Effect of PGPR on plant growth: A mini-review

[1]Ankita Manna, [2]Parnabi Roy, [3]Tanbir Rahman, [4]Jigisha Roy Panda

Guru Nanak Institute of Pharmaceutical Science and Technology
Kolkata, India

***Abstract*- The problem on a worldwide scale is population expansion and the rise in food demand. So chemical fertilizers are being introduced into the soil to fulfill the demand of the population of developing nations like India, Pakistan, etc, AS everything has bad effects, nowadays, chemical fertilizers not only harm soil microflora and fauna, but they also create pollution, water pollution, and health problems as well as raising production costs. As a result, there is an immediate need to discover a replacement for these harmful substances. New agricultural efficiency practices will inevitably be introduced using plant growth-promoting rhizobacteria (PGPR) which has the potential to be a successful sustainable agricultural technology. PGPR is a heterogeneous group of bacteria that colonizes the rhizosphere quickly and provides plants with direct or indirect agricultural protection. Seed treatment rates but also protected against harmful bacteria. These PGPR can promote plant growth through a variety of mechanisms, including phosphate solubilization, siderophore production, biological nitrogen fixation, rhizosphere engineering, production of 1-Aminocyclopropane-1-carboxylate deaminase (ACC), interference with quorum sensing (QS) signaling, inhibition of biofilm, exhibiting antifungal activity, induction of systemic resistance, etc. Thus, the mechanism of action is biocontrol, biofertilization, and biostimulation. For scientists, PGPR is an intriguing area of study, and a variety of PGPR formulations are now commercially accessible. Many researchers demonstrated the importance of PGPR as a growth promoter. The current analysis demonstrated the importance of PGPR as a viable alternative to harmful chemical fertilizers for environmentally friendly and sustainable agriculture.**

***Keywords*- Plant growth-promoting rhizobacteria (PGPR), rhizosphere, nitrogen fixation, biofertilization, and sustainable agriculture.**

I. INTRODUCTION

The rhizosphere is the tapered region of soil that is most fertile. influence the plant chemically, physically as well as biologically by providing nutrients that are absorbed by the root of the host cell from the surrounding region of soil. By rhizosphere researchers, it had been observed that over the past few decades, agricultural policies of India are being modified which is giving fruitful results. The term 'Rhizosphere' was introduced by Sir Hiltner [1]. Plant Growth Promoting Rhizobium are mainly free-living bacteria that colonies in the rhizosphere and benefit crop plants [2]. Bacteria of the rhizosphere (rhizobacteria) include symbiotic rhizobium, mycorrhiza, actinomycetes, and free-living bacteria, sustain their life in the narrow region of soil here roots are being influenced by various functions. Various well-known genera of bacteria are *Pseudomonas, Bacillus, Variovorax, Klebsiella, Enterobacteria, Burkholderia, Azospirillum, Serratia,* and *Azotobacter* These rhizobacteria have given impacted by solubilizing phosphate and other mineral complexes or by converting atmospheric nitrogen into organic compound (NH3) which is being readily used up by the plant and enhance its growth mad metabolism, the process is called nitrogen fixation or by the synthesis of phytohormones. Not only that, but these rhizobacterial strains can also enhance plant tolerance against salinity, drought, flood, and heavy metal toxicity which results in the survival of the host plant life in unfavorable or harsh environmental conditions [3]. Several experiments were done in the past to explain how Plant Growth Promoting Rhizobacteria (PGPR) benefits the host plants. This includes; the release of phytohormones for plant growth such as indole acetic acid (IAA), cytokines, and gibberellins by the nitrogen fixation process. Solubilizing phosphate and other mineral complexes, [4]; Production of siderophores, enzymes, and fungicidal compounds for antipathetic effect [5]. For agricultural production, several PGPR formulations are being offered as commercial goods. Phytoremediation of polluted soils and forest regeneration are two newly developed PGPR applications. There may be more effective plant-bacteria pairings for new and beneficial applications when the mechanisms of these bacteria's support of plant development are revealed.[6]. When plant growth promotion is required, these rhizobacteria can be used in different ways [6]. Especially two main ways are there by which PGPR can facilitate growth and development, including, direct and indirect mechanisms [7].

Besides these, fungi also represent a significant part of soil rhizosphere microflora and benefit plants by promoting plant growth. By symbiotic association of fungi, the surface area of the roots of the plant gets larger which results in the absorption of nutrients and water in increasing amounts, besides this, it also protects the plant from abiotic effects [8]. Still, now, mycorrhizae are of two types i.e., ectomycorrhiza in which hyphae of fungus form a surrounding layer on roots and growth there to exchange nutrients, another type endo-mycorrhizae in which hyphae of fungus enter into the cells of a plant root to exchange nutrients. Thus, both PGPR and fungus play a vital role in enhancing plant growth.

PGPR are those bacteria that can produce hormones, vitamins, and growth factors that improve plant growth and increase plant production. An ideal PGPR strain can be categorized as follows, they can represent a large spectrum of action, and they should be highly rhizosphere-competent as well as eco-friendly. They can enhance plant growth, they unite with other bacteria present in the rhizosphere, and they should have the ability to tolerate physicochemical factors i.e., heat radiation and oxidants.

According to Vessey [9], bacteria living in the rhizosphere, in or around the root tissue, and enhancing plant growth are collectively known as PGPR. PGPR can be classified in various ways:

Based on the types of association of PGPR with the root - ePGPR exists on the rhizosphere as well as the rhizoplane or in the space of cells of the root cortex. Examples are *Agrobacterium sp., Arthrobacter sp, Azospirillum sp, Bacillus sp, Chromobacterium*

sp, Micrococcus sp, Pseudomonas sp, Caulobacter sp, and Serratia sp.. iPGPR exist inside root cells generally present in the specialized structure, nodules. Examples are *Allorhizobium sp, Bradyrhizobium sp, and Frankia sp.* Based on the relationship with plants there are two types, symbiotic rhizobium, and free-living Rhizobium.

II. Influence of PGPR on Plant Growth

The two types of PGP mechanisms are known as direct and indirect mechanisms. Although, the difference between the two, in general, indirect mechanisms are those that take place outside of the plant, whereas, direct mechanisms are those that happen inside the plant and have a direct impact on the metabolism of the lant. [10]. The isolation of 140 halotolerant bacterial strains resulted in the production of extracellular hydrolytic enzymes like protease, chitinase, pectinase, cellulase, and lipase under in vitro conditions, as well as the production of multiple plant growth-promoting traits like nitrogen fixation, phosphorus (P) and zinc (Zn) solubilization, thiosulfate (S2O3) oxidation 36 strains was chosen from the initial 140 examined for additional analysis based on the latter tests for plant growth promotion activities. Then, the activity of 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase was examined in these 36 halotolerant bacterial strains. 25 of these were discovered to be positive and to be showing noticeably different degrees of activity. [11]. Given all this, direct methods involve those that influence the balance of plant growth regulators, either the microorganisms themselves release integrated growth regulators hormones that the plant releases into the soil, or the microorganisms act as a sink for those hormones which they change the plant's metabolism, which enhances its potential for adaptation [12]. Meanwhile, indirect mechanisms are required for the involvement of the plant's defense mechanisms, which react to the signal supplied by the bacterium affecting the plant. Induction of systemic resistance to plant infections (biotic stress) and defense against unfavorable environmental conditions (abiotic stress) are two vital mechanisms that belong to this group. [13]. The genus Enterobacter is a facultatively anaerobic, motile, straight rod that is gram-negative and has peritrichous flagella. There are many PGP traits that Enterobacter spp. are known to possess, including the ability to fix nitrogen, solubilize soil phosphorus, create antibiotics, secrete siderophore products, chitinase, ACC deaminase, hydrolytic enzymes in addition to exopolysaccharides, and increase soil porosity. Many Enterobacter strains have these traits, which aid in the growth of plants and inhibit soil-borne plant diseases. Enterobacter may be a possibility for plant growth and development because of their PGP capabilities. Due to their diverse roles in crop growth, many of these strains have been commercially produced as plant growth promoters and biocontrol agents [14].

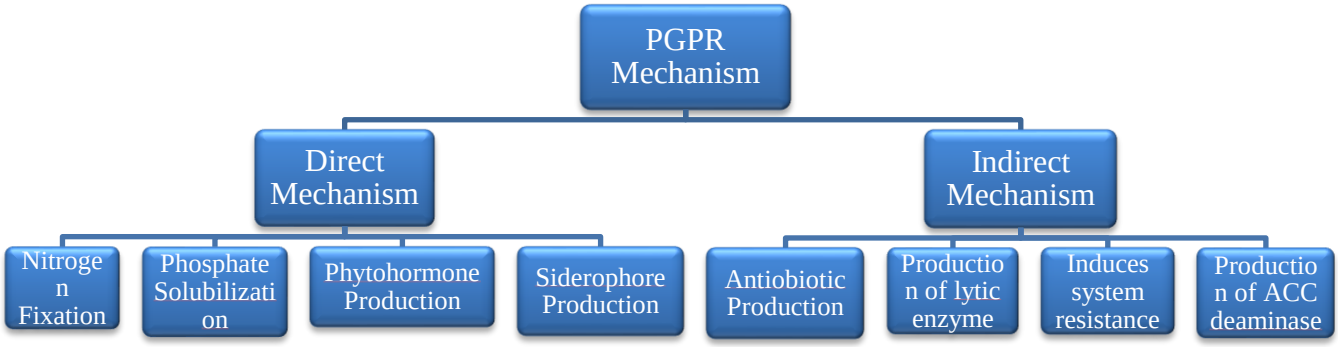

Fig. 1: Classification of PGPR Mechanism

1. Direct Mechanism

1.1. Nitrogen fixation

Biological nitrogen fixation is the mechanism, by which atmospheric nitrogen is converted into ammonia by the symbiotic, nonsymbiotic, associate, and free-living bacteria, which are nitrogen-fixing micro-organisms using a complex enzyme called nitrogenase. Nitrogenases catalyze the biological reduction of dinitrogen to ammonia. These are complex metalloenzymes and contain two components known as dinitrogenase (MoFe protein) and dinitrogenase reductase (Fe protein). Dinitrogenase contains Molybdenum (Mo) and Iron (Fe), and they contain a co-factor called MoFe-cofactor. Dinitrogenase reductase contains Iron (Fe) only. Denitrogenase reductase provides electrons with high reducing power, dinitrogenase uses those electrons to reduce nitrogen to ammonia. The Nif gene is the complex of genes encoding enzymes involved in nitrogen fixation, found in nitrogen-fixing bacteria, bacterium controlled the nif gene expression. The regulation of nif gene expression is mainly based on two elements, an external system involving ntr genes and an internal system mediated by nif A and nif L genes. The ntr gene system is mainly responsible for the transcription of nif genes while nif A and nif L genes act as regulatory systems through a 'switch on and 'switch off mechanism. Gene nif A produces Nif A protein, which activates the transcription genes, and on the other side nif, L gene produces Nif L protein, which inhibits the nif gene transcription.

In one study, Orhan found that two *Bacillus* strains OSU-142 and M3 were tested alone and in combinations using the dipping method on organically grown primocane fruiting raspberry plants in terms of yield, growth, nutrient composition of leaves, and variation of soil nutrient element composition. After this experiment, it was seen that the yield, cane length, berry weight, no. of cluster per cane, no. of berries per cane, and Nutrient content were increased by using the M3 strain and the combined strain (OSU-

142+M3). But after using the OSU-142 strain the yield, cane length, berry weight, no. of cluster per cane, no. of berries per cane, and Nutrient content were decreased [15]. In another study, by Islam et al., 2012 the RFNB3 strain of *Pseudomonas* sp. and RFNB14 were inoculated on red pepper and tomato under greenhouse conditions and also increase the N content compared to the control [16]. Palai et al, inoculate *Rhizobium* in groundnut, it improved crop yield, and nutrient uptake, and facilitates maintenance of soil fertility along with multiple environmental benefits [17]. Also, Oliveira et al. found that *Frankia* sp. inoculated in *Alnus glutinosa* helps to increase plant growth, and nitrogen and phosphorus content in the leaf highly [18].

1.2. Phosphate solubilization

Phosphorus (P), the second most important plant growth-limiting nutrient after nitrogen, is abundantly available in soils in both organic and inorganic forms. Organic phosphorus (generally 30 to 50% of the total), which is mostly in the form of inositol hexaphosphate, or phytate, which is the principal storage form of phosphorus in plants that can be degraded by bacteria or fungi; and inorganic phosphorus, which usually forms insoluble mineral compounds with calcium, aluminum, or manganese [19]. Micro-organisms in soil by solubilizing complex-structured phosphates viz. tricalcium phosphate, rock phosphate, aluminum phosphate, etc. mineralize organic phosphorus in soil which turns organic phosphorous into inorganic form ultimately aiding the phosphate availability to plants. These phosphate-solubilizing bacteria use different mechanisms to solubilize the insoluble forms of the phosphate. The primary phosphate solubilization mechanism is based on microbes' organic acid secretion because of sugar metabolism. Organisms residing in the rhizosphere utilize sugars from root exudates; metabolize them to produce organic acids. These acids released by the micro-organisms act as good chelators of divalent Ca2+ cations accompanying the release of phosphates from insoluble phosphatic compounds [20].

In one study, Borgi et l. found that after using the BMA1 strain of *Serratia plymuthica* on *Vicia faba* L. the phosphorus uptake in root and shoot is improved, plant biomass and plant height are also increased, carotenoid and chlorophyll content in leaves are also enhanced [21]. Zheng et al. found that the use of the CS22 strain of *Bacillus megaterium* on Brassica napus increases phosphorus content and biomass production [22]. In another study, Ahmad et al. found that shoot biomass, seed protein content, and phosphorus in shoots are increased after using the PSE3 strain of *Pseudomonas putida* on *Pisum sativum* [23]. Baig et al., also found that the use of *Bacillus* sp. strains KAP5 and KAP6 on *Triticum aestivum* increases the root trait, root length, and root biomass and improves the phosphorus uptake in the shoot, root, and grains of inoculated plants [24]. Rajapaksha and Senanayake found that after using *Staphylococcus sciuri*, *Bacillus pumilus*, *B. subtilus*, and *B. cereus* on *Oryza sativa* L. phosphorus uptake in the root, shoot, grains, and yield was increased [25].

1.3. Phytohormone production

Phytohormones are chemical messengers that affect how a plant responds to its surroundings. They are primarily organic substances that are transferred to different locations after being created and are active at very low concentrations. Auxins, gibberellins, cytokinins, ethylene, and abscisic acid are examples of well-known phytohormones, and soil microorganisms, particularly rhizosphere bacteria, can create these hormones [26]. Plants respond to phytohormones in the rhizosphere that are supplemented externally or created by rhizosphere microbial flora. These phytohormones can regulate plant cell enlargement, division, and extension in both symbiotic and nonsymbiotic roots.[27].

1.3.1. Auxin (Indole-3-acetic acid)- Auxins are the primary phytohormones that regulate numerous stages of plant growth and development, including cell elongation, cell division, and tissue differentiation, as well as support apical dominance. Auxin, also known as indole-3-acetic acid (IAA), is a crucial phytohormone produced by some strains of PGPR and treating rhizobacteria that make IAA promotes plant growth [28]. IAA is principally recognized as an inducer of both short-term (e.g., an increase in cell elongation) and long-term (e.g., cell division and differentiation) responses in plants. The highly developed roots of a plant receiving IAA therapy over an extended period boost the plant's ability to absorb nutrients, eventually promoting plant development [29]. Applying such microorganisms in the field raises the endogenous IAA levels of plants, which has a tremendous impact on plant growth. Around 80% of the bacterial flora in the rhizosphere creates IAA. Auxins have an impact on the entire plant, but because PGPRs make IAA in the rhizosphere, which benefits plant roots more than other parts of the plant, plant roots are the ones that are primarily impacted [30]. IAA produced by rhizobacteria has a major impact on the root system by enlarging the size and weight, the number of branches, and soil-contact surface area. All of these modifications enhance the plant's potential for growth and boost its capability to probe the soil for nutrient exchange [31]. PGPR with plant nutrition-related molecular processes should be employed in the appropriate soil; for example, phosphate-solubilizing bacteria will demonstrate their effect in soil with low phosphorous content, and siderophore-producing bacteria will exhibit their effect in soil with low accessible iron. Otherwise, the bacteria will be ineffective.[32]. Plant-associated microorganisms use independent and L-tryptophan-dependent mechanisms to manufacture IAA. The majority of these PGPRs use L-tryptophan, a precursor for IAA synthesis that is secreted in root exudates. *Azospirillum brasilense*, one of the most researched species that produce IAA via this pathway, produces more than 90% of it via the L-tryptophan independent pathway and the remaining 10% by using L-tryptophan. IAA is still synthesized by this mechanism, but the precise pathway and enzymes involved are yet unknown [33]. The Indole-3-pyruvic acid (IPA) route is used by bacteria such as Rhizobium, *Bradyrhizobium*, and *Azospirillum* to manufacture IAA [34]. However, some pathogenic microorganisms, including *Agrobacterium tumefaciens*, *Pseudomonas syringae, Pantoea agglomerans*, *Rhizobium*, *Bradyrhizobium*, and *Erwinia herbicola*, manufacture IAA primarily viaIndole-3-acetamide (IAM) pathway [35] whereas, *Bacillus subtilis, B. licheniformis, B. megaterium*, etc. produce IAA via. tryptamine pathway.

1.3.2. Cytokine- Similar to IAA, plants respond to exogenous cytokinin treatments by increasing cell division, root development, the creation of root hairs, inhibiting root elongation, initiating shoot growth, or other physiological reactions [36]. Cytokines are aminopurines with an N6 substitution that can affect a plant's physiological and developmental activities [37]. Cytokines have a significant impact on a variety of other activities, including the development of embryonic vasculature, nutritional signaling, leaf

expansion, branching, chlorophyll production, root growth, enhancement of seed germination, and postponement of senescence [38]. Numerous microbes from various genera, including *Pseudomonas, Azospirillum*, and *Bacillus*, that generate cytokines have been isolated from a variety of plant species, including barley, canola, bean, and *Arabidopsis* [39]. Castro et al. reported the discovery of a Bacillus megaterium strain that, via producing cytokinins, stimulated the growth of *A. thaliana and P. Vulgaris seedlings. Proteus, Klebsiella, Escherichia, Pseudomonas*, and *Xanthomonas* are some more bacterial genera that can create cytokines [40].

1.3.3. Gibberellins- The broad class of phytohormones known as gibberellins (GAs) includes up to 136 distinct structural molecules. Many developmental processes in higher plants, such as seed germination, stem lengthening, blooming, and fruit set, are influenced by this group of phytohormones [41]. Only 4 GAs (GA1, GA3, GA4, and GA20) from 7 bacterial species have been found to date out of the 136 GAs from 128 plant species that are currently known [42]. The tetracyclic diterpenes that make up the GA group have a significant impact on the processes of seed germination, leaf expansion, stem elongation, fruit development, and flower and trichome initiation, among other things [43]. Gibberellins and the genera that produce them continue to be the main targets during environmental stress conditions because of their critical role in enhancing effective photosynthetic processes in plants. This makes them an important plant growth bioregulator that can raise the stress tolerance of many crop plants. There have been reports of certain rhizobacteria (PGPR) generating gibberellins enhancing plant growth [44]. These growth hormones can be applied exogenously and may help increase crop performance and amend polluted soil [45]. By reducing stomatal resistance and increasing water use efficiency, GA application has been found to significantly improve grain yield in wheat, barley, and tomato. In conclusion, gibberellin affects the biochemistry of plants and promotes the growth of aerial parts [46], which are still a great choice for increasing stress resistance.

1.3.4. Ethylene- A special phytohormone with a variety of biological functions is ethylene. Low concentrations are ideal for this biomolecule's positive effects to be seen. Ethylene has some developmental qualities at high concentrations, including root elongation, defoliation, and other cellular processes that impair crop performance [47]. According to Pierik et al., ethylene is classified as a senescence hormone because it inhibits plant growth. An enzyme called 1- Aminocyclopropane-1 Carboxylic acid (ACC) deaminase is required to reverse these worrying effects. This biocatalyst's function is to convert plant ACC, which serves as the direct precursor of the plant's ethylene production, into -ketobutyrate and ammonium [48]. Through several methods, the degradation reduces the amount of ethylene produced by the plant, whereas the PGPR-producing ACC-deaminase controls the ethylene level in the plant and prevents the growth inhibition brought on by excessive amounts of ethylene [49]. By employing enzymes from *Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Serratia,* and *Rhizobium* to break down the endogenous product, PGPR can induce the generation of ethylene exogenously. Studies have demonstrated that PGPR ACC deaminase activities were essential for the growth of Brassica napus [50]. According to Pierik et al., *Arabidopsis thaliana* plant production, growth performance, and germination characteristics are increased at low ethylene concentrations via PGPR. However, this vaporous hormone also controls seed germination, fruit ripening, and root initiation [51].

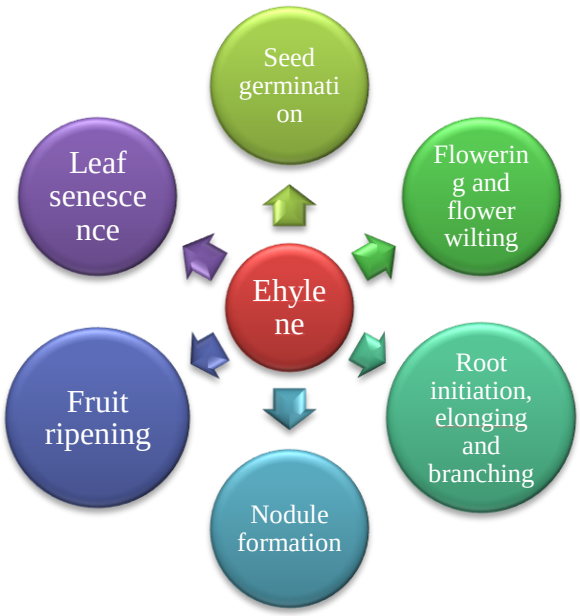

Fig. 2: Various effects of ethylene on plant growth and development

1.4. Siderophore production

A crucial ingredient for plants is iron. Because it serves as a cofactor in various enzymes necessary for vital physiological activities like photosynthesis, respiration, and nitrogen fixation, its lack manifests as severe metabolic changes. Although soils are fairly rich in iron, neither plants nor soil microbes can always access it. Fe+3 is the most common chemical form and is oxidized, forming insoluble oxides and hydroxides that are inaccessible to plants and microbes. Plants have developed two methods for effectively absorbing iron. The first method involves the release of organic compounds that can chelate iron, making it soluble so that it can diffuse toward the plant, get reduced, and then be absorbed using an enzymatic system found in the cell membrane of the plant. In the second method, the iron is reduced inside the plant and quickly absorbed as a complex with the organic component and

Fe+3. Some bacteria in the rhizosphere can release iron-chelating compounds into the rhizosphere, which draws iron there so that the plant can absorb it [52].

Siderophores are low-molecular-weight substances, typically under 1 kDa, that have functional groups capable of reversibly binding iron. The most prevalent functional groups are hydroxamates and catechols, where the spacing between the individual groups is ideal for binding iron. The concentration of siderophores in the soil is roughly 1030 M. Pseudomonas fluorescens and Pseudomonas aeruginosa, which emit siderophores of the pyochelin and pyoverdine types, are the most researched members of this group of bacteria [53]. Since these chemicals have antibacterial activity and enhance the plant's iron nutrition, rhizosphere bacteria release them to raise their competitive potential [54]. With the release of its antibiotic molecule, siderophore-producing rhizobacteria prevent the development of other microorganisms while also enhancing iron nutrition and reducing the amount of iron available for pathogens, most commonly fungi, which are unable to absorb the iron-siderophore complex.

List of some of PGPR in direct mechanism:

Table 1

PGPR	PGPR mechanism	Crops
Burkholderia sp.	Nitrogen fixation	Rice
Chryseobacterium sp.	Siderophore production	Tomato
Frankia sp.	Nitrogen fixation	Alnus
Mycobacterium sp.	Induction of plant stress resistance	Maize
Phyllobacterium sp.	Siderophore production, phosphate solubilization.	strawberries
Pseudomonas sp.	Chitinase and beta-glucanase production	Pigeon pea
Rhizobium and allied genera	Nitrogen fixation (symbiotics)	Legumes, eg soybeans, peanuts, chickpeas etc.
Cyanobacteria sp., Azotobacter sp., Azospirillum sp., Beijerinckia sp.	Nitrogen fixation (Free-living)	Wheat, rice, and maize.

2. Indirect Mechanism

2.1. Production of antibiotics

One of the biocontrol methods used by PGPR that has received the most research is antibiotic synthesis. They are Amphisin, 2, 4-diacetylphloroglucinol (DAPG), oomycin-A, phenazine, pyoluteorin, pyrrolnitrin, tensin, tropolone, and the manufacture of cyclic lipopeptides are a few instances that come to mind [55]. Usually, Pseudomonas strains, Bacillus, Streptomyces, and Stenotrophomonas sp. emerged from these biochemicals. They are impacted by biotic and abiotic variables since they are an active chemical agent. Antibiotics are low-molecular-weight compounds that inhibit the growth of pathogenic microorganisms in plants. Successful biocontrol agents include phloroglucinols (Phl), gluconic acid, and 2-hydroxymethyl-chroman-4-one. The non-fluorescent Australian bacterial isolate Pseudomonas strain AN5 (Ps. str. AN5) is a successful biological control (biocontrol) agent of the take-all disease of wheat brought on by the fungus Gaeumannomyces graminis var. [56]. The source of avocado Dematophora root rot, Dematophora necatrix, was tested for antagonistic activity against a collection of 905 bacterial isolates from the rhizospheres of healthy avocado trees (also called white root rot). Eight strains were chosen based on their ability to prevent the growth of D. necatrix and other significant soilborne phytopathogenic fungi.[57]. The antagonistic metabolites generated by Pseudomonas aeruginosa PNA1, phenazines, and rhamnolipid-biosurfactants, were examined in this study to determine their potential roles. Pythium splendens biological control trials Xanthosoma sagittifolium L Schott and Pythium myriotylum on bean (Phaseolus vulgaris L) [58]. Phloroglucinol is a benzenetriol that is primarily used in the pharmaceutical manufacturing of Flopropione [59]. Phloroglucinols occur naturally in some plant species and soil bacteria also manufacture them. The most extensively researched phloroglucinol made by Pseduomonad is 2,4-diacetylphloroglucinol (DAPG). It harms Pythium sp. membranes and zoospores. Aldose reductase, an enzyme involved in the conversion of glucose to fructose, is inhibited by these antibiotics [60]. Phenazine also improves bacterial survival in anaerobic conditions by using endogenous phenazines, As evidenced by P. aeruginosa's survival supported by extracellular electron transfer [61]. Increased productivity due to biocontrol inoculants has also been reported in other cases, including *S. rochei* inhibition of phytophthora-caused pepper root rot [62] and S. platensis resistance to *R. solani* leaf blight/seedling blight of rice [63].

2.2. Production of Lytic Enzyme

Extracellular enzyme synthesis by rhizobacteria, such as chitinases, ß-1-3 glucanases, lipases, cellulases, and proteases, has also been proposed as an important form of biocontrol [64]. They are hydrolytic enzymes that break down a variety of compounds, most of which are from plants. Additionally, they effectively lyse the fungal cell wall [65]. According to Palumbo et al., [66] beta-1, 3-glucanase plays a substantial role in Lysobacter enzymogenes strain C3's biocontrol activity against *Phytium sp*. caused Bipolaris leaf spot. These enzymes, as multifunctional organic proteins, provide protection against desiccation as well as abiotic and climatic

factors [67]. The lytic enzyme can be utilized to control *Phytophthora capsici* [68], Fusarium infection [69], and *Pythium ultimum* blight in sugar beet [70]. Chauhan et al., demonstrated the antagonistic potential of PGPR by the synthesis of chitinase, 1, 3 glucanase, proteolytic enzymes, and cellulase at low concentrations. Using chitinases, mycoparasitic and Trichoderma species have been implicated in antagonistic biocontrol activities against Rosellinia necatrix and other plant pathogens [71]. Mature natural trees from both upland and bottomland areas in central Tennessee were studied for their microbial populations from their root endophytic and rhizospheric habitats. While Gammaproteobacteria (54%) and Alphaproteobacteria (23%) made up the majority of endophytes, Acidobacteria (31%) and Alphaproteobacteria (30%) dominated the rhizosphere bacteria. 34% of the genomes of endophytic bacteria belonged to a single operational taxonomic unit (OTU) that was similar to *Pseudomonas*. The diversity of endophytic bacteria was likewise quite varied and 10 times lower than in rhizosphere samples taken from the same roots. Pezizomycotina were present in almost comparable proportions in both fungal rhizosphere and endophyte samples (40%), although Agaricomycotina were more prevalent in the rhizosphere (34%) than endosphere (17%). The most common bacterial and fungal OTUs tended to be prominent in either the endophyte or rhizosphere samples, but not both, according to hierarchical clustering of OTU relative abundance patterns. These results demonstrate that root endophytic communities are separate assemblages as opposed to opportunistic rhizosphere subgroups. [72].

2.3. Induced Systemic resistance

The importance of PGPR is recognized as a by-product of biological control of soil-borne pathogens. Exogenous chemical-induced systemic tolerance and pathogens are called systemically acquired resistance (SAR); PGPR-mediated protection is commonly referred to as ISR. [73]. All plants have active defense mechanisms against attack by pathogens. for defense which is triggered by a stimulus before infection with plant pathogens. Induced resistance is not about creating resistance where there is no resistance, but about activating potential resistance mechanisms expressed in a subsequent so-called challenge inoculation with the pathogen [74]. The terms "induced" and sometimes "acquired" are systemic resistance was used interchangeably by various research groups until published by Ryals et al., who defined types of resistance induced by pathogenic organisms and/or chemical that uses salicylic acid as an arbiter of SAR as a tribute to Ross, apart from many previous publications describing the same phenomenon used ISR as synonyms, but Van Loon's and his colleagues used the term ISR as resistance mediator by PGPR' [75]. ISR in PGPR can take the form of salicylic acid, siderophores, lipopolysaccharide flagella, N-acyl homoserine lactone molecules [76]. The wide range of PGPR, according to the kind of plant type and nutrients, PGPR varies significantly. [77]. The most common are *Pseudomonas* and *Bacillus* sp. among the diversity of PGPR. In recent years, the application of PGPR as an inducer of systemic resistance in agricultural plants against several pathogens has been demonstrated. [78]. There have been numerous experiments done to induce ISR by PGPR in plants. PGPR has accomplished ISR in a variety of crops, including Arabidopsis. they created an Arabidopsis-based model sysutilizingsing the difficult pathogens *Fusarium oxysporum f sp raphani* and *Pseudomonas syringae PV tomato* to examine the molecular underpinnings underlying this kind of systemic resistance. The biological control strain WCS417r of P. fluorescens colonized the rhizosphere and induced a plant-mediated resistance response that greatly decreased symptoms caused by both difficult pathogens. Additionally, plants treated with *P. fluorescens* WCS417r showed significant inhibition of *P. syringae* growth in infected leaves. Both wild-type plants and transgenic Arabidopsis NahG plants, which are unable to accumulate SA, responded well to the induction of resistance caused by *P. fluorescens* WCS417r. Additionally, the development of PR mRNAs before challenge inoculation did not overlap with the systemic resistance caused by *P. fluorescens* WCS417r. [79], tomato where a reference strain of each type of microorganism was used to examine the relative significance of systemically induced resistance in the suppression of fusarium wilt of tomato under commercially relevant conditions (*P. fluorescens* WCS417r and nonpathogenic *F. oxysporum* Fo47). Since the production of PR-proteins has frequently been linked to systemic induced resistance, their accumulation in tomato plants exposed to WCS417r or Fo47 was examined. The analysis of the data shows that systemic-induced resistance, not the tested PR-proteins, was responsible for the suppression of fusarium wilt by *P. fluorescens* WCS417r (PR-1 and chitinases). [80] potato where, when challenged by spraying with a zoospore suspension, potato plants (cv. "Irish Cobbler," lacking major resistance genes to *Phytophthora infestans*), whose lower or upper leaves had previously been treated with hyphal wall components (HWC) of the fungus by rubbing with carborundum, developed an induced resistance in other untreated leaves against cultivar-pathogenic races of *P. infestans*. As a result, whereas non-induced control plants eventually succumbed to the illness, the treated plants were shielded from the most severe late blight sickness. The decrease in successfully germinating zoospores, subsequent penetration, and eventual emergence of a hypersensitive-like cell response to the invading organisms were the causes of the induced resistance [81], carnation, was looked into if *Pseudomonas sp*. strains WCS417r's biological control of *Fusarium oxysporum f. sp. dianthi* of carnation involved additional mechanisms besides competing for iron. By bacterizing the roots and irradiating the stem with the pathogen, the antagonist and pathogen were spatially separated. In all trials with cultivar Pallas, the number of infected plants decreased from roughly 50 to 20% when the roots were bacterized with strain WCS417r 1 week before the stems were inoculated with F. o. dianthi, and in one experiment with cultivar Lena, from 69 to 38%. [82], brinjal, where the results confirm that *P. fluorescens* is a biocontrol agent of bacterial wilt in brinjal by showing that bacterial wilt was suppressed in bioformulation-treated brinjal crops compared to inoculation control crops. When used in conjunction with carboxymethyl cellulose as an adhesive and the biocontrol agent, vermicompost and farmyard manure were found to be superior bio formulations in terms of the biocontrol agent's shelf life and the suppression of bacterial wilt. In comparison to standard storage settings of 30°C, it was also discovered that low temperature (4°C) storage conditions retained a greater *P. fluorescens* population in the bio formulations. [83], rice, the study tells those upper leaves of rice plants also displayed resistance to the rice bacterial blight pathogen Xanthomonas oryzae pv. oryzae after being inoculated with a powder formulation of a saprophytic strain of Pseudomonas fluorescens, Pfl. The disease intensity in upper leaves dropped from 6.7 to 1.1 when the leaves were challenge-inoculated with *X. oryzae pv. oryzae* four days after P. fluorescens treatment on lower leaves. When *X. oryzae pv. oryzae* was challenge-inoculated into the induced resistant leaves, and a rapid rise in lignification and the activities of peroxidase, phenylalanine ammonia-lyase, and 4-coumarate: CoA ligase

was seen. Five days after challenge inoculation with *X. oryzae pv. oryzae*, rice leaves pretreated for five days with P. fluorescens, showed an increase in lignin content of about three times, peroxidase activity, phenylalanine ammonia-lyase activity, and a fivefold increase in 4-coumarate: CoA ligase activity. At later phases of interactions when there was no evidence of pathogen resistance, a similar rise in defense-related activities was not noticed in susceptible interactions or in plants treated with P. fluorescens. [84] and mango whose study tells that the ability of talc-based bio formulations containing *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Saccharomyces cerevisiae* cells to combat the endemic pathogen of mango anthracnose, *Colletotrichum gloeosporioides Penz*., was tested. Preharvest aerial spraying took place at monthly and biweekly intervals. In order to maximize blooming, a yield attribute in the preharvest stage, the plant growth-promoting rhizobacteria *Pseudomonas fluorescens* (FP7) supplemented with chitin were sprayed at intervals of every two weeks. As a result, postharvest latent symptoms were minimized. Following FP7 + chitin treatment, colorimetric assays showed significant induction of the defense-mediating lytic enzymes chitinase and -1,3-glucanase as well as the development of distinct bands in native PAGE analysis. The anthracnose pathogen may be suppressed by the production of defense-mediating enzymes, improving yield characteristics, [85] against a broad spectrum of pathogens like fungi [86] and bacteria. Alstrom P aimed to investigate the immunity of plant growth affecting rhizosphere pseudomonads, the seed of a sensitive bean (*Phaseolus vulgaris L*) cv. [87].

2.4. Production of ACC deaminase

ACC Deaminase is an enzyme that was initially discovered in 1978 and it catalyzes the cleavage of ACC to ammonia and ketobutyrate. [88]. This deaminase is rhizobacteria with favorable activities that should be isolated and characterized in microenvironments like the rhizosphere to uncover ACC deaminase as well as other plant growth-promoting processes [89]. Searching for the acdS gene is one method to find out whether ACC deaminase is active in PGPB. The acdS gene has been found through population searches, either in silico or in vivo, in the genomes of soil microorganisms and endophytes, demonstrating the wide bacterial dispersion of this activity [90]. Some of these Plant Growth-Promoting Rhizobacteria (PGPR) display a variety of organic traits, suggesting that these bacteria may have been selected to accumulate the corresponding genes. Based on genome sequence analysis of 304 compared Alpha- Beta- and Gamma proteobacteria, this issue was tackled utilizing 23 genes contributing directly or indirectly to documented PGPR effects. None of the 23 genes were shared by any of the 25 PGPR genomes under study, and the majority of them were also observed in non-PGPR Proteobacteria. However, ancestral character reconstruction revealed that PGPR strains have distinct gene combinations as a result of ancient gene transfers, which were prominent. This shows that the PGPR-plant collaboration may have developed independently in different species, leading to PGPR strains with distinct gene combinations. Animal pathogens, phytopathogens, saprophytes, endophytes/symbionts, and PGPR simultaneously showed a rise in the number of genes involved in plant-beneficial functions, indicating that the accumulation of these genes—and perhaps other plant-beneficial traits—could be a characteristic of PGPR itself.

It's interesting to determine that the authors also detected several acdS genes in plant and human pathogens. The expression of AcdS genes in proteobacteria is regulated by the presence of Lrp-like regulatory protein along with AcdR [91]. Other groups of plant-friendly organisms have demonstrated phytopathogenic biocontrol and plant growth-promoting activity, eg., the fungus *Trichoderma asperellum* also possesses ACC deaminase. *Agrobacterium*, *Mesorhizobium*, *Rhizobium*, and various other Rhizobiaceae, as well as Phyllobacteriaceae (*Phyllobacterium* and *Mesorhizobium*) and Azospirillum, have all been found to contain ACC deaminase in recent. [92].

III. DISCUSSION

PGPR has made promises to support eco-sustainable farming. Researchers are starting to gain a far more complicated and in-depth understanding of the mechanisms used by PGPR to promote plant development.

PGPR colonize at the host plant root and provide fruitful effects on the growth and development of plants by various mechanism. To be an effective PGPR, bacteria must be able to grow roots since bacteria must grow themselves in the rhizosphere at densities high enough to provide the desired effects. The second most important nutrient after nitrogen that plants need is phosphorus. Most of the phosphorus in the soil exists in insoluble form and cannot be used up by plants. [94]. Agricultural microbiologists have been interested in bacteria's ability to solubilize mineral phosphates since it can increase the availability of phosphorus and iron for plant growth. Although agriculturists in developing countries and less developed world, PGPR has long been used for agro practices in advanced countries and emerging economies. Some of the countries that formulated bioproducts with PGPRs are:

Table 2

Countries	Organisms	Crops
Australia	Azoarcus indigen, Azospirillum brasilense, Azorhizobium caulinoden.	Sugar cane, vegetables, cereals, sugar beet
Brazil	PGPR consortia	Bean, maize, sugarcane, rice, carrot, cotton
Canada	B. amyloliquefaciens, Bradyrhizobium japonicum.	Cereals and horticulture plants
China	PGPR consortia	Bean, maize, sugarcane, rice, carrot, cotton, cereals, and horticulture plants.
France	P. Fluorescens	Horticulture plants.
Finland	S*treptomycin* griseoviridis	Ornamental plants
Germany	B. amyloliquefaciens	Vegetables

India	P. Fluorescens, Azotobacter, PGPR consortia, and Phosphobacteria	Field crops
Italy	B. subtillis, Streptococcus sp.	Tomato, soybean
Japan	The rhizobium-based formulation in peat, legume seeds, and grass-legume seeds.	Legumes
Spain	B. polymyxa, B. subtillis	Cereals
UK	Azotobacter, Bacillus, Rhizobium, Cheatonium, Pseudomonas.	Tomato, Peper
USA	Ageobacterium radiobacter, B. pumilus, B. subtilis, B. licheniformis, B. polymyxa, B. azotofixan, B. megaterium.	Ornamental plants, Fruits, nuts, nursery trees, and field crops.

IV. Conclusion

The current review covers PGPR formulations and their use in the biological promotion of various traits of plant growth. Most PGPR isolates enhanced plant height, root length, and dry matter production of matter in different crops. The establishment of stable expression of antagonistic PGPR in sustainable agriculture system thus established another approach by replacing the utility of pesticides as well as playing a major role in integrating pest management. PGPR has a wide variety of mechanisms for promoting plant growth and development are nitrogen fixation, phosphate solubilization, phytohormone production, and siderophore these are categorized as direct mechanism and production of the lytic enzyme, antibiotic production, induced system resistance and production of ACC deaminase can be categories as an indirect mechanism. the presence of the ACC deaminase gene, phosphate, phytohormones like IAA, siderophore, nodulation, cytokinin, gibberellins, etc., and it seemed that their synchronized look was responsible. in improving the productivity, development, and uptake of nutrients by plant varieties in distinct agroecosystems.

V. Acknowledgment

I would like to thank Professor (Dr.) Abhijit Sengupta, Director GNIPST and Professor (Dr.) Lopamudra Datta, Principal GNIPST, for providing us with this opportunity to work on this review at Department of Life Sciences, Guru Nanak Institute of Pharmaceutical Sciences.

REFERENCES:

1. Hartmann A, Rothballer M, Schmid M. Lorenz Hiltner, a pioneer in rhizosphere microbial ecology and soil bacteriology research. Plant and soil. 2008 Nov;312:7-14.
2. Kloepper JW, Leong J, Teintze M, Schroth MN. Enhanced plant growth by siderophores produced by plant growth-promoting rhizobacteria. Nature. 1980 Aug 28;286(5776):885-6.
3. Belimov AA, Safronova VI, Sergeyeva TA, Egorova TN, Matveyeva VA, Tsyganov VE, Borisov AY, Tikhonovich IA, Kluge C, Preisfeld A, Dietz KJ. Characterization of plant growth promoting rhizobacteria isolated from polluted soils and containing 1-aminocyclopropane-1-carboxylate deaminase. Canadian Journal of Microbiology. 2001 Jul 1;47(7):642-52.
4. Jeon IS, Spångberg LS, Yoon TC, Kazemi RB, Kum KY. Smear layer production by 3 rotary reamers with different cutting blade designs in straight root canals: a scanning electron microscopic study. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology. 2003 Nov 1;96(5):601-7.
5. Dey RK, Pal KK, Bhatt DM, Chauhan SM. Growth promotion and yield enhancement of peanut (Arachis hypogaea L.) by application of plant growth-promoting rhizobacteria. Microbiological research. 2004 Dec 15;159(4):371-94.
6. Lucy M, Reed E, Glick BR. Applications of free living plant growth-promoting rhizobacteria. Antonie van leeuwenhoek. 2004 Aug;86:1-25.
7. Glick BR. The enhancement of plant growth by free-living bacteria. Canadian journal of microbiology. 1995 Feb 1;41(2):109-17.
8. Evelin H, Kapoor R, Giri B. Arbuscular mycorrhizal fungi in alleviation of salt stress: a review. Annals of botany. 2009 Dec 1;104(7):1263-80. Evelin H, Kapoor R, Giri B. Arbuscular mycorrhizal fungi in alleviation of salt stress: a review. Annals of botany. 2009 Dec 1;104(7):1263-80.
9. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. Plant and soil. 2003 Aug;255:571-86.
10. Antoun H, Prévost D. Ecology of plant growth promoting rhizobacteria. PGPR: Biocontrol and biofertilization. 2006:1-38.
11. Siddikee MA, Chauhan PS, Anandham R, Han GH, Sa TM. Isolation, characterization, and use for plant growth promotion under salt stress, of ACC deaminase-producing halotolerant bacteria derived from coastal soil. Journal of Microbiology and Biotechnology. 2010;20(11):1577-84.
12. Govindasamy V, Senthilkumar M, Magheshwaran V, Kumar U, Bose P, Sharma V, Annapurna K. Bacillus and Paenibacillus spp.: potential PGPR for sustainable agriculture. Plant growth and health promoting bacteria. 2011:333-64.
13. Aeron A, Kumar S, Pandey P, Maheshwari DK. Emerging role of plant growth promoting rhizobacteria in agrobiology. Bacteria in agrobiology: crop ecosystems. 2011:1-36.
14. Jha CK, Aeron A, Patel BV, Maheshwari DK, Saraf M. Enterobacter: role in plant growth promotion. Bacteria in agrobiology: Plant growth responses. 2011:159-82.
15. Orhan E, Esitken A, Ercisli S, Turan M, Sahin F. Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically growing raspberry. Scientia Horticulturae. 2006 Dec 4;111(1):38-43.

16. Islam MR, Sultana T, Joe MM, Yim W, Cho JC, Sa T. Nitrogen-fixing bacteria with multiple plant growth-promoting activities enhance growth of tomato and red pepper. Journal of basic microbiology. 2013 Dec;53(12):1004-15.
17. Palai JB, Malik GC, Maitra S, Banerjee M. Role of rhizobium on growth and development of groundnut: A review.
18. Oliveira RS, Castro PM, Dodd JC, Vosátka M. Synergistic effect of Glomus intraradices and Frankia spp. on the growth and stress recovery of Alnus glutinosa in an alkaline anthropogenic sediment. Chemosphere. 2005 Sep 1;60(10):1462-70.
19. Rodríguez H, Fraga R. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnology advances. 1999 Oct 1;17(4-5):319-39.
20. Maheshwari DK, Dheeman S, Agarwal M. Phytohormone-producing PGPR for sustainable agriculture. Bacterial metabolites in sustainable agroecosystem. 2015:159-82.
21. Borgi MA, Saidi I, Moula A, Rhimi S, Rhimi M. The attractive Serratia plymuthica BMA1 strain with high rock phosphate-solubilizing activity and its effect on the growth and phosphorus uptake by Vicia faba L. plants. Geomicrobiology Journal. 2020 Apr 11;37(5):437-45.
22. Zheng BX, Ding K, Yang XR, Wadaan MA, Hozzein WN, Peñuelas J, Zhu YG. Straw biochar increases the abundance of inorganic phosphate solubilizing bacterial community for better rape (Brassica napus) growth and phosphate uptake. Science of the total environment. 2019 Jan 10;647:1113-20.
23. Ahmad E, Khan MS, Zaidi A. ACC deaminase producing Pseudomonas putida strain PSE3 and Rhizobium leguminosarum strain RP2 in synergism improves growth, nodulation and yield of pea grown in alluvial soils. Symbiosis. 2013 Oct;61:93-104.
24. Baig KS, Arshad M, Shaharoona B, Khalid A, Ahmed I. Comparative effectiveness of Bacillus spp. possessing either dual or single growth-promoting traits for improving phosphorus uptake, growth and yield of wheat (Triticum aestivum L.). Annals of microbiology. 2012 Sep;62(3):1109-19.
25. Rajapaksha CP, Senanayake AP. Potential use of rock-phosphate-solubilizing bacteria associated with wild rice as inoculants for improved rice (Oryza sativa). Archives of Agronomy and Soil Science. 2011 Oct 1;57(7):775-88.
26. Arshad M, Frankenberger Jr WT. Plant growth-regulating substances in the rhizosphere: microbial production and functions. Advances in agronomy. 1997 Jan 1;62:45-151.
27. Glick BR. Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiological research. 2014 Jan 20;169(1):30-9.
28. Amara U, Khalid R, Hayat R. Soil bacteria and phytohormones for sustainable crop production. Bacterial metabolites in sustainable agroecosystem. 2015:87-103.
29. Aeron A, Kumar S, Pandey P, Maheshwari DK. Emerging role of plant growth promoting rhizobacteria in agrobiology. Bacteria in agrobiology: crop ecosystems. 2011:1-36.
30. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. Plant and soil. 2003 Aug;255:571-86.
31. Gutiérrez-Mañero FJ, Ramos-Solano B, Probanza AN, Mehouachi J, R. Tadeo F, Talon M. The plant-growth-promoting rhizobacteria Bacillus pumilus and Bacillus licheniformis produce high amounts of physiologically active gibberellins. Physiologia Plantarum. 2001 Feb;111(2):206-11.
32. Steindler L, Venturi V. Detection of quorum-sensing N-acyl homoserine lactone signal molecules by bacterial biosensors. FEMS microbiology letters. 2007 Jan 1;266(1):1-9.
33. Jha CK, Saraf M. Plant growth promoting rhizobacteria (PGPR): a review. Journal of Agricultural Research and Development. 2015;5(2):108-19.
34. Spaepen S, Vanderleyden J. R Firemans.(2007). Indole-3-acetic acid in microbial and microorganism-plant signaling. Federation of European Microbiological Societies Microbiology Reviews.;31:425-48.
35. Dobbelaere S, Vanderleyden J, Okon Y. Plant growth-promoting effects of diazotrophs in the rhizosphere. Critical reviews in plant sciences. 2003 Mar 1;22(2):107-49.
36. Amara U, Khalid R, Hayat R. Soil bacteria and phytohormones for sustainable crop production. Bacterial metabolites in sustainable agroecosystem. 2015:87-103.
37. Cepoi L, Donţu N, Şalaru V, Şalaru V. Removal of organic pollutants from wastewater by cyanobacteria. Cyanobacteria for bioremediation of wastewaters. 2016:27-43.
38. Cepoi L, Donţu N, Şalaru V, Şalaru V. Removal of organic pollutants from wastewater by cyanobacteria. Cyanobacteria for bioremediation of wastewaters. 2016:27-43.
39. Alexandre G, Jacoud C, Faure D, Bally R. Population dynamics of a motile and a non-motile Azospirillum lipoferum strain during rice root colonization and motility variation in the rhizosphere. FEMS microbiology ecology. 1996 Apr 1;19(4):271-8.
40. Persello-Cartieaux F, David P, Sarrobert C, Thibaud MC, Achouak W, Robaglia C, Nussaume L. Utilization of mutants to analyze the interaction between Arabidopsis thaliana and its naturally root-associated Pseudomonas. Planta. 2001 Jan;212:190-8.
41. Hedden P, Thomas SG, editors. Annual plant reviews, the gibberellins. John Wiley & Sons; 2016 May 2.
42. MacMillan J. Occurrence of gibberellins in vascular plants, fungi, and bacteria. Journal of plant growth regulation. 2001 Dec 1;20(4).
43. Wong WS, Tan SN, Ge L, Chen X, Yong JW. The importance of phytohormones and microbes in biofertilizers. Bacterial metabolites in sustainable agroecosystem. 2015:105-58.
44. Bastián F, Cohen A, Piccoli P, Luna V, Bottini* R, Baraldi R, Bottini R. Production of indole-3-acetic acid and gibberellins A 1 and A 3 by Acetobacter diazotrophicus and Herbaspirillum seropedicae in chemically-defined culture media. Plant growth regulation. 1998 Jan;24:7-11.

45. Gutiérrez-Mañero FJ, Ramos-Solano B, Probanza AN, Mehouachi J, R. Tadeo F, Talon M. The plant-growth-promoting rhizobacteria Bacillus pumilus and Bacillus licheniformis produce high amounts of physiologically active gibberellins. Physiologia Plantarum. 2001 Feb;111(2):206-11.
46. Wong WS, Tan SN, Ge L, Chen X, Yong JW. The importance of phytohormones and microbes in biofertilizers. Bacterial metabolites in sustainable agroecosystem. 2015:105-58.
47. BhattacharyyaPN J. Plantgrowth-promotingrhizobacteria (PGPR): Emergencein agriculture. World J. Microbiol. Biotechnol. 2012;28:1327-50.
48. Glick BR, Cheng Z, Czarny J, Duan J. Promotion of plant growth by ACC deaminase-producing soil bacteria. New perspectives and approaches in plant growth-promoting Rhizobacteria research. 2007:329-39.
49. Dell'Amico E, Cavalca L, Andreoni V. Improvement of Brassica napus growth under cadmium stress by cadmium-resistant rhizobacteria. Soil Biology and Biochemistry. 2008 Jan 1;40(1):74-84.
50. Kaur R, Macleod J, Foley W, Nayudu M. Gluconic acid: an antifungal agent produced by Pseudomonas species in biological control of take-all. Phytochemistry. 2006 Mar 1;67(6):595-604.
51. Pierik R, Tholen D, Poorter H, Visser EJ, Voesenek LA. The Janus face of ethylene: growth inhibition and stimulation. Trends in plant science. 2006 Apr 1;11(4):176-83.
52. Tian F, Ding Y, Zhu H, Yao L, Du B. Genetic diversity of siderophore-producing bacteria of tobacco rhizosphere. Brazilian Journal of Microbiology. 2009;40:276-84.
53. Persello-Cartieaux F, Nussaume L, Robaglia C. Tales from the underground: molecular plant–rhizobacteria interactions. Plant, Cell & Environment. 2003 Feb;26(2):189-99.
54. Robin A, Vansuyt G, Hinsinger P, Meyer JM, Briat JF, Lemanceau P. Iron dynamics in the rhizosphere: consequences for plant health and nutrition. Advances in agronomy. 2008 Jan 1;99:183-225.
55. Bangera MG, Thomashow LS. Identification and characterization of a gene cluster for synthesis of the polyketide antibiotic 2, 4-diacetylphloroglucinol from Pseudomonas fluorescens Q2-87. Journal of bacteriology. 1999 May 15;181(10):3155-63.
56. Kaur R, Macleod J, Foley W, Nayudu M. Gluconic acid: an antifungal agent produced by Pseudomonas species in biological control of take-all. Phytochemistry. 2006 Mar 1;67(6):595-604.
57. Cazorla FM, Duckett SB, Bergström ET, Noreen S, Odijk R, Lugtenberg BJ, Thomas-Oates JE, Bloemberg GV. Biocontrol of avocado dematophora root rot by antagonistic Pseudomonas fluorescens PCL1606 correlates with the production of 2-hexyl 5-propyl resorcinol. Molecular plant-microbe interactions. 2006 Apr;19(4):418-28.
58. Perneel M, D'hondt L, De Maeyer K, Adiobo A, Rabaey K, Höfte M. Phenazines and biosurfactants interact in the biological control of soil-borne diseases caused by Pythium spp. Environmental Microbiology. 2008 Mar;10(3):778-88.
59. Singh IP, Sidana J, Bharate SB, Foley WJ. Phloroglucinol compounds of natural origin: Synthetic aspects. Natural product reports. 2010;27(3):393-416.
60. Odoh CK. Plant growth promoting rhizobacteria (PGPR): a bioprotectant bioinoculant for sustainable agrobiology. A review. Int J Adv Res Biol Sci. 2017;4(5):123-42.
61. Wang Y, Kern SE, Newman DK. Endogenous phenazine antibiotics promote anaerobic survival of Pseudomonas aeruginosa via extracellular electron transfer. Journal of bacteriology. 2010 Jan 1;192(1):365-9.
62. Del Ponte EM, Fernandes JM, Bergstrom GC. Influence of growth stage on Fusarium head blight and deoxynivalenol production in wheat. Journal of Phytopathology. 2007 Oct;155(10):577-81.
63. Wan M, Li G, Zhang J, Jiang D, Huang HC. Effect of volatile substances of Streptomyces platensis F-1 on control of plant fungal diseases. Biological Control. 2008 Sep 1;46(3):552-9.
64. Markovich NA, Kononova GL. Lytic enzymes of Trichoderma and their role in plant defense from fungal diseases: a review. Applied Biochemistry and Microbiology. 2003 Jul;39:341-51.
65. Mabood F, Zhou X, Smith DL. Microbial signaling and plant growth promotion. Canadian journal of plant science. 2014 Aug;94(6):1051-63.
66. Palumbo JD, Yuen GY, Jochum CC, Tatum K, Kobayashi DY. Mutagenesis of β-1, 3-glucanase genes in Lysobacter enzymogenes strain C3 results in reduced biological control activity toward Bipolaris leaf spot of tall fescue and Pythium damping-off of sugar beet. Phytopathology. 2005 Jun;95(6):701-7.
67. Qurashi AW, Sabri AN. Bacterial exopolysaccharide and biofilm formation stimulate chickpea growth and soil aggregation under salt stress. Brazilian Journal of Microbiology. 2012;43:1183-91.
68. Jung WJ, Jin YL, Kim KY, Park RD, Kim TH. Changes in pathogenesis-related proteins in pepper plants with regard to biological control of phytophthora blight with Paenibacillus illinoisensis. BioControl. 2005 Feb;50:165-78.
69. Hariprasad P, Divakara ST, Niranjana SR. Isolation and characterization of chitinolytic rhizobacteria for the management of Fusarium wilt in tomato. Crop Protection. 2011 Dec 1;30(12):1606-12.
70. Dunne C, Crowley JJ, Moënne-Loccoz Y, Dowling DN, Bruijn S, O'Gara F. Biological control of Pythium ultimum by Stenotrophomonas maltophilia W81 is mediated by an extracellular proteolytic activity. Microbiology. 1997 Dec;143(12):3921-31.
71. ten Hoopen GM, Krauss U. Biology and control of Rosellinia bunodes, Rosellinia necatrix and Rosellinia pepo: a review. Crop protection. 2006 Feb 1;25(2):89-107.
72. Gottel NR, Castro HF, Kerley M, Yang Z, Pelletier DA, Podar M, Karpinets T, Uberbacher ED, Tuskan GA, Vilgalys R, Doktycz MJ. Distinct microbial communities within the endosphere and rhizosphere of Populus deltoides roots across contrasting soil types. Applied and environmental microbiology. 2011 Sep 1;77(17):5934-44.
73. Kloepper JW. Plant growth-promoting rhizobacteria on radishes. InProc. of the 4th Internet. Conf. on Plant Pathogenic Bacter, Station de Pathologie Vegetale et Phytobacteriologie, INRA, Angers, France, 1978 1978 (Vol. 2, pp. 879-882).

74. Van Loon LC. Induced resistance in plants and the role of pathogenesis-related proteins. European journal of plant pathology. 1997 Dec;103:753-65.
75. Pieterse CM, Van Loon LC. Salicylic acid-independent plant defence pathways. Trends in plant science. 1999 Feb 1;4(2):52-8.
76. del Carmen Jaizme-Vega M, Rodríguez-Romero AS, Guerra MS. Potential use of rhizobacteria from the Bacillus genus to stimulate the plant growth of micropropagated bananas. Fruits. 2004 Mar;59(2):83-90.
77. Tilak KV, Ranganayaki N, Pal KK, De R, Saxena AK, Nautiyal CS, Mittal S, Tripathi AK, Johri BN. Diversity of plant growth and soil health supporting bacteria. Current science. 2005 Jul 10:136-50.
78. Wei G, Kloepper JW, Tuzun S. Induction of systemic resistance of cucumber to Colletotrichum orbiculare by select strains of plant growth-promoting rhizobacteria. Phytopathology. 1991 Dec;81(11):1508-12.
79. Pieterse CM, Van Wees SC, Van Pelt JA, Knoester M, Laan R, Gerrits H, Weisbeek PJ, Van Loon LC. A novel signaling pathway controlling induced systemic resistance in Arabidopsis. The Plant Cell. 1998 Sep;10(9):1571-80.
80. Duijff BJ, Pouhair D, Olivain C, Alabouvette C, Lemanceau P. Implication of systemic induced resistance in the suppression of fusarium wilt of tomato by Pseudomonas fluorescens WCS417r and by nonpathogenic Fusarium oxysporum Fo47. European Journal of Plant Pathology. 1998 Dec;104:903-10.
81. Doke N, Ramirez AV, Tomiyama K. Systemic induction of resistance in potato plants against Phytophthora infestans by local treatment with hyphal wall components of the fungus. Journal of Phytopathology. 1987 Jul;119(3):232-9.
82. Van Peer R, Niemann GJ, Schippers B. Induced resistance and phytoalexin accumulation in biological control of Fusarium wilt of carnation by Pseudomonas sp. strain WCS 417 r. Phytopathology. 1991 Jul 1;81(7):728-34.
83. Chakravarty G, Kalita MC. Comparative evaluation of organic formulations of Pseudomonas fluorescens based biopesticides and their application in the management of bacterial wilt of brinjal (Solanum melongena L.). African Journal of Biotechnology. 2011;10(37):7174-82.
84. Vidhyasekaran P, Kamala N, Ramanathan A, Rajappan K, Paranidharan V, Velazhahan R. Induction of systemic resistance byPseudomonas fluorescens Pf1 againstXanthomonas oryzae pv. Oryzae in rice leaves. Phytoparasitica. 2001 Apr 1;29(2):155.
85. Vivekananthan R, Ravi M, Ramanathan A, Samiyappan R. Lytic enzymes induced by Pseudomonas fluorescens and other biocontrol organisms mediate defence against the anthracnose pathogen in mango. World Journal of Microbiology and Biotechnology. 2004 Apr;20:235-44.
86. Liu L, Kloepper JW, Tuzun S. Induction of systemic resistance in cucumber against Fusarium wilt by plant growth-promoting rhizobacteria. Phytopathology. 1995 Jun 1;85(6):695-8.
87. ALSTRÖM S. Induction of disease resistance in common bean susceptible to halo blight bacterial pathogen after seed bacterization with rhizosphere pseudomonads. The Journal of General and Applied Microbiology. 1991;37(6):495-501.
88. MaganaAB RE, Melati M, PurnamawatiC H, PratiwiD E. Enrichment of Organic Manure with Plant Growth Promoting Rhizobacteria Improved the Root and Shoot Growth of Okra (Abelmoschus esculentus L.) Moench. Journal of Tropical Crop Science Vol. 2020 Oct;7(3).
89. Wu Y, Zhou J, Li C, Ma Y. Antifungal and plant growth promotion activity of volatile organic compounds produced by Bacillus amyloliquefaciens. MicrobiologyOpen. 2019 Aug;8(8):e00813.
90. Nascimento FX, Rossi MJ, Soares CR, McConkey BJ, Glick BR. New insights into 1-aminocyclopropane-1-carboxylate (ACC) deaminase phylogeny, evolution and ecological significance. PLoS One. 2014 Jun 6;9(6):e99168.
91. Fairclough DV, Brown JI, Carlish BJ, Crisafulli BM, Keay IS. Breathing life into fisheries stock assessments with citizen science. Scientific reports. 2014 Nov 28;4(1):7249.
92. Pradhan N, Sukla LB. Solubilization of inorganic phosphates by fungi isolated from agriculture soil. African Journal of Biotechnology. 2006;5(10).