Agriculture Association of Textile Chemical and Critical Reviews Journal (2023) 398-408

AATCC Review

29 March 2023: Received
22 July 2023: Revised
24 September 2023: Accepted
27 November 2023: Available Online

www.aatcc.peerjournals.net

Review Article **Open Access**

Biofertilizers and Biopesticides: Microbes for Sustainable Agriculture diseases management of crops: a review

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ABSTRACT

Agriculture development initiatives on the part of humans have long been documented. Since learning about the significance of this area, farmers and researchers have not stopped looking for strategies and solutions to increase agricultural output and quality while also shielding it from potential threats and stress. In place of agrochemicals, mechanisms using microorganisms as biofertilizers, and biocontrol agents have recently gained popularity. Utilizing advantageous microorganisms is an environmentally benign tactic that plays a significant part in promoting plant growth and in the biocontrol of plant diseases. Reduced chemical inputs and the usage of harmful pesticides in agricultural soils may be possible with a greater understanding of how these bacterial communities are used. The focus of the current review is on plant growth-promoting bacteria (PGPB), and it provides a summary of their function in soil fertilization and plant protection with a focus on their methods of action. This chapter includes a number of PGPB examples that were taken from the literature. Examples of how these bacteria have been used in agriculture are also included in this review.

Keywords: *Agriculture, Biofertilizers, Biopesticides, Microorganisms, Soil, biocontrol, fertilization, chemical*

1. Introduction

Human efforts to boost food production and cut expenses have detrimental repercussions on a variety of levels. Chemical solutions are seen as the most practical solution, but their widespread usage is harmful to both human health and the environment (1,2). Other obstacles to agriculture besides chemical products include salinity, heavy metals and desert regions. In reality, agriculture has intensified because of market globalization, rapid population growth and rising living standards in the most industrialized nations. This intensification is based on mechanization and sophisticated agronomic techniques, which have increased crop output. Due to environmental harm, intensive agriculture is coming under increasing criticism. These environmental degradations have led to a number of new agricultural science problems, including those related to depollution, waste management, rural development, and biological control (3). Plant infections have disastrous consequences on plant health and crop yields, which further endangers food production and ecological stability. Chemical products have recently been the most popular crop protection method among farmers. These substances, often known as biostimulants, frequently provide cutting-edge fertilization and crop protection techniques. The majority of these biologically generated stimulants are created by plant growth-promoting bacteria (PGPB) (4). This collection of microorganisms greatly increases sustainable agriculture by regulating the rhizosphere's biological activity and safeguarding and promoting plant growth and health (5). These substances, often known as biostimulants, frequently provide cutting-edge fertilisation and crop protection techniques. The majority of these biologically generated stimulants are created by plant growth-promoting bacteria (PGPB). This collection of microorganisms greatly increases sustainable agriculture by regulating the rhizosphere's biological activity and safeguarding and promoting plant growth and health. The selection of beneficial bacteria and their byproducts can enhance plant rhizosphere colonization, create a wide range of agricultural prospects, and preserve the environment. In fact, a better knowledge of how these bacterial communities function might enable the usage of toxic pesticides and chemicals in agricultural soils to be reduced (6).

2. Plant Growth-Promoting Bacteria

The microorganisms, which are mainly bacteria from the *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Enterobacter*, *Pseudomonas*, *Serratia*, and *Streptomyces* spp. genera, encourage the growth of plants. Moreover, these bacteria protect plants from biotic and abiotic threats (7,8,9,10). These microbes can grow in number and compete with other soil microbes for nutrients and rhizospheric space. Rhizobacteria boosting plant nodulation and plant growth-promoting bacteria (PGPB) are the names given to these microorganisms (11,12). Plant growth-promoting rhizobacteria, or PGPRs, are the subset of PGPBs that have received the greatest research attention (13). Yet, unlike other rhizosphere bacteria, these bacteria provide plants with a number of beneficial effects through a variety of direct and indirect mechanisms. These bacteria infiltrate the plant rhizosphere by using root exudates as nutrient substrates (14,15,16). Auxins, cytokinins, gibberellins, nitrogen fixation, phytohormone synthesis (auxins, cytokinins, and gibberellins), siderophores production, and inhibition of ethylene synthesis by the enzyme 1-aminocyclopropane-1-carboxylic deaminase

