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Review

Role of Plant Growth Promoting Rhizobacteria (PGPR) as a Plant Growth Enhancer for Sustainable Agriculture: A Review

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Abstract: The rhizosphere of a plant is home to helpful microorganisms called plant growth-promoting rhizobacteria (PGPR), which play a crucial role in promoting plant growth and development. The significance of PGPR for long-term agricultural viability is outlined in this review. Plant growth processes such as nitrogen fixation, phosphate solubilization, and hormone secretion are discussed. Increased plant tolerance to biotic and abiotic stress, reduced use of chemical fertilizers and pesticides, and enhanced nutrient availability, soil fertility, and absorption are all mentioned as potential benefits of PGPR. PGPR has multiple ecological and practical functions in the soil's rhizosphere. One of PGPR's various roles in agroecosystems is to increase the synthesis of phytohormones and other metabolites, which have a direct impact on plant growth. Phytopathogens can be stopped in their tracks, a plant's natural defenses can be bolstered, and so on. PGPR also helps clean up the soil through a process called bioremediation. The PGPR's many functions include indole acetic acid (IAA) production, ammonia (NH_3) production, hydrogen cyanide (HCN) production, catalase production, and more. In addition to aiding in nutrient uptake, PGPR controls the production of a hormone that increases root size and strength. Improving crop yield, decreasing environmental pollution, and guaranteeing food security are only some of the ecological and economic benefits of employing PGPR for sustainable agriculture.

Keywords: PGPR; crop production; rhizosphere; plant nutrition; soil fertility; sustainable agriculture

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1. Introduction

The global agricultural system is facing additional difficulties in the twenty-first century, including a drop in productivity and deterioration in the sustainability of agricultural ecosystems [1]. Forecasts by the United Nations [2] project that the global population will reach 9.7 billion people by 2050, resulting in a steady rise in food demand and its constrained available supply [3]. Due to climate change, major cereal crops have seen significant production losses, with yield decreases of about 3.8 percent and five percent in reference to corn and wheat separately [4]. Temperature rises have brought major rises in global temperatures and the appearance of various abiotic factors that have a negative impact on agricultural output [5]. Many harmful abiotic environmental factors, such as salinity, are turning arable land into barren land. This is because salinity drastically changes plant growth and metabolism, resulting in changes in plant physiology, morphology, and biochemistry [6]. By 2050, climate change will cause drought to impact over 50% of arable land [7]. Drought affects crop hydration association, photosynthetic integration, and supplement utilization [7]. Heavy metal contamination is hard to remove and needed in small amounts for plant metabolic activities, but high levels harm the phytological and microbiological networks.

Food is a necessity for survival and plays a crucial role in individual and societal development. Reduced crop yields are a major cause for alarm. Pressure from a growing population on farmland to produce more food has resulted in the widespread usage of chemical inputs like fertilizers, herbicides, and insecticides. Through bioaccumulation and biomagnification, the effects of agrochemical runoff from such land have a negative impact on life on Earth. The use of insecticides to combat plant diseases has unintended consequences for beneficial insects, soil fertility, and soil microbiota [8]. Current harmful farming methods do not meet our needs and cannot provide a sustainable future. Sustainable agriculture has become increasingly important in recent times due to its focus on long-term environmental and social benefits.

Recognizing the importance of sustainable farming practices is crucial for meeting the future economic needs of the world, as they can help reduce the use of artificial pesticides and fertilizers while improving plant health and soil quality [9].

To secure long-term environmental health worldwide and produce adequate food for future generations, sustainable agriculture must preserve the soil's inherent diversity [3]. Thus, eco-friendly alternatives, including the sustainable use of beneficial microorganisms, are crucial for alleviating environmental stress. Bacteria, known as PGPR, are the most important of all the soil microbes. The benefits for the crop are achieved in many ways, such as fixing nitrogen, breaking down phosphate, getting rid of heavy metals, making phytohormones (like auxin, gibberellins, cytokinin, etc.), breaking down crop residue, and stopping phytopathogens from growing [10].

Researcher [11] demonstrated that PGPRs boost plant vitality and promote development without releasing harmful byproducts into the atmosphere. With over 500 species, Streptomyces is the largest genus of Actinobacteria and a type genus of the Streptomycetaceae family among PGPRs [12].

Crop production requires PGPR to boost plant nutrient availability. PGPR influences plant growth either directly or indirectly through root colonization [13]. PGPR enhances plant growth by bioremediating polluted soils through the sequestration of toxic heavy metal species and the degradation of xenobiotic compounds like pesticides. Additionally, they mobilize nutrients in soils, produce plant growth regulators, protect plants from phytopathogens by controlling or inhibiting them, and improve soil structure [14].

Rhizosphere bacteria help cycle carbon through the earth and the environment and prevent soil carbon loss through metabolic activity. PGPRs can effectively control plant diseases brought on by fungi and bacteria. The phytomicrobiome—a group of beneficial bacteria—improves plant resilience to biotic and abiotic stress and agricultural productivity. PGPR, a beneficial phytomicrobiome component, promotes plants' responses to biotic stress by producing chemical messengers, boosting their intake of nutrients, and releasing antibiotics [15].

This research review delves into the positive aspects of PGPR and how it can be combined with nanotechnology to make plants more resilient to harmful biotic and abiotic elements, improve agricultural production, and ultimately benefit the environment and the economy.

2. Benefits of Rhizobial Associations for Plant Growth

Two to five percent of rhizobacteria have a major impact on plant development when reintroduced by plants inoculated in soil containing competing microorganisms; these are known as PGPR.

The social network in which a plant grows in nature is both dynamic and constant; the plant does not exist in isolation. Microorganisms surrounding the plant always organize and maintain the colony [16]. PGPRs are rhizobacteria that help plants flourish. In the soil's rhizosphere, its lowermost layer near plant roots, a group of helpful bacteria is found. These bacteria establish a cooperative relationship with plants and offer a variety of benefits that promote plant growth [17]. Microbiome interactions exist in all multicellular creatures and, presumably, all eukaryotes. These interactions may actually predate the settlement of plants in the region. Soil contains a wide variety of microbes, with bacteria being the most common type. Where soil bacteria and plant roots come into contact with one another is in the rhizosphere, which frequently has a higher microbial density. The beneficial bacteria either live in the soil freely or work in symbiotic relationships with the plant, but they are present nearby or even inside the plant [18]. The root-tip environment (or rhizosphere) harbors a multitude of living creatures. Lazarovits [19] discovered that root system functions, such as breathing and root secretion, affect the rhizosphere quantitatively and qualitatively. The plant, soil, bacteria, and soil microbes all interact significantly and widely in the rhizosphere. According to researcher [20], these predate the arrival of plants in the region. It is possible that these connections matter greatly and affect plant development and crop yield. When two or more types of microflora are present, PGPR can multiply and colonize every ecological niche on the roots at every stage of plant development. The age, stage of growth, species of plant, soil tissue, and ecological circumstances all have an effect on the activities of the microbes in the rhizosphere. Because of their quick development and adaptability, bacteria can take up carbon and nitrogen from the bulk of the rhizosphere's microbial population. Some PGPRs can create antimicrobial substances that stop the development of plant pathogens, shielding the plant from disease, as highlighted in Figure 1 [21].

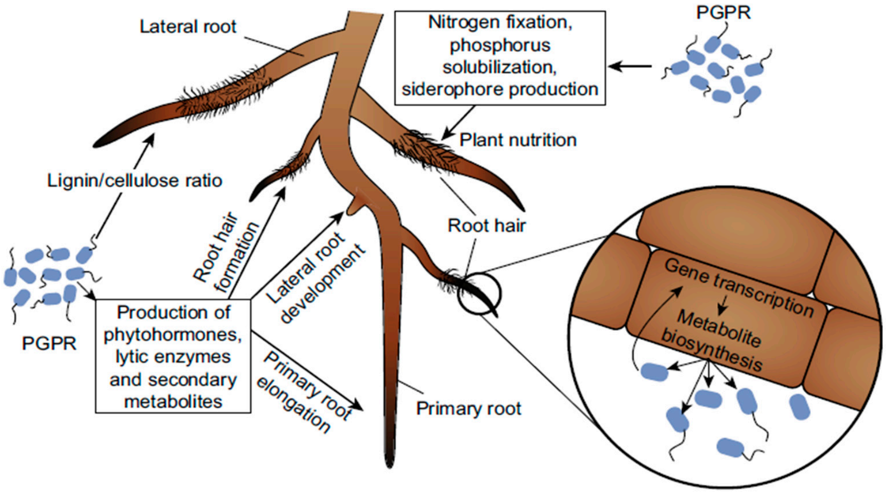

Figure 1. The probable modes of effect that PGPR employsin order to promote increased plant development, based on work by Vacheon [21].

Researchers have thoroughly studied the positive impacts of PGPR, a naturally occurring soil bacterium, on plant vitality and output. In addition to protecting plants from pathogens and harsh conditions, they can also boost nutrient availability, spur plant growth, fortify root development, and more [18]. Several different mechanisms are involved in how PGPR helps plants. Some PGPR form auxins, cytokinins, and gibberellins, which encourage root and shoot growth [18].

PGPRs can easily use the process of "fixation" to convert nitrogen in the air into a plant-available form, thereby augmenting the plant's nitrogen needs. PGPRs solubilize phosphorus and other mineral nutrients, increasing their availability to plants. PGPR competes with dangerous microbes for oxygen, food, and room by colonizing the rhizosphere, which lowers the danger of pathogen invasion and boosts plant health in general. PGPR improves plant resistance by activating defensive systems and enhancing tolerance to a wide range of environmental factors, including dryness, salinity, and extreme heat. Soil has many different kinds of bacteria and viruses, primarily bacteria.

In sustainable agricultural techniques, the application of PGPR as bio-fertilizers and bio-pesticides has attracted a lot of attention. The frequent use of chemical pesticides and fertilizers in conventional agricultural practices can have negative impacts on human health, the environment, and the sustainability of agricultural output [22]. Therefore, sustainable and environmentally friendly methods are becoming increasingly important to increase plant growth and improve agricultural productivity. In recent years, PGPR has surfaced as a viable option for long-term farming success [23].

PGPR provides a viable method to promote plant development, enhance crop output, and mitigate ecological damage caused by agricultural practices, considering all variables. Furthermore, this text reveals the mechanisms of PGPR and their applications in microbial and plant interactions, as well as sustainable agriculture.

3. The Growth-Promoting Mechanism in Plants: PGPR as a Mediator

Rhizosphere microorganisms are beneficial microbes that use a range of strategies to promote plant growth, as illustrated in Figure 2 on plant-PGPR interactions [24]. The following are significant contributions that PGPR makes to environmentally friendly farming: direct and indirect means exist for PGPR to stimulate plant development.

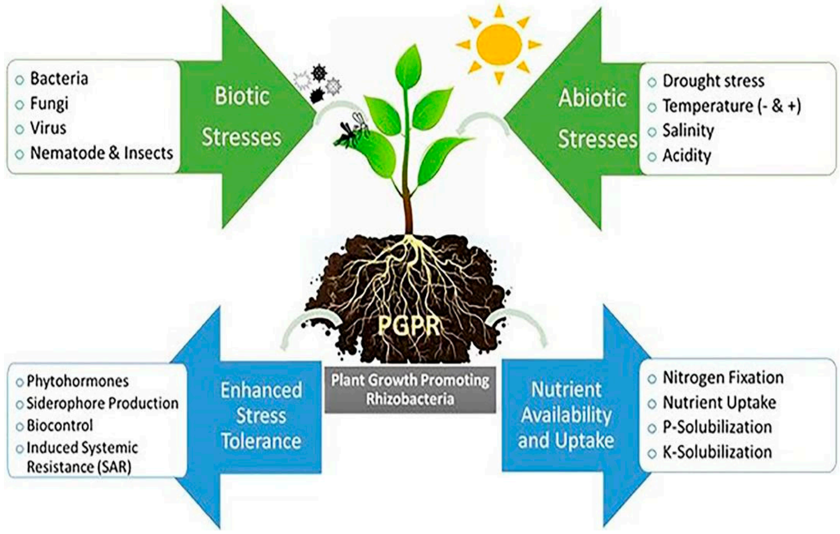

Figure 2. Insights on plant-PGPR interactions in the rhizosphere [24].

3.1. Direct Mechanism

By fixing nitrogen, mineralizing organic compounds, solubilizing mineral nutrients, and producing phytohormones, PGPR can directly help plant growth and development through processes like nutrient intake or increased access to nutrition [24].

3.1.1. Nitrogen (N) Fixation

The majority of plant biochemical processes, like the synthesis of proteins and photosynthesis, depend on nitrogen (N), making it one of the most crucial minerals plants need to thrive [25]. Dinitrogen, which comprises 79% of nitrogen in the atmosphere, has a triplet covalent bond and a relatively small amount of reactivity; therefore, plants cannot utilize it directly. As the most effective method of adding nitrogen, nitrogen fertilizers have become an essential component of the cultivation of crops and methods in agriculture. But their disproportionate and persistent use is polluting the environment, causing eutrophication, deadly discharges into the environment, poisonous deposition in water in the ground, and other water bodies—all of which are either directly or indirectly contributing to climate change. According to Bouchet [26], cropping systems only recover about half of the applied nitrogen; the other half either escapes from the soil by volatilization, leaching, or runoff or stays in the soil as organic complexes, which make up roughly 98% of the overall quantity of soil nitrogen. Symbiotic nitrogen-fixing organisms form a mutually beneficial connection with their host, as opposed to free-living nitrogen fixers and their host plants. *Rhizobium*, *Azoarcus*, *Mesorhizobium*, *Frankia*, *Burkholderia*, and several strains of *Achromobacter* are all symbiotic nitrogen fixers [27,28]. These bacterial taxa, along with a few others, have earned their reputation as nitrogen-fixing PGPRs capable of significantly boosting plant growth and harvest [29]. A highly conserved and energy-demanding enzyme known as nitrogenase is responsible for fixing nitrogen. Two metalloprotein subunits make up the typical nitrogenase. The energy required by these bacteria to convert atmospheric nitrogen into usable forms is considerable. The bacteria require 16 moles of ATP to fix every mole of nitrogen, with the majority of this energy originating from the oxidation of organic molecules. Photoautotrophs are microorganisms that can photosynthesize their own carbohydrates, while nitrogen fixers that do not use photosynthesis rely entirely on other organisms to obtain these energy-rich molecules.

Legumes make up 80 Tg of the 175 Tg of nitrogen fixed annually as a result of symbiotic nitrogen fixation. Each legume fixes between 20 kg to 200 kg of nitrogen annually. Industrial nitrogen fixation, which produces nitrogen fertilizers, accounts for approximately half of the nitrogen fixed annually [30]. Seventy-plus percent of legumes form mutualistic relationships with rhizobia and are capable of fixing up to two hundred kg of nitrogen per square meter. Through symbiotic links with bacteria, legumes fix nitrogen from the atmosphere, reducing their need for additional nitrogen until large amounts of N-fertilizers are applied. Using the provided fertilizer requires a lesser amount of energy than atmospheric N_2 repair, which causes them to reduce or stop their nitrogen fixation. Spraying biologically nitrogen-fixing PGPR onto crops and crop fields increases growth, combats illness, and keeps the soil's nitrogen content stable for farming.

3.1.2. Phosphate Dissolution

The second essential ingredient for plants is phosphorus (P). Important functions that rely on it include breathing, signal transduction, transmission of energy, photosynthesis, and macromolecular biosynthesis [30]. Plants struggle to absorb phosphorus because 99 percent of the available phosphorus becomes immobilized or precipitated, rendering it water-insoluble. Researchers have estimated that only 0.1% of the combined phosphorus concentration in soil and plant availability is due to the poor solubility of phosphorus and its preference for organic compounds and the soil matrix [31]. Plants absorb phosphorus exclusively as monobasic (H_2PO_4) and dibasic $(HPO_4)^{2-}$ ions [32].

Applying phosphorus-based fertilizers to the soil replenishes a plant's quick access to the phosphorus already present in the substrate, remedying phosphate deficiency. Commercial fertilizer supplementation with phosphorus, however, is a costly process, and the phosphorus is frequently inhospitable to vegetation because the soil might readily lose it, mix with local waterways, and contaminate aquatic as well as terrestrial ecosystems [33].

A wide variety of advantageous microorganisms, such as soil-dwelling bacteria and fungi and those affiliated with plant roots, possess the ability to solubilize soil phosphorus that would otherwise be insoluble. Researcher [34] reported a 25% decrease in the amount of P required by phosphorus solubilizing bacteria (PSB). Khan et al. [32] reported an increase in PSB's influence when mixed with other PGPRs.

The primary method used by practically all bacteria that can dissolve metabolites, most often organic acids, requires phosphorus for their synthesis in the ketone and gluconic acid ketoforms, in which the cations are chelated and attached to their respective hydroxyl and carboxyl groups in phosphate [35] so that they can be dissolved into the soil solution and made available for plant uptake. *Arthrobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Microbacterium*, *Pseudomonas*, *Rhizobium*, *Mesorhizobium*, *Flavobacterium*, and *Serratia* are some of the genera that have PGPR bacteria that can dissolve phosphorus [36]. *Mesomerhizobium ciceri* and *Mesomerhizobium mediterraneum*, both of which have been isolated from chickpea nodules [37], are two of these phosphate-solubilizing bacteria. Despite the fact that these bacteria solubilize phosphorus by increasing soil fertility, there have been few investigations into their application as biofertilizers. The low solubility of phosphorus often limits its availability in the soil [38]. Solubilizing insoluble phosphorus molecules in the soil is a special property of some PGPRs that makes them more accessible to plants.

3.1.3. Potassium Dissolution

Potassium (K) is the third essential component plants need. Since more than ninety percent of potassium is already in existence as insoluble rocks and mineral silicates, the soluble potassium content in soil is often quite low. The potassium deficit severely limits the production of crops. Without enough potassium, plants produce fewer seeds, grow more slowly, and produce less of a crop.

Numerous microorganisms can solubilize potassium (K) in soil and interact closely with plants, particularly bacterial and fungal species [39]. Researchers have extensively investigated the potential of PGPR to produce and secrete organic acids that can dissolve potassium rocks. *Acidothiobacillus* sp., *Bacillus edaphicus*, *Ferrooxidans* sp., *Bacillus mucilaginosus*, *Pseudomonas* sp., and *Burkholderia* arearesome PGPRs that can dissolve potassium [40]. Researchers have found that *Paenibacillus* sp. converts potassium from inaccessible mineral forms found in soils. According to research on the effects of plant growth-stimulating microorganisms (PGPM), K-solubilizing microbes make organic acids that make potassium more available, which in turn helps plants grow. Soil microorganisms increase the acidity of the soil's rhizosphere by producing oxalate, acid citrate, acetate, ferulic acid, and coumaric acid, all examples of organic acids. This accelerates the rate at which minerals dissolve and generate protons, resulting in the solubilization of the mineral K. Therefore, scientists have concluded that PGPM, like PSB, could be an efficient organic fertilizer, boosting the accessibility of plant nutrients and permitting less use of artificial fertilizers [41].

3.1.4. Producing Siderophore

Bacteria produce siderophores, small chemical compounds, in situations with little iron to enhance their iron absorption capacity. Iron is essential for all photosynthesis-based organisms due to its role as a vital enzyme cofactor in several metabolic activities, including photosynthesis, amino acid synthesis, oxygen transfer, nitrogen fixation, and respiration [42]. Iron is a prevalent chemical component on Earth, often found in two oxidative states: Fe^{2+} and Fe^{3+}. Plants have limited access to the later state due to the formation of insoluble iron oxides and hydroxides [43]. Research indicates that some plant growth-promoting bacteria (PGPB) produce low-molecular-weight chemicals (400–1500 Da) that have the ability to extract iron from the soil [44]. Siderophores are chemicals that bind to iron and enhance its bioavailability in plants [45]. Scientists have isolated and analyzed several microorganisms from both oceanic and land environments in order to assess their ability to produce siderophores [46]. The four main chemical structures of siderophores are phenolates, hydroxamates, pyoverdines, and carboxylates. The main Gram-negative bacteria that make siderophores are *Enterobacter* and *Pseudomonas*. On the other hand, only 2% of Gram-positive species, like *Bacillus* and *Rhodococcus*, can do the same [47]. Siderophore production by good microbes in the soil and on plants is an important biological control mechanism because it out competes harmful plant pathogens for iron resources, stopping them from accessing them [43].

3.1.5. Zinc Solubilization

Zinc (Zn) is a necessary plant micronutrient that ranges in concentration from 5 to 100 mg kgand is vital for plant growth and development [48]. The production of chlorophyll, the activation of enzymes involved in auxin and glucose metabolism, and the biosynthesis of proteins, lipids, and nucleic acids are only a few of the important physiological processes for which Zn is essential in plants [49]. It also aids plant survival in emerging climate circumstances, when plants must withstand increased temperatures and drought swings [50]. According to the FAO [51], zinc deficiency affects more than fifty percent of global soils, mostly because Zn is associated with naturally occurring mineral forms that are often inaccessible to plants, like zincite, zinc silicates, willemite, and zinc sulfide [52].

Application of inorganic fertilizers can correct a zinc shortage, although doing so causes some environmental harm and renders a significant portion of the fertilizer unavailable to plants. PGPR is preferable due to its ability to completely fill cation-containing minerals found in nature [53]. Certain bacteria and fungi saturate zinc in insoluble forms in the rhizosphere, thereby increasing the availability of zinc nutrients. Zn-mobilizing PGPR significantly boosts the yield of cereal crops like maize, wheat, and rice, as proven in numerous experiments [52]. Because of the rapidly expanding global population, there is a growing demand for staple foods, which in turn increases the demand for pesticides and artificial fertilizers. However, this could have a negative impact on the environment. Even though biofertilizers may not totally replace mineral fertilizers, increasing crop yields with the use of synthetic fertilizers and pesticides is essential to feed the world's growing population.

3.2. Indirect Mechanism

By creating repressive chemicals that boost the host's inherent resistance, PGPR uses roundabout means to protect plants from or lessen the impact of phytopathogens. The roles that PGPR plays in this process include making hydrolytic enzymes (chitinases, cellulases, etc.), antibiotics in response to plant pathogens or disease resistance, protecting the plant's whole system from different pathogens and pests, and making VOCs and exudates viaphotosynthesis, among other things.

3.2.1. Stress Management

Stress refers to anything that acts as a barrier to development in a plant. A fundamental hurdle to long-term agricultural output is the multitude of stresses caused by the soil environment on plant growth. We can divide these pressures into biotic and abiotic groups. The main factor behind the more than 30% global crop loss is abiotic stress. The most common type of abiotic stress that hinders plant growth and productivity is drought or aridity stress, caused by dryness, salinity, and high temperatures, as shown in Figure 3 [54]. Researchers have extensively studied the role of PGPR in protecting plants from environmental stresses, utilizing microorganism strains like *Pseudomonas putida* and *Pseudomonas fluorescens*, which significantly affect water salinity and other abiotic stresses and are capable of removing cadmium ions from the ground [55]. Various pathogens, including bacteria, viruses, fungi, nematodes, protists, insects, and viroids, can produce biotic stress, which significantly lowers agricultural productivity [56]. Biotic stress has far-reaching consequences for plant health, including effects on plant health in greenhouses, natural habitat ecology, nitrogen cycling in ecological systems, and other horticultural concerns. These issues could be addressed and worked on using strains of *Paenibacilluspolymyxa* B2, B3, and B4, *Bacillus amyloliquefaciens* HYD-B17, HYDGRFB19, *P. favisporus* HYTAPB30, and *B. subtilis* RMPB44.

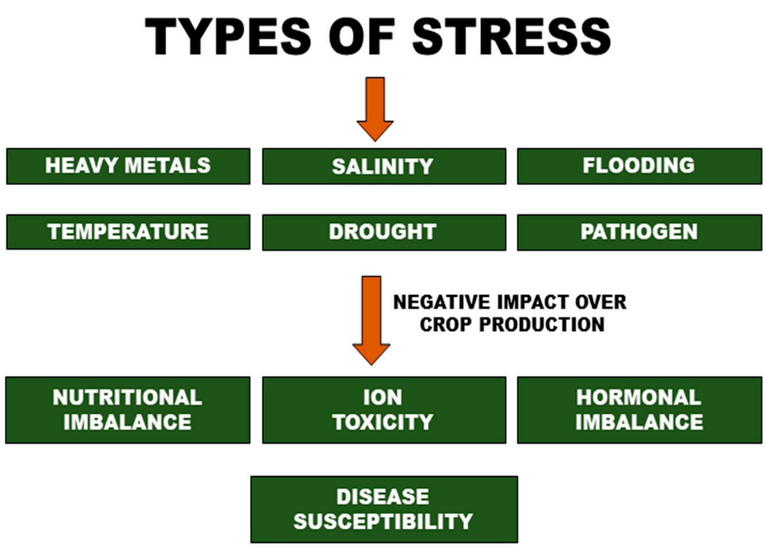

Figure 3. Graphical representation of different stressors.

3.2.2. Hydrolytic Enzymes Production

PGPR generates protective enzymes, categorizing its action as a biopesticide. By inhibiting phytopathogenic agents, PGPR stimulates plant growth and produces compounds with antibiosis and antifungal characteristics that serve as defense mechanisms. Chitinase and glucanase are two examples of hydrolyzing enzymes created throughout the process. Bacteria that produce chitinases and beta-glucanases would inhibit fungal growth because these components make up the bulk of a fungal cell wall. *Sinorhizobiumfredii KCC5* and *Pseudomonas fluorescens LPK2* make chitinase and beta-glucanase, which stop *Fusarium udum* from making plants wilt [57].

3.2.3. VOCs Formation

Inducing systemic resistance in plants against phytopathogens and suppressing bacterial, fungal, and nematode infections are only a few of the many benefits that result from the production of volatile organic compounds (VOCs) by PGPR. Several microbial genera, like *Pseudomonas*, *Bacillus*, *Arthrobacter*, *Stenotrophomonas*, and *Serratia,* include specific bacterial species that have an impact on plant growth. *Bacillus* spp. produce the best VOCs, including 2-butanediol and acetoin, for preventing the spread of fungi and encouraging plant development [58].

3.2.4. Exopolysaccharide (EPS) Production

Diverse types of bacteria, algae, and plants create biodegradable polymers called EPSs. Bacteria, algae, and plants construct EPSs from glucose residues and their analogs [59]. EPSs sustain the host under stress (from salty soil, drought, or too much moisture) by holding water reserves, aggregating soil particles, and facilitating obligatory rhizobacteria, which are bacteria that interact with plant roots. Some PGPRs that make EPS, like *Rhizobium leguminosarum*, *Azotobacter*, *Bacillus drentensis*, *Agrobacterium* sp., *Xanthomonas* sp., and *Rhizobium* sp, make the soil more fertile and help farming. Mahmood et al. [60] examined how salinity affected mung bean physiology, growth, and yield. In hard natural saline conditions, researchers evaluated the efficiency of foliar spraying of silicon (Si) (1 and 2 kg ha^{-1}) and two potential PGPRs (*E. cloacae* and *B. drentensis*). Their study revealed that adding 2 kg Si ha^{-1} to the PGPR strain *B. drentensis* increased gaseous exchange, water relations, photosynthetic pigments, growth, and seed production in saline irrigation. Si and PGPR in agriculture reduce mung bean salinity stress sustainably.

3.2.5. Antibiotic Production

Microbial antagonists can replace traditional pesticides to combat plant diseases in agricultural crops. By producing antibiotics, PGPR is crucial in preventing the spread of disease-causing bacteria, together with *Bacillus* spp. and *Pseudomonas* sp. One of the most promising areas of plant sciences in the last 20 years has been the production of antibiotics by PGPR to fend off numerous plant-based pathogens and extensively researched biocontrol mechanisms [61]. The vast majority of *Pseudomonas* species produce antibiotics such as oomycin A, cepaciamide A, ecomycins, and viscosin. Other medicines manufactured by *Pseudomonas* include pyrrolnitrin, pyoluteorin, 2,4-diacetylphloroglucinol, rhamnolipids, and pyoluteorin. Bacillus species produce a number of lipopeptide antibiotics, such as surfactin and bacillomycin, along with an assortment of other antibiotics and antifungal drugs. Further classification of the bactericides involves dividing them into volatile and non-volatile substances. Polyketides, cyclic lipopeptides, aminopolyols, heterocyclic nitrogenous chemicals, etc., are all examples of non-volatile antibiotics. To name a few examples, volatile antibiotics include alcohols, aldehydes, ketones, hydrogen cyanide, and so on [62].

3.2.6. Plant Growth Hormone Production

Phytohormones, as well as plant growth hormones, have an impact on plant maturation and growth even at minimal doses (<1 mM) [63]. When certain bacteria possess the intrinsic ability to control the production of different growth regulator enzymes, they are considered plant growth regulators or phytostimulators. It may even encourage plants to produce these phytohormones. The root cell produces an excess of auxins, cytokinins, abscisic acid, ethylene, brassinosteroids, and gibberellins. These chemicals affect the root's beginning, roots on both sides, and hairs on the roots, which makes the plant take in more water and nutrients. Symbiotic and endophytic bacteria, which live in close proximity to plants' roots, produce phytohormones that affect seed germination, root system expansion to increase nutrient absorption, the development or elaboration of vascular tissues, shoot extension, flowering, and general plant growth [64].

IAA, cytokinins, gibberellins, and ethylene synthesis inhibitors are among the compounds that PGPRs generate. IAA phytostimulators made by PGPRs affect plant growth at the tips, phototropism, geotropism, cell division, root initiation, and other things [65]. An amino acid that is frequently present in root exudates is tryptophan. It serves as the primary precursor molecule in bacteria for the production of IAA [66]. IAA-producing microbes might be able to remove potentially toxic levels of tryptophan and tryptophan analogs from their cells. Plant cytokinins stop the main root system from growing bigger and encourage cell division, lateral root development, and the growth of root hairs. Gibberellins, on the other hand, encourage stem tissue, root lengthening, and root elongation to the side. One important phytohormone, ethylene, has many biological processes that might influence plant growth and improvement. It accelerates seed germination, limits the elongation of roots, aids in the maturation of the fruit, cuts down on leaf withering, boosts crop production, and causes further plant hormone synthesis to increase. It is also crucial in the process of root formation. Some of the PGPRs that are linked to making phytostimulatorsare Bacillus, Pantoea, Arthrobacter, Pseudomonas, Enterobacter, Brevundimonas, and Burgholderia [67].

4. PGPR Used in Vegetable Production

Various processes, such as the mineralization of organic matter, nutrient immobilization, phosphate solubilization, nitrogen nitrification, and phytohormone production, combine to enhance soil fertility and crop productivity. Rhizobacteria attached to roots produce a high quantity of biomolecules in the soil for further health benefits. Numerous volatile substances and additional compounds (such as enzymes, proteins, etc.) produced by PGPR improve soil quality and encourage plant growth. Numerous bacteria from various genera, such as *Bacillus*, *Pseudomonas*, *Arthrobacter*, and *Stenotrophomonas*, have been identified as producers of volatile compounds [18]. As researchers discover more about the plant growth-promoting mechanism of PGPR, they anticipate an increase in tomato production and a decrease in chemical inputs. Researchers in Ethiopia measured the effects of greenhouse conditions on root development in tomatoes and the role of Pseudomonas isolates, stems, and leaves differently, with the dry weight of leaves showing the most variability [68]. Additionally, *Pseudomonas* APF1 and *B. subtilis* B2G treatments resulted in the highest dry and fresh weight tomatoes ever reported [69]. *Trichoderma* spp. and *Bacillus* spp. established new benchmarks for growth rates, fruit production, and nutrient accessibility.

5. PGPR Used in Crops

The Poaceae family includes the cereal plant *Zea mays* L., more commonly known as corn. Among the many cereal crop species, it ranks among the biggest and most important on Earth. According to the International Grains Council [70], maize consumption worldwide will continue to rise until 2024, and the crop will see increased usage as animal feed. One of the three most important crop species in the world, maize provides almost half of the energy required by organisms in Africa and the Americas each day [71]. If we want to keep improving maize yield, we have to use more fertilizer, which will drive up production costs and make environmental problems worse. There are many well-established benefits to crop development and production from rhizobacteria that encourage plant growth. The biological answer that might boost crop productivity, adjust the atmospheric nitrogen, and slow down maize nitrogen recovery plants could be PGPR, according to researchers Kuan et al. [72]. Increased year rates of up to 39% with less fertilizer-N input are encouraged by the finding that plant-N remobilization is closely linked to plant aging. Because of its capacity to increase growth and grain output, PGPR is useful for cereal crops, particularly maize. Many different kinds of bacteria may produce IAA, antibiotics and this has positive effects on the nutrient uptake capacity of plants, as illustrated in Table 1. Phosphate solubilization and other as-yet-unstudied PGPR properties also contribute to plant development. Researchers are also studying the bioprotective role of PGPR in maize crops. One dangerous fungus that is intimately associated with maize is *Fusarium*. According to Pereira et al. [73], some PGPR strains, like *Bacillus amyloliquefaciens* and *Microbacterium oleovorans*, were able to keep *Fusarium verticillioides* away from maize seeds. Additionally, some PGPR species may aid plant growth by acting as biocontrol agents and biofertilizers at the same time. As an example, isolates of *B. cepacia* have been identified that have biocontrol capabilities against *Fusarium* spp. Bevivino et al. [74] found that these microbes can promote maize development in environments with low iron levels by producing siderophores.

Sugarcane is one of the first and most significant agricultural products. It is a hybrid of the *Saccharum* plant and has several uses in industry. It is best to grow sugarcane in tropical and subtropical climates for sugar production [75]. Sugarcane is significant on a worldwide scale due to the benefits associated with biofuel and biogas generation. When compared to other methods, PGPR has environmental and economic advantages since it increases sugarcane output while decreasing fertilizer use. One of the biggest challenges of growing sugarcane is soil that is not rich enough or nutrient-rich enough to meet the plant's needs, which makes it difficult to achieve significant yields. The element phosphorus (P) has the greatest impact on soil. Despite its relative insignificance compared to N and K, it plays a major role in sugarcanes ability to survive and build its root system [76].

Table 1. Function of the Rhizosphere by a few chosen PGPR candidates.

Species	Role	Mechanism Involved	Participating Plant	Reference
Agrobacterium radiobacter	Improves bioprotection	Antibiotics		Mohanram and Kumar, 2019 [77]
Azotobacter chroococcum	Assists in biostimulation	Production of gibberellin	Cereals	Zhang et al., 2019 [78]
Azospirillumbrasilense	Biofertilisation	Phosphate solubilisation	Maize (*Zea mays*), Wheat (*Triticum aestivum* L.) and Rice (*Oryza sativa*)	Lucy et al., 2004 [79]
Bacillus cereus	Boosts bioprotection	Lipopeptides Induced and acquired systemic resistance	Bean (*Phaseolus vulgaris*) Tomato (*S. lycopersicum*)	Hashami et al., 2019 [80]
Bacillus subtilis	Biofertilisation Aids in biostimulation Bioprotection	Ammonia synthesis Through IAA and Cytokinin production Lipopeptides Catalase production	Maize (*Zea mays*) Chickpea (*Cicer arietinum)* Tomato (*S. lycopersicum* L.) Cucumber (*Cucumis sativus*)	Ouhaibi-Ben Abdeljali et al., 2016 [81], Tahir et al., 2017 [82]
Klebsiella pneumonia	Aids biofertilisation Bioprotection	Nitrogen fixation Acquired and induced systemic resistance	Maize (*Zea mays*) Peanut (*Arachis hypogaea*)	Sharma et al., 2019 [83]
Pseudomonas aeruginosa	Bioremediation	Cellulase production	Rice (*O. sativa*), Pea (*P. sativa)*	Cheng et al.,2019 [84]
Staphylococcus saprophyticus	Biostimulation	Manufacturing of IAA	Ornamental species	Manzoor et al., 2019 [85]

A combination of factors, including the absence of phosphorus in the initial material, clay absorption of phosphorus, and the precipitation of phosphorus with iron and aluminum oxides and hydroxides, causes inadequate phosphorus availability. Consequently, the usage of P fertilizers in sugarcane growing is substantial, leading to an increase in production costs. In the first year, a significant amount of the applied phosphorus fertilizer becomes fixed in the soil, rendering it unavailable for plant uptake. However, cane crop roots only absorb around 10 to 30 percent of that amount [86]. Therefore, it is critical to find fertilizers that do not include phosphate as soon as possible.

A potential alternative to using mineral fertilizers like phosphate is PGPR, which may help enhance their performance while also producing sugarcane with little environmental impact [87]. Many studies that evaluated the effects of inoculating sugarcane with three different PGPR species and five different doses of P. Researchers discovered that inoculation improved crop yields while decreasing fertilizer expenses for farmers [88]. The most effective fertilizer management for sugarcane production, according to their data, was a combination of *Azospirillum umbrasilense, Bacillus subtilis*, and cheap (P_2O_5). Using *B. subtilis* along with byproducts can improve soil fertility, lessen the bad effects of vinasse fertilization, encourage shoot and root growth, and create a synergistic effect that makes it possible to grow a lot of sugarcane with little damage to the environment [89]. Sugarcane crops treated with Azospirillum had better root systems, which meant more water and nutrient absorption and maybe higher yields [29]. This research showcased the complex relationship between several factors, such as auxin pools seen in native plants, by showing how cultivar, water regime, and Azospirillum inoculation interact with one another.

6. Integration of PGPR and Nanotechnology

Genetic manipulation opens a transformative avenue for enhancing PGPR strains, offering improved efficacy and the development of innovative variants. This integration of genetic advancements holds the promise of elevating PGPR-biotechnologies, fostering effectiveness, sustainability, and environmental friendliness in addressing plant stresses. In the realm of nanotechnology, advanced nations such as the United States, China, and Japan strategically harness sophisticated methodologies to substantially enhance agricultural productivity [90]. This strategic implementation involves a multifaceted exploration of cutting-edge techniques, encapsulating a variety of approaches aimed at optimizing key aspects of agricultural processes. Within the United States, nanotechnology applications in agriculture span various domains. Targeted delivery systems, precision farming, and enhanced nutrient management deploy nanomaterials, ranging from nanoparticles to nanostructured materials [91]. Nanosensors play a pivotal role in monitoring soil conditions, providing real-time data for precise irrigation and fertilization strategies. Additionally, nanomaterials contribute to controlled release systems for pesticides, minimizing environmental impact while maximizing effectiveness. China's approach involves integrating nanotechnology to address challenges in soil fertility and crop protection [92]. China's approach involves utilizing nanoparticles like zinc oxide and silica to enhance nutrient absorption, mitigate soil degradation, and improve overall crop health. The use of nanomaterials in nanofertilizers improves nutrient release and absorption by plants, which increases agricultural productivity. Table 2 suggests that PGPR-mediated heavy metal bioremediation involves nanomaterials [92].

Table 2. PGPR-mediated heavy metal bioremediation.

Species	Participating Plant	Metals	Role of PGPR	References
Brevundimonas Diminuta	ScripusMucronatus	Mercury	Soil toxicity decreased; Enhanced phytoremediation	Mishra et al., 2016 [93]
Rhizobium sp., *Microbacterium* sp.	Pisum sativum	Chromium (VI)	Reduced chromium toxicity; Increased plant nitrogen concentration	Mishra et al., 2016 [93]

Table 2. *Cont.*

Species	Participating Plant	Metals	Role of PGPR	References
Bacillus megaterium	Brassica napus	Lead	Reducing soil contamination; Maximizing plant dry-matter output	Reichman, 2014 [94]
Mesorhizobiumhuakuii subsp. *rengei B3*	Tomato	Cadmium	Increased PCSAt gene expression enhances cell Cd2 binding.	Sriprang, 2003 [95]
Azotobacter chroococcum HKN-5, Bacillus megaterium HKP-1, B. mucilaginosus HKK-1	Brassica juncea	Lead, zinc	Promoted plant development and shielded it from metal toxicity.	Wu et al., 2006 [96]

Renowned for technological innovations, Japan explores nanotechnology to bolster sustainable agriculture. Nanomaterials, such as carbon nanoparticles and nanostructured materials, enhance seed germination, root development, and nutrient absorption [97]. Japan's focus on smart nanomaterials enables precise and efficient delivery of agricultural inputs, responding dynamically to environmental cues and ensuring optimal plant growth.

The combination of PGPR and this sophisticated use of nanomaterials shows tremendous promise [98]. This interplay is crucial for agricultural nutrient absorption, disease detection, and increasing organismal tolerance to environmental and biological challenges [99]. Deliberately altering an organism's genetic material, usually DNA, is genetic manipulation, which is identical to genetic engineering. Genetic engineering enhances the favorable characteristics of strains in PGPR [100]. By carefully changing the bacterial genome, scientists can change many genes at once. This can help the bacteria make chemicals that help them grow, deal with stress, or use nutrients better [99]. You can manipulate the genetic composition of PGPR strains using techniques like CRISPR-Cas9, which permits specific modifications in bacterial DNA. By strategically integrating nanomaterials, the synergistic benefits of nanotechnology and PGPR may increase the overall efficacy of agriculture. The use of nanoparticles as delivery vehicles allows for the precise distribution of chemicals generated by PGPR to the roots of plants [101]. When you combine nanomaterials like nano-fertilizers with PGPR-enhanced nutrient availability, you can achieve the most out of absorption by controlling the release of nutrients.

Smart nanomaterials respond instantly to environmental changes, such as changes in humidity, temperature, pH, or specific compounds [101]. These materials can adapt to various conditions, such as drought, by releasing chemicals like PGPR precisely when and where they are detected. Smart nanoparticles can precisely target the distribution of growth-promoting chemicals with minimal impact on the surrounding environment due to their adaptability. Complex systems that detect their environment, convey messages, and prohibit unauthorized access are the basis of intelligent nanomaterials' responses [90]. In reaction to environmental signals, PGPR may integrate with plant roots after detection via a controlled release. By incorporating feedback loops into specific systems, they may continuously adjust to new conditions, maximizing advantages while minimizing unnecessary application dangers. By utilizing nanotechnology and genetic engineering, the developed world demonstrates its commitment to improving agricultural practices. We can revolutionize global food production if we band together. Like in India, this may make it more efficient, eco-friendly, and capable of meeting the demands of a growing population.

7. Conclusions and Future Prospects

PGPR brings about positive developments in sustainable agriculture through processes such as phytohormone synthesis, nitrogen fixation, phosphate solubilization, and the biocontrol of plant diseases. Researchers have extensively studied the positive impacts of PGPR on many crops. These benefits include accelerated root and shoot growth rates, improved nutrient absorption, and enhanced tolerance to biotic and abiotic stresses. In view of the changing climate and limited resources, the ability of PGPR to improve plant development under harsh circumstances, such as drought and salinity, is very important.Final thoughts: PGPR is a promising plant growth enhancer for sustainable agriculture; fewer chemical inputs might lead to higher harvests. Further field research and testing must be conducted to completely discover the potential of PGPR and develop feasible, widespread applications. Eco-friendly PGPR approaches that significantly enhance plant growth and increase crop yields are now achievable due to these improvements.

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References

1. Edward Paice. By 2050, a Quarter of the World's People Will Be African—This Will Shape Our Future. 2022. Available online: https://www.theguardian.com/global-development/2022/jan/20/by-2050-a-quarter-of-the-worlds-people-will-be-african-this-will-shape-our-future (accessed on 20 January 2023).
2. United Nations. 2019. Available online: https://www.un.org/development/desa/news/population/world-population-prospects-2019.html (accessed on 10 June 2020).
3. Kumar, A.; Maurya, B.R.; Raghuwanshi, R.; Meena, V.S.; Islam, M.T. Co-inoculation with Enterobacter and Rhizobacteria on Yield and Nutrient Uptake by Wheat (*Triticum aestivum* L.) in the Alluvial Soil Under Indo-Gangetic Plain of India. *J. Plant Growth Regul.* **2017**, *36*, 608–617. [CrossRef]
4. Lipper, L.; Thornton, P.; Campbell, B.M.; Baedeker, T.; Braimoh, A.; Bwalya, M.; Caron, P.; Cattaneo, A.; Garrity, D.; Henry, K.; et al. Climate-smart agriculture for food security. *Nat. Clim. Change* **2014**, *4*, 1068–1072. [CrossRef]
5. Pareek, A.; Dhankher, O.P.; Foyer, C.H. *Mitigating the Impact of Climate Change on Plant Productivity and Ecosystem Sustainability*; Oxford University Press: Oxford, UK, 2020. [CrossRef]
6. Gupta, B.; Huang, B. Mechanism of Salinity Tolerance in Plants: Physiological, Biochemical, and Molecular Characterization. *Int. J. Genom.* **2014**, *2014*, 701596. [CrossRef]
7. Osakabe, Y.; Osakabe, K.; Shinozaki, K.; Tran, L.S.P. Response of plants to waters tress. *Front. Plant Sci.* **2014**, *5*, 86. [CrossRef] [PubMed]
8. Khatoon, Z.; Huang, S.; Rafique, M.; Fakhar, A.; Kamran, M.A.; Santoyo, G. Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. *J. Environ. Manag.* **2020**, *273*, 111118. [CrossRef] [PubMed]
9. De Andrade, L.A.; Santos, C.H.B.; Frezarin, E.T.; Sales, L.R.; Rigobelo, E.C. Plant growth-promoting rhizobacteria for sustainable agricultural production. *Microorganisms* **2023**, *11*, 1088. [CrossRef] [PubMed]
10. He, Y.; Pantigoso, H.A.; Wu, Z.; Vivanco, J.M. Co-inoculation of *Bacillus* sp. and *Pseudomonas putida* at different development stages acts as a biostimulant to promote growth, yield and nutrient uptake of tomato. *J. Appl. Microbiol.* **2019**, *127*, 196–207. [CrossRef] [PubMed]
11. Calvo, P.; Nelson, L.; Kloepper, J.W. Agricultural uses of plant biostimulants. *Plant Soil* **2014**, *383*, 3–41. [CrossRef]
12. Mohammadipanah, F.; Dehhaghi, M. Classification and Taxonomy of *Actinobacteria*. In *Biology and Biotechnology of Actinobacteria*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 51–77.
13. Hassanisaadi, M.; Bonjar, G.H.S.; Hosseinipour, A.; Abdolshahi, R.; Barka, E.A.; Saadoun, I. Biological Control of *Pythium aphanidermatum*, the Causal Agent of Tomato Root Rotby Two *Streptomyces* Root Symbionts. *Agronomy* **2021**, *11*, 846. [CrossRef]
14. Backer, R.; Rokem, J.S.; Ilangumaran, G.; Lamont, J.; Praslickova, D.; Ricci, E.; Subramanian, S.; Smith, D.L. Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Front. Plant Sci.* **2018**, *9*, 1473. [CrossRef]
15. Lyu, D.; Zajonc, J.; Pagé, A.; Tanney, C.A.; Shah, A.; Monjezi, N.; Msimbira, L.A.; Antar, M.; Nazari, M.; Backer, R.; et al. Plant holobiont theory: The phytomicrobiome plays a central role in evolution and success. *Microorganisms* **2021**, *9*, 675. [CrossRef] [PubMed]

16. Kloepper, J.W.; Schippers, B.; Bakker, P.A.H.M. Proposed elimination of the term endorhizosphere. *Phytopathology* **1992**, *82*, 726–727.
17. Saravanan, V.; Kumar, M.R.; Sa, T. Microbial zinc solubilization and their role on plants. In *Bacteria in Agrobiology: Plant Nutrient Management*; Maheshwari, D., Ed.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 47–63. [CrossRef]
18. VanPeer, R.; Schippers, B. Plant growth responses to bacterization with selected *Pseudomonas* spp. strains and rhizosphere microbial development in hydroponic cultures. *Can. J. Microbiol.* **1989**, *35*, 456–463.
19. Lazarovits, G.; Nowak, J. Rhizobacteria for improvement of plant growth and establishment. *HortScience* **1997**, *32*, 188–192. [CrossRef]
20. Miao, G.; Jianjiao, Z.; Entao, W.; Qian, C.; Jing, X.; Jianguang, S. Multiphasic characterization of a plant growth promoting bacterial strain, *Burkholderia* sp. 7016 and its effect on tomato growth in the field. *J. Integr. Agric.* **2014**, *14*, 1855–1863.
21. Vacheron, J.; Desbrosses, G.; Bouffaud, M.-L.; Touraine, B.; Moënne-Loccoz, Y.; Muller, D.; Legendre, L.; Wisniewski-Dyé, F.; Prigent-Combaret, C. Plant growth-promoting rhizobacteria and root system functioning. *Front. Plant Sci.* **2013**, *4*, 356. [CrossRef] [PubMed]
22. Liu, X.M.; Feng, Z.B.; Zhang, F.D.; Zhang, S.Q.; He, X.S. Preparation and testing of cementing and coating nano-subnanocomposites of slow/controlled-release fertilizer. *Agric. Sci. China* **2006**, *5*, 700–706. [CrossRef]
23. Gupta, G.; Parihar, S.S.; Ahirwar, N.K.; Snehi, S.K.; Singh, V. Plant growth promoting rhizobacteria (PGPR): Current and future prospects for development of sustainable agriculture. *J. Microb. Biochem. Technol.* **2015**, *7*, 96–102.
24. Shah, A.; Nazari, M.; Antar, M.; Msimbira, L.A.; Naamala, J.; Lyu, D.; Rabileh, M.; Zajonc, J.; Smith, D.L. PGPR in agriculture: A sustainable approach to increasing climate change resilience. *Front. Sustain. Food Syst.* **2021**, *5*, 667546. [CrossRef]
25. Alori, E.T.; Dare, M.O.; Babalola, O.O. Microbial inoculants for soil quality and plant health. In *Sustainable Agriculture Reviews*; Lichtfouse, E., Ed.; Springer: Cham, Switzerland, 2017; pp. 281–307. [CrossRef]
26. Bouchet, A.-S.; Laperche, A.; Bissuel-Belaygue, C.; Snowdon, R.; Nesi, N.; Stahl, A. Nitrogen use efficiency in rapeseed: A review. *Agron. Sustain. Dev.* **2016**, *36*, 38. [CrossRef]
27. Babalola, O.O. Beneficial bacteria of agricultural importance. *Biotechnol. Lett.* **2010**, *32*, 1559–1570. [CrossRef] [PubMed]
28. Pérez-Montaño, F.; Alías-Villegas, C.; Bellogín, R.; DelCerro, P.; Espuny, M.; Jiménez-Guerrero, I.; López-Baena, F.J.; Olero, F.J.; Cubo, T. Plant growth promotion in cereal and leguminous agricultural important plants: From microorganism capacities to crop production. *Microbiol. Res.* **2014**, *169*, 325–336. [CrossRef]
29. Moura, R.T.D.A.; Garrido, M.D.S.; Sousa, C.D.S.; Menezes, R.S.C.; Sampaio, E.V.D.S.B. Comparison of methods to quantify soil microbial biomass carbon. *Acta Sci. Agron.* **2018**, *40*, 39451. [CrossRef]
30. Hillel, D. Soil biodiversity. In *Soil in the Environment*; Hillel, D., Ed.; Academic Press: San Diego, CA, USA, 2008; pp. 163–174. [CrossRef]
31. Anand, K.; Kumari, B.; Mallick, M.A. Phosphate solubilizing microbes: An effective and alternative approach as bio-fertilizers. *Int. J. Pharm. Sci.* **2016**, *8*, 37–40.
32. Khan, A.A.; Jilani, G.; Akhtar, M.S.; Naqvi, S.M.S.; Rasheed, M. Phosphorus solubilizing bacteria: Occurrence, mechanisms and their role in crop production. *J. Agric. Biol. Sci.* **2009**, *1*, 48–58.
33. Adesemoye, A.O.; Kloepper, J.W. Plant–microbes interactions in enhanced fertilizer-use efficiency. *Appl. Microbiol. Biotechnol.* **2009**, *85*, 1–12. [CrossRef]
34. Bechtaoui, N.; Raklami, A.; Benidire, L.; Tahiri, A.-I.; Göttfert, M.; Oufdou, K. Effects of PGPR co-inoculation on growth, phosphorus nutrition and phosphatase/phytase activities of faba bean under different phosphorus availability conditions. *Pol. J. Environ. Stud.* **2020**, *29*, 1557–1565. [CrossRef]
35. Heydari, A.; Misaghi, I.J.; Balestra, G. Pre-emergence herbicides influence the efficacy of fungicides in controlling cotton seedling damping-off in the field. *Int. J. Agric. Res.* **2007**, *2*, 1049–1053. [CrossRef]
36. Riaz, U.; Murtaza, G.; Anum, W.; Samreen, T.; Sarfraz, M.; Nazir, M.Z. Plant growth-promoting rhizobacteria (PGPR) as biofertilizers and biopesticides. In *Microbiota and Biofertilizers: A Sustainable Continuum for Plant and Soil Health*; Hakeem, K.R., Dar, M.G.H., Eds.; Springer: Berlin/Heidelberg, Germany, 2021.
37. Parmar, P.; Sindhu, S.S. Potassium solubilization by rhizosphere bacteria: Influence of nutritional and environmental conditions. *J. Microbial. Res.* **2013**, *3*, 25–31.
38. Archana, D.; Nandish, M.; Savalagi, V.; Alagawadi, A. Screening of potassium solubilizing bacteria (KSB) for plant growth promotional activity. *Bioinfolet-A Q. J. Life Sci.* **2012**, *9*, 627–630.
39. Setiawati, T.C.; Mutmainnah, L. Solubilization of potassium containing mineral by microorganisms from sugarcane rhizosphere. *Agric. Agric. