2.1.4.2. Gibberellins production. Gibberellins are tetracyclic diterpenoid compounds, involved in various physiological as well developmental processes in plants [126]. There are more than 136 known gibberellins that are widely spread in nature [127], but GA_3 is the most frequently used while GA_1 is the most active among all. Gibberellins are synthesized from geranyl diphosphate via several pathways. GAs induces maximum biological activities such as seed germination as it breaks the dormancy of seeds, stem elongation, activation, and synthesis of amylolytic enzymes, floral induction and fruit growth in plants [128]. Stem growth is highly dependent upon the production of gibberellins and its absence or low concentration results in the minimum height of plants. The gibberellins are produced by plants themselves as well as by the fungal strain *Gibberella fujikuroi*. However, several reports showed that PGPRs like *Azospirillum*, *Rhizobium Bacillus, Micrococcus, Agrobacterium, Clostridium, Xanthomonas,* and *Pseudomonas* also produce gibberellins [129–132].

2.1.4.3. Cytokinin production. Cytokinins are adenine derivatives that regulate cytokinesis in plant tissues [133]. Numerous microorganisms, including *Azospirillum, Bacillus, Pseudomonas fluorescens, Pseudomonas putida, Bradyrhizobium, and Paenibacillus polymyxa*, have produced cytokinin, primarily zeatin [132,134–136] and by certain streptomycetes. Cytokinins induce cell division, root hair proliferation, inhibit lateral root elongation, and control root meristem differentiation in plants [137]. In addition, cytokinins have a significant impact on plants, encouraging mitotic cell division in roots and shoots and delaying the aging of leaves [138]. Arkhipova et al. [139] described that cytokinin producing bacterial inoculation in plants rouses shoot growth in plants and reduced root to shoot ratio. A maize plant inoculated with cytokinins producing bacteria *A. chroococcum* which enhanced its growth conditions [140].

2.1.4.4. Abscisic acid production. Abscisic acid (ABA) is also known as stress hormone which is primarily involved in plant development and environmental stresses like drought, temperature, and high salinity [141]. ABA production provides drought as well as water tolerance in plants. Bacteria such as *A. brasilense* are capable to enhance the production of ABA in plants under drought or water stress by causing the closure of stomata, consequently preventing water loss [142]. Additionally, lateral roots are also developed as a result of this.

2.1.4.5. Aminocyclopropane-1- carboxylate (ACC) deaminase production. Ethylene is a crucial growth hormone involved in the regulation of the usual growth and development of plants at very low concentrations [143]. It is also called stress hormone due to its production during biotic and abiotic stress conditions [29]. However, it is beneficial for plant growth at low levels but proved to be harmful at higher levels. Ethylene inhibits auxin transportation and stops root elongation, promoting fruit ripening, senescence, and abscission of different plant parts [144,145]. ACC is the direct precursor of ethylene and some PGPRs such as *Azospirillum brasilense, Enterobacter, Pseudomonas, Achromobacter, Azospirillum, Agrobacterium, Alcaligenes, Ralstonia, Serratia, Burkholderia* spp., *Rhizobium*, etc. have ACC deaminase activity and support the plant development by decreasing the levels of ethylene and provide tolerance to plants under stress conditions [146–148]. ACC deaminase hydrolyses are the immediate precursor of ethylene produced ammonia and α-ketobutyrate which is utilized by microbes as carbon and nitrogen source for their growth [149]. Microbes with ACC deaminase activity are accredited to enhanced growth and productivity and therefore are considered potential agents for biofertilizer origination [150]. The various kind of phytohormones produced by PGPRs in several crops is listed in Table 4.

2.2. Indirect mechanism of PGPRs

2.2.1. Induced system resistance

Plants possess a wide range of active defense systems that are expressed in response to phytopathogens. These pathogens affect plant health and create a chronic threat to food production and ecosystem sustainability. Plants possess an induced system resistance (ISR) which protects the plant from biotic challenges and is effective against numerous pathogens [164]. In plants, ISR is instigated by microbes mostly by *Pseudomonas* sp via pathways regulated by ethylene and jasmonic acid [165–168]. It was observed that *P. fluorescens* triggered ISR in various plants such as *Arabidopsis,* tobacco, and radish via jasmonic acid/ethylene (JA/ET) signaling pathways and substantially reduced the pathogenicity caused by phytopathogens like viruses, fungi as well as bacteria [169]. It was reported that microbes derived some compounds called elicitors which have been proposed to be responsible for the induction of ISR is mediated by a variety of plant hormones [170,171]. Microbial elicitors include cell wall components such as flagellin, lipopolysaccharides, and chitin [172], volatile organic compounds (VOC) like alkanes, terpenoids, sulfides, alcohols, phenolic compounds and ketones [171] or metabolites including antibiotics, siderophores [173]. These elicitors act synergistically to induce ISR against different pathogens, and control plant diseases as well. Sometimes the elicitors generate ISR by affecting phytohormones that are crucial to the plant signaling process and leading to the initiation of defense response [174]. Besides, various strains of *Pseudomonas,* different *Bacillus* sp. such as *B. pumilus, B. subtilis, B. amyloliquefaciens, B. cereus, and B. mycoides* were reported to induce in opposition to a variety of diseases [175]. It was observed that *B. cereus* synthesize dimethyl disulfide (DMDS) and showed ISR-eliciting action toward various pathogenic fungi [176]. *Arabidopsis* plants inoculated with *P. simiae* release elicitor coumarin scopoletin, which is a phenolic compound and inhibits the soil borne pathogens [177]. It was also observed that PGPRs can change the morphology or physiology of plant roots upon pathogen attack by secreting the phytohormones such as JA, auxin, NO and cytokinins, thus protecting the plant from pathogen attack [178–180]. Sometimes, microbes amplified the ISR in plants via structural barrier, production of molecules such as chitinase, β-1,3-glucanase, peroxidases, and phenylalanine ammonia-lyase [181].

Table 4
Phytohormones produced by PGPRs and their role in plants.

S. No.	PGPR	Phytohormones	Plant	References
1.	*Pseudomanas putida*	ACC deaminase	Tomato	[151]
2.	*Bacillus circulans*	ACC deaminase	Mustard	[152]
3.	*Achromobacter xylosoxidans, Enterobacter Cloacae*	ACC deaminase, IAA	Maize	[153]
4.	*Bacillus* spp.	ACC deaminase, IAA, EPS	Rice	[154]
5.	*Pseudomonas putida*	IAA	Canola	[155]
6.	*Bacillus subtilis*	IAA	Edible tubercle	[124]
7.	*Herbaspirillum seropedicae*	IAA	*Ocimum sanctum*	[17]
8.	*Bacillus amyloliquefaciens* QST713	IAA, EPS	*Alfalfa (Medicago sativa* L.)	[156]
9.	*Azospirillum* sp	Cytokinin production	Mimosa pudica	[157]
10.	*Bacillus*	Cytokinin production	Cucumber	[158]
11.	*Pseudomonas* BA-8	Cytokinin production	Strawberry	[159]
12.	*25Acinetobactersp.* ALEB16	Abscisic acid	*Atractylodes lancea*	[160]
13.	*Bacillus* sp.	Gibberellin production	Alder	[161]
14.	*Sphingomonas*	Gibberellin production	Tomato	[162]
15.	*Bacillus*	Gibberellin production	Pepper	[163]

2.2.2. Biocontrol of phytopathogen

Pathogen attack and disease development in agricultural plants are the dominating factor in reducing crop productivity and contamination of food products. Therefore, to protect crop productivity from pathogens different chemical constituents like pesticides are used [182]. However, prolonged utilization of these chemical compounds has advanced resistance to pathogens and creates a threat to the environment. Therefore, biological control is intended as a substitute for chemicals to manage the pathogen attack. Rhizobacteria encourage plant development, are potential biological agents for phytopathogens, and are used as biofertilizers due to their substantial influence on plant health, suppression of pathogens and diseases. The use of beneficial microbes in crop fields is non-toxic and ecofriendly thus preventing pathogen attacks through different mechanisms. PGPRs belonging to genera *Acetobacter, Burkholderia Arthrobacter, Klebsiella, Azoarcus, Azotobacter, Azospirillum, pseudomonas, Enterobacter, Beijerinckia, Alcaligenes, Bacillus, Derxia, Gluconacetobacter, Rhodococcus, Acinetobacter* and *Stenotrophomonas*, etc. have the property of biocontrol agents [183]. The production of antibiotics is the well-known mechanism of PGPRs to counter the toxic effects of pathogens in plants. Antibiotics such as amphisin, pyrrolnitrin, phenazines, hydrogen cyanide (HCN), oomycin A, tropolone, kanosamine, etc. produced from *Streptomyces, Stenotrophomonas, Pseudomonas,* and *Bacillus* that have antifungal, antibacterial, antiviral properties and protects the plant from diseases and pathogens [184].

2.2.3. Chitinase

The production of enzymes by PGPRs is another mechanism to control phytopathogens. PGPR's such as *S. plymuthica, P. stutzeri, S. marcescens, and Paenibacillus* sp. secrete enzymes including chitinase, protease, lipase, and various other enzymes that hydrolyze the chitin, proteins, cellulose, and hemicellulose as well as other cell wall components of fungal pathogens [185,186].

2.2.4. Hydrogen cyanide (HCN)

Microbes such as *Rhizobium, Bacillus,* and *Pseudomonas* secrete hydrogen cyanide that degrades pathogens and provides the plant defense against pathogenic diseases [187]. El-Rahman et al. [188] recorded that rhizobacteria produce HCN, and inhibit the growth of *Agrobacterium tumefacience* and *Meloidogyne incognita*.

So, the PGPRs are vital microorganisms and played significant role in plant growth development and enhancing crop improvement by performing several activities like nitrogen fixation, potassium solubilization, phosphate solubilization phytohormone production, pest and disease management, siderophore production, improved soil structure. The aforementioned substantial contribution of microbial inoculants in improving crop yield and productivity is documented in Fig. 2.

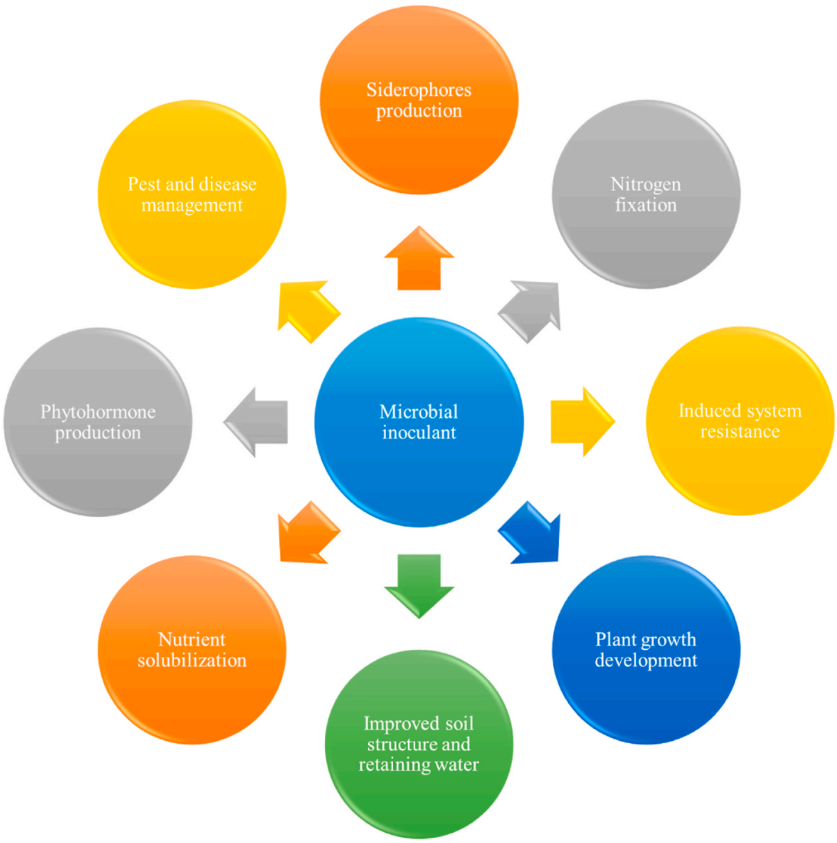

Fig. 2. Diagrammatic representation of role of microbial inoculants/PGPRs.

3. Future perspective and challenges

The utilization of biofertilizers as an integral aspect of agricultural techniques is rapidly becoming widespread worldwide. To ensure food security on a global scale, it is imperative to enhance crop yields while adapting to varying climatic conditions. The potential use of PGPRs as biofertilizers and biopesticides provides hope for doing this. However, additional investigation is required to understand the contradictory results regarding the advantages of PGPRs in field settings [189]. The future prospects of microbial inoculants as biofertilizers are promising as they offer several advantages over traditional chemical fertilizers. With the growing concerns about the environmental impacts of traditional farming practices, there is a need to increase sustainable agricultural practices. In addition, microbial inoculants as biofertilizers can contribute to sustainable agriculture by reducing the dependence on chemical fertilizers and promoting soil health. The ability of PGPR with the potential to be converted into inoculants for a variety of crops is being evaluated in an increasing number of studies [190,191]. Therefore, it is reasonable to anticipate that the widespread use of biofertilizers will give a variety of strategies for the overall growth of sustainable crop production systems in near future [192].

Furthermore, advanced technology, such as precision agriculture, can help optimize the use of microbial inoculants by providing information on soil conditions and plant nutrient requirements leading to the precise and targeted application of biofertilizers, improving their efficacy and reducing waste. The impact of climate change on agricultural productivity can be mitigated by the use of microbial inoculants, which can assist in adapting to changing conditions. Certain strains of beneficial microorganisms have shown promise in assisting plants in coping with various stresses associated with climate change, such as drought and salinity. Besides, advances in microbiology and genetic engineering can lead to the development of new microbial strains with improved capabilities, for instance, researchers are working on developing microbial strains that can fix nitrogen in non-leguminous plants, which could greatly reduce the need for nitrogen fertilizers. Despite being the third most important macronutrient for plant growth and development, research on K solubilization by plant growth-promoting rhizobacteria (PGPRs) has not progressed as rapidly as studies on nitrogen fixation and phosphorus solubilization [193]. The outcome of this research will serve to promote and instill confidence in the application of bioinoculants. Additionally, future studies should concentrate on the optimization of growth conditions that are economical to maintain, can withstand unfavorable environmental conditions, and increase productivity [194]. Overall, microbial inoculants as biofertilizers are promising, and their use is likely to increase as more farmers adopt sustainable and environmentally friendly farming practices.

As we know that microbial inoculants are a promising alternative to chemical fertilizers but, there are several limitations and challenges associated with the use of microbial inoculants as biofertilizers. They possess a restricted shelf life and may lose their effectiveness if not stored properly or used within a certain period. Further investigations are required in this area to advance knowledge, enable broad-scale application and commercialization, and enhance the ability to harness and manipulate plant microbiomes in situ for agricultural purposes [195]. The inoculant industry faces several difficulties when creating formulations with extended shelf lives. The creation of formulations with longer shelf lives, broader therapeutic spectra, and constant field performance may help this technology to become quicker and commercially viable [196]. To create formulations with longer shelf lives, new biotechnological methods should be assessed. Besides, there are also certain limitations to the use of microbial inoculants including control of quality and consistency of microbial inoculants, application methods, compatibility of microbial inoculants with chemical fertilizers, and environmental factors such as temperature, moisture, and pH. To overcome these challenges, researchers and industry professionals should explore several strategies, including the selection of improved microbial strains, the development of new formulations, standardized quality control, and educating farmers and agricultural professionals regarding the benefits and proper use of microbial inoculants.

4. Conclusion

Pesticides and chemical fertilizers are effective for the production and disease control of plants but, their continuous application is a threat to the soil ecosystem, plants as well as human beings. Thus to overcome this problem, use of beneficial microbes as biofertilizers and biocontrol agents is an ecofriendly and cheap method for sustainable agriculture. Biofertilizers have the potential to replace chemical fertilizers as well as pesticides and exert a positive impact on crop productivity and encouragement should be given to its implementation in agriculture. Farmers should be made aware of the benefits of using PGPRs as biofertilizers, and the commercialization of PGPRs should be emphasized. Thus in general we concluded that PGPRs have countless benefits in agriculture. Consequently, we can say that the use of biofertilizers in agricultural fields is the best alternative to chemical fertilizers which influence hazardous effects on flora as well fauna and soil health.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

No data was used for the research described in the article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

Authors do not have any conflict of interest.

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