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DOI: https://doi.org/10.58321/AATCCReview.2023.11.04.398

(ACC-deaminase) are examples of direct mechanisms (17, 18, 19). Some examples of indirect mechanisms include the production of hydrolytic enzymes, the inhibition of pathogen-produced enzymes or toxins, the induction of plant resistance mechanisms, and the suppression of phytopathogenic agents through competition for nutrients and space (19, 20, 21). PGPB diversity varies widely depending on the kind of plant, the kind of soil, and the availability of nutrients. Of the PGPBs that have been discovered, *Pseudomonas* and *Bacillus* are the most widespread and thoroughly studied. Strains from the genera *Aeromonas*, *Azospirillum*, *Azotobacter*, *Arthrobacter*, *Clostridium*, *Enterobacter*, *Gluconacetobacter*, *Klebsiella* and *Serratia* are also included in the PGPB group (22,23,24,25). In addition to being efficient biofertilizers and having the enzymes (lipase, esterase, protease, phosphatase, urease, chitinase, and amylase) to hydrolyze all varieties of organic polymers, PGPB has the capacity to enhance the growth of all plant growth parameters (seed germination, root and shoot length and weight, leaf area, and chlorophyll content) (26,27). As a result, they facilitate nutrient uptake by plants and help to enrich the soil with nutrients (23,28). Rhizoremediers (degrade organic pollutants and lessen their toxicity), phytostimulators (stimulate the growth and the development of different plant growth parameters), phytopesticides (protect the plants from various aggressions caused by phytopathogenic agents), and biopesticides (degrade organic pollutants and mitigate their toxicity) are some applications for PGPB (29,10,27).

2.1 PGPB as Biofertilizers

Biofertilizers are substances that contain useful microorganisms (living or dormant) that have the ability to enrich soil with nutrients and stimulate plant growth when applied to soil. They do this by improving nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop productivity and quality. Biofertilizers are preparations of active or dormant cells of strains with the ability to fix nitrogen, solubilize phosphate, and produce cellulase (30). To improve soil and boost plant productivity, PGPBs employ a number of techniques, such as nitrogen fixation, phosphate solubilization, siderophores, and hydrolytic enzyme production (31,32,33). In particular, nitrogen is produced by bacteria that fix nitrogen (34), iron is produced by bacteria that produce siderophores, sulfur is produced by bacteria that oxidise sulfur (35), and phosphorus is produced by bacteria that solubilize phosphate. Plants can more readily absorb nutrients thanks to biofertilizers (36). We may utilize these beneficial microorganisms and boost crop productivity by comprehending how these bacteria work with other rhizospheric germs (37).

2.1.1 Enzymatic Activities

The fact that microbial enzymes are used so frequently in biotechnology—including agro-food, detergents, textile, pharmacy, and molecular biology—is due to the fact that these microorganisms have attracted so much attention in agriculture as biofertilizers. Enzymes including proteases, esterases, lipases, amylases, and cellulases are crucial to the agricultural business because they play a crucial part in soil fertilization through the breakdown of organic polymers (38). During these processes, these microbes release nutrients such as phosphate, iron, carbon, nitrogen, potassium, and sulphur into the soil, which are then utilized by plants and other soil microorganisms Cell wall-degrading enzymes, such as those secreted by the PGPR, such as glucanases, chitinases, cellulases, and proteases, are one of the main strategies used by biocontrol agents to control plant diseases (39,40). The essential conversion of cellulose into carbon dioxide or methane by bacteria is the primary role of cellulose degradation in the carbon cycle (41). There is a lot of interest in the prospect of converting agricultural waste utilizing cellulases made by soil microorganisms. The number of nodules increases as a result of this enzyme making it simpler for these bacteria to access the intercellular space or the root hair (42). Bacteria including *Pseudomonas aeruginosa, Bacillus prodigiosus, Bacillus pyocyaneus, and Bacillus prodigiosus* were found to have lipases and esterases in 1901. Protein breakdown by microbial proteases has a significant impact on the nitrogen cycle in soil because it makes nitrogen available to plants and microorganisms (43). It is well known that the creation of lytic enzymes like proteases is one of the indirect strategies employed by PGPR to eliminate undesirable bacteria (44). Proteases are utilized in the disintegration of worm cuticles (45). The nitrogen cycle in soil depends on microbial proteases because it makes nitrogen available to plants and microbes (43). It is well known that one of the indirect methods employed by PGPR to eliminate harmful microorganisms is the development of lytic enzymes such as proteases (44). Several authors have shown the effect of microbial proteases on biological control (39,40). Pythium ultimum, a phytopathogenic fungus, is suppressed in the sugarcane rhizosphere by extracellular protease produced by *Stenotrophomonas maltophilia* W81,(46). The protease activity may indirectly alter the synthesis of auxin by releasing amino acids like tryptophan, a precursor for the synthesis of the IAA (47). A sizable amount of urea is continuously released into the environment as a result of biological processes. Urease is an extracellular enzyme that hydrolyzes urea into CO_2 and ammonia, which accounts for 63% of all soil activity (NH3). Due to the fact that the rate of organic matter synthesis has an impact on its concentration, it is employed as a soil quality indicator (48). Since Rotini, first reported on the activity of urease in soils, it has attracted a lot of attention (49). According to Polacco, microbes and plants that produce both intracellular and extracellular enzymes are the primary producers of soil urease (50).

2.1.2 Nitrogen Fixation

Nitrogen is one of the most important factors in plant growth. As the majority of this element exists as gas (N2), neither plants nor animals can utilize it (51). In order to meet the plants' needs for nitrogen and to improve productivity, agriculture has become dependent on artificial fertilizers; however, the harm these products caused was substantially more than their beneficial effects. A study on the harm that synthetic nitrogen fertilizers can cause to human health as well as the environment was released by the US National Institutes of Health. It was postulated that increased nitrate levels in drinking water may contribute to cancer and that cardiac disorders may be becoming more common due to nitrogen-related air pollution (52,53). Farmers consequently depended more and more on biological mechanisms to provide nitrogen to plants. Bacteria repair this element and also change it into ammonia (assimilable form). Examples of free-living bacteria include *Azotobacter*, *Bacillus*, *Acetobacter*, *Clostridium*, *Klebsiella*, *Corynebacterium*, *Arthrobacter*, *Diazotrophicus* and *Pseudomonas*. An illustration of a symbiotic bacteria is *Rhizobium* (54,55). The benefit of diazotrophic bacteria is that they can exchange the carbon they create in the form of root exudates for plants' need for nitrogen. Yet, the presence of carbon as an energy source is required for the substantial nitrogen fixation. This calls for the presence of these diazotrophs around plants, either as endophytes, in the rhizosphere, or in the rhizoplane. Nitrogen fixation has the potential to boost soil fertility and productivity. Many studies have examined the inoculation of plants with nitrogen-fixing bacteria, and several authors have demonstrated the role of PGPR in enhanced nodulation in root plants as well as nitrogen fixation (56). By utilizing these microorganisms, the need for chemical fertilizers can be greatly reduced. *Azotobacter* sp., *Paenibacillus polymyxa* and the endophytic bacteria *Azoarcus* sp., *Burkholderia* sp., *Gluconacetobacter diazotrophicus*, and *Herbaspirillum* sp. have all been shown to fix nitrogen, and this ability is closely correlated with their ability to promote plant growth (57). Three nitrogen-fixing bacteria, known as *Azotobacter diazotrophicus*, *Herbaspirillum seropedicae*, and *Azoarcus* spp., are found in the rhizosphere of plants, namely in their roots. Barley, wheat, rice, and sugar cane production are all increased by these bacteria (58). Inoculating plants with nitrogen-fixing bacteria including *Azospirillum*, *Enterobacter*, and Rhizobium while they were under axenic conditions increased potato output (59). For instance, *Azospirillum* sp. TN10 increased the fresh and dry weight of the potato in comparison to control (non-inoculated) plants. It was also discovered that the nitrogen content of the stems and roots of the infected plants had greatly risen.

2.1.3 Phosphate Solubilization

Like nitrogen, phosphorus (P) is an essential nutrient for the growth of plants and a nutrient that restricts plant growth (57). It is an essential component of DNA and adenosine triphosphate (ATP) (60). This element is immobilized in the soil by chemical precipitation, which renders it less soluble and unavailable to plants (61). The majority of the phosphorus taken during the developmental phases is transferred to the fruits and seeds; however, phosphorus-deficient plants show growth retardation (reduction of growth of cells and leaves, disruption of respiration and photosynthesis). In agricultural soils, the solubilization of inorganic phosphates is directly influenced by the activity of microorganisms (62,60). Bacterial species such as *Bacillus*, *Pseudomonas*, *Rhizobium*, *Aspergillus* and *Penicillium* can transform phosphorus into a form that plants can utilise (63,64,65). The two main procedures employed by PGPRs to convert phosphate into an assimilable state are solubilization and mineralization. The solubilization is brought on by the release of low molecular weight organic acids like gluconic acid and citric acid (66,67). These molecules lower the pH by chelating the cations attached to the insoluble phosphates and converting them to soluble forms (68). The mineralization process carried out by the release of extracellular enzymes including phosphatase and phytases that catalyze the breakdown of the phosphoric esters. Both of these tactics can coexist in the same bacterial species (66). It has been shown by many writers that bacteria can solubilize phosphate (64). According to Gull et al., there is a significant potential for phosphate solubilization in soil by species of the genera Bacillus and Pseudomonas. Bacteria could be used in crop fields because of their capacity to solubilize phosphate. The species *Achromobacter xylosoxidans*, *Bacillus polymyxa*, *Pseudomonas putida*, *Acetobacter diazotrophicus*, *Agrobacterium radiobacter*, *Bradyrhizobium mediterraneum*, Pseudomonas and other phosphate-solubilizing bacteria can increase the amount of phosphate in the soil. Pseudomonas species boost plant growth by enhancing their ability to absorb different minerals from the soil and as plant growth promoters. Pseudomonas and other phosphate-solubilizing bacteria can increase the amount of phosphate in the soil (69). Pseudomonas species, increase plant growth by increasing their capacity to absorb various minerals from the soil. Pseudomonas species such as *P. cissicola*, *P. fluorescens*, *P. pinophillum*, *P. putida*, *P. syringae*, *P. aeruginosa*, *P. putrefaciens* and *P. stutzeri* that have been identified from the rhizosphere of cereals such as chickpea, corn, and soybean greatly solubilize phosphates. According to several studies, *Pisum sativum* L. grown in soil deficient in soluble phosphate produces significant quantities of gluconic acid as a result of being stimulated to develop (67). The inoculation of Chickpea by single and dual phosphate-solubilizing Bacillus megaterium (M3) and nitrogen-fixing *Bacillus subtilis* (OSU-142) has improved all its parameters growth compared to control equal to or higher than N, P, and NP treatments (70).

2.2 PGPB as Biocontrol Agents

Biocontrol, also referred to as biological control or biocontrol, is the employment of living animals to defend plants against various threats. It refers to the practise of controlling some pathogenic insects in entomology with the use of predatory insects or entomopathogenic nematodes. In phytopathology, this statement describes the use of microorganisms to manage hazardous plants and avoid disease. The International Organization for Biological Control (IOBC) defines biological control as the use of live organisms to prevent or reduce harm caused by pests. These microorganisms go by the moniker "Biological Control Agent" (71). Many studies examining the use of these bacteria as pesticide substitutes have shown how crucial a part these biocontrol agents may play in raising horticulture and agriculture productivity (72). Many varieties of bacteria and fungi, especially those belonging to the genera *Bacillus, Pseudomonas* and *Burkholderia*, have been referred to as unfriendly microorganisms (73). There is a broad search for novel biological control strategies to stop the formation of phytopathogenic bacteria because of environmental concerns. It has been proposed that the inhibition of phytopathogenic fungi by bacteria may be caused by the synthesis of antibiotics, the secretion of hydrolytic enzymes, the creation of plant resistance, the competition for resources and space, or a combination of these processes (74,75,76,77,78). Changes in environmental parameters (such as pH, plant area, etc.) are one of the mechanisms used by several biocontrol agents to indirectly control plant diseases (79).

2.2.1 Siderophores Production

A protein called a siderophore has the ability to solubilize and bind iron from the soil so that it can be given to plant cells. These low-molecular-weight iron-binding molecules have an affinity for Fe^{3+}. This chemical is utilized by PGPRs in the biocontrol of phytopathogens as well as biofertilization mechanisms. Siderophores, which are released by PGPRs, bind Fe^{3+} from the soil and carry it back to the PGPRs cell, where it will be changed into a form that is useful for plant and microbial growth (80,81). Siderophores are produced in substantial amounts in soil, which enables PGPRs to take all the iron required for their growth and deny phytopathogen bacteria access to it. Numerous authors have demonstrated the generation of siderophores by Bacillus and Pseudomonas species (82,83,84,85,60). Numerous studies have demonstrated that the sidorophores produced by the

PGPR have a substantial impact on how plants absorb different metals, such as Fe, Zn, and Cu (86,87,88). The bacterial siderophores are able to sequester iron from the rhizosphere, which prevents pathogenic fungi from growing and has a negative impact on plant nutrition. *Pseudomonas fluorescens'* pseudobactin and pyoverdin siderophores have a definite function in the management of *Fusarium* species (89,90). *Pseudomonas* species produced sidorophores that were used in the biocontrol of plant infections like *Aspergillus niger* (91). These substances are crucial in promoting plant growth, and some plants can directly absorb iron from *Pseudomonas* siderophore (92). Seed inoculation with PGPRs that produce siderophores enhances plant development and boosts chlorophyll content (93). There is potential for using PGPRs that produce siderophores in agriculture as biocontrol agents and microorganisms that stimulate plant growth.

2.2.2 Chitinase Production

Insoluble linear polymers of ß (1,4) N-acetylglucosamine serve as the main structural constituents of the cell walls of many fungi, insect exoskeletons, and crustacean shells. Chitinase hydrolyzes these polymers to form cell walls (94). Bacillus cereus, which inhibits *Botrytis elliptica* growth, and *Bacillus* sp. S7LiBe, which inhibits *B. cinerea* growth, are two microbes that generate this enzyme and act as biological control agents (94,95). Multiple investigations have shown that chitinases contribute to antifungal effect and can increase the activity of *Bacillus spinsecticidal* (96). The majority of *Bacillus* spp. have significant chitinase activity (97). Some investigations have found a connection between the capacity of Bacillus species and Pseudomonas species to prevent the mycelial growth of *Fusarium oxysporum* and *Fusarium solani*. The ability of the chitinase-producing actinomycete (*Streptomyces vinaceusdrappus* S5MW2) to promote tomato development and act as a biocontrol agent against *Rhizoctonia solani*. Chitinases are created as a biocontrol method to stop phytopathogenic fungi's spores from germinating (98). In a greenhouse experiment, chitin addition and usage of the bacterial strain S5MW2 significantly increased tomato plant growth and reduced *Rhizoctonia solani* disease symptoms. Bacteria that produce chitinase have been identified as potential biocontrol agents (99,100).

2.3 Competition for Space and Nutrients

Many and various microorganisms interact in soil, or more specifically in the rhizosphere, and plant roots, which are frequently the only sources of nutrients, are frequently insufficient to support the whole microbial flora. These bacteria compete with one another for all nutrient elements in order to maintain their levels of growth, development, and activity. Competition includes the use of or control over access to resources, such as food, space, or any other finite resource (101). Hattori describes how PGPRs can outcompete harmful organisms by receiving the bulk of nutrients and occupying favorable niches, which causes them to make up a significant fraction of the rhizosphere-rhizoplane population. By competing with them for resources like nitrogen, carbon, or macro or micronutrients, antagonist PGPRs can stop the growth of a variety of phytopathogenic diseases (102). The battle for iron is one particular example of nutritional rivalry. In an effort to live, bacteria release siderophores, as previously mentioned, depriving phytopathogenic agents of one of their growth factors (71). *Pseudomonas* bacteria may effectively chelate substances by utilizing siderophores made by other bacteria (103). Plant illness can be lessened by enabling helpful bacteria to colonize a substantial portion of a plant's roots. Because of this colonization, there are fewer places where harmful germs can exist and grow. Two ways for which biocontrol agents can prevent plant growth have been proposed: competition for the substrate (104) and siderophores' competition for iron (105,106).

2.3.1 Antibiosis

Antibiosis, a process where chemicals with antifungal and/or antibiotic properties are produced, inhibits pathogens (103). For instance, among the metabolic products that PGPR produced that possessed bioactive qualities were lytic enzymes (chitinase, protease, glucanase, etc.), antimicrobial proteins or peptides, polyketides, phenolic compounds, bio-surfactants, etc (22). *Bacillus* and *Pseudomonas* produce the antibiotics fengycin A and B, iturin A, mycosubtilin, bacillomycin D and pyochelin to attack aflatoxigenic fungus (107). Several publications have discussed PGPR's capacity to produce volatile substances such as ammonia, hydrogen cyanide, acetoin, and 2,3-butanediol. An further class of antibiotic compounds is volatile compounds (108,109,110). *Fusarium oxysporum's* mycelial development and spore germination were greatly prevented by the volatile chemical produced by bacteria. *Gaeumannomyces graminis* var. tritici "take-all" of wheat was once more suppressed by a cyanide-negative mutant of CHA0 that was complemented by the hcn+ genes (111). *Pseudomonas* is able to produce significant amounts of the enzymes chitinase and 1,3-glucanase, which degrade the chitin and glucan present in the cell walls of phytopathogenic fungus. Moreover, *Pseudomonas* can make metabolites that are antifungal. A cyanogenic *Pseudomonas* bacterium called *P. fluorescens* CHA0 was engaged in the Competition for nutrients, particularly for carbon and suggested as one of the mechanisms creating the fungistatic effect, which is characterised by the inhibition of spore germination in soil (112). bacteria can parasitize and degrade the spores or hyphae of fungal infections by the creation of a number of enzymes (113). The infection process depends on the generation of hydrolytic enzymes during the early host-pathogen interaction (114). Control of several plant diseases, particularly fungi (111,115). Rhizosphere bacteria produce this chemical, which gives plants a generalized resistance to a variety of diseases (116). One such strain that creates antimicrobial metabolites with a wide range of antifungal activity is P. protegens CHA0, a strain of Pseudomonas fluorescens that produces the antibiotic metabolites 2,4-diacetylphloroglucinol (DAPG), pyoluteorin (PLT), and pyrrolnitrin (PRN) (117). One example of how Weller classified several strains of *P. fluorescens* in which the production of chemicals like phenazines and DAPG is directly related to an antagonistic activity against various pathogens is the antagonistic activity of P. fluorescens 2-79 and CHAO on *Gaeumannomyces graminis*. Pseudomonas PsJN has also been shown by Siddiqui to reduce the *Botrytis cinerea* caused tomato disease(118,119). The strains of *Pseudomonas fluorescens* PF1, FP7, and PB2 have been shown to inhibit the germination of *Rhizoctonia solani* sclerotia.

2.3.2 Induced Systemic Resistance

The stimulation of plant defence mechanisms is a component of the PGPRs-plant interaction involved in the control of infections. The term "induced systemic resistance" (ISR) refers to this occurrence, which increases the host's resistance to pathogen aggressiveness in the future. ISR consequently has phenotypic characteristics with RSA, which is brought on by phytopathogenic agents. ISR is as efficient against several pathogens as SAR, however it differs from SAR in that the bacterium that causes PGPR colonises roots and does not manifest any symptoms on the host plant (120,121). When PGPRs interact with plants, they cause structural and physiological changes that lead to the production of molecules involved in plant defense mechanisms. Bacterial lipopolysaccharides, siderophores, and salicylic acid (SA) are found to be the major determinants of ISR. Systemic resistance may be induced by various microorganisms, Gram-positive bacteria such as Bacillus pumilus, or Gramnegative bacteria belonging to the genus Pseudomonas (fluorescens, putida, aeruginosa) (122). Arabidopsis seedlings exposed in divided Petri dishes to PGPR B. subtilis GB03 and B. amyloliquefaciens IN937a for 10 days developed significantly less symptomatic leaves 24 h after inoculation with the soft rot-causing pathogen *Erwinia carotovora* ssp. *carotovora*, this suggests that the volatile compounds play an important role in the induction of plant resistance (120,108). In an experiment carried out in the field, Jetiyanon reported that a combination of *B. amyloliquefaciens* strain IN937a and *B. pumilus* strain IN937b induced systemic resistance against southern blight of tomato, caused by *Sclerotium rolfsii*, anthracnose of long cayenne pepper, caused by *Colletotrichum gloeosporioides* (123) and mosaic disease of cucumber (124), *P. fluorescens* 63-28-inoculated pea roots produced more chitinase at the *Fusarium oxysporum* penetration site. The suppression of *Rhizoctonia solani* by *Pseudomonas fluorescens* through the induction of plant resistance system has also been documented. *P. fluorescens* spp. release an insecticidal toxin and make plants more resistant to aphid assault. It can be said that PGPR will be of great interest, especially to protect plants and avoid issues encountered when pesticides fail to control pathogen populations that have developed resistance (125). PGPR belonging to Pseudomonas spp. are commercially exploited to protect plants by inducing their systemic resistance against various pests and diseases (126).

2.3.3 Agricultural Application

The use of PGPB as agricultural inoculants is a possible substitute based on these bacteria's capacity for biofertilization and biocontrol. The application and fate of inoculants on field-grown crops must be thoroughly checked in order to ensure that inoculants can boost yields in a way that can be demonstrably shown (127). Understanding the factors that control and direct the generation of bioactive compounds is vital for increasing the quantity and consistency of PGPB activity. It may be required to first look at how these parameters affect PGPB activities in vitro in order to optimize these activities in vivo or to develop bioactive metabolites. Environmental factors such as soil type, pH, plant surface, and climatic conditions are known to have an effect on how well PGPR operates. Abiotic factors are also the main determinants of PGPR effectiveness (86). The pH and incubation temperature have an effect on antagonist activity, Several authors have discussed how different abiotic factors, like temperature and nutritional components, affect the generation of antifungal chemicals by biocontrol agents (128). According to Naik and Sakthivel, bacteria that are related to pseudomonas may use a range of carbon sources as a substrate and can adapt to different conditions (129). A wide range of abiotic factors, including glucose, Fe+3, Zn+2, Cu+2, and Mo+2, influence the production of antifungal compounds. Due to the presence of Fe+ 3 and sucrose, diacetyl-phloroglucinol (DAPG) was formed in P at a greater rate. In contrast to P. fluorescens Pf-5 and CHA0, glucose increases the development of *P. fluorescens* strain F113 (130). One illustration of how nutrients and environmental factors might impact the antifungal activity of *P. cepacia* is the carbon supply, which promotes antagonist action and inhibits the formation of the spores (128). Temperature has a significant impact on bacteria's capacity to produce antifungal compounds. Another element that may affect the bioactive potential of bacterial inoculants is their ability to adapt to the soil's conditions and compete with native species (127). By using mathematical modelling and computer-based simulation, Strigul and Kravchenko aimed to evaluate microbial inoculants in the rhizosphere and the impact of different abiotic and biotic stress on PGPBs survival and activity (127). Strigul and Kravchenko have shown that the most important factor affecting the survival of inoculants was the struggle for few resources between the introduced population and the native microorganisms (131). The survival of the inoculants was also influenced by the inoculated bacteria's capacity to utilise specific elements found in the exudates from the roots of the host plant. Understanding the many pathways involved in promoting plant development and squelching disease is essential for the selection and application of suitable biocontrol strains for sustainable agriculture (132). As was previously said, in order to ensure an improvement in field-grown crop yields, due consideration must be given to the choice of PGPBs inoculants as well as the impact of the various environmental conditions. The application method (seed treatment, post-harvest treatment, foliar spray, etc.) for the bacterial inoculant may also affect how active it is.

3. Conclusion and Future Prospects

Use of PGPBs in agriculture is a workable solution that can enhance plant health and performance. One can boost food production and meet increased demand by knowing how to protect plants and encourage their growth. The PGPB findings indicate a cultural change towards "bio-agriculture," which is beneficial to both the national economy and human health. The usage of PGPBs in agriculture can serve as a feasible alternative to chemical products (such fertilizers and pesticides) that are harmful to the environment and the health of the general people. PGPBS have all been previously reported as having the ability to biofertilize soil, biocontrol phytopathogenic agents and promote plant growth, which encourages their commercial exploitation and usage as inoculants.

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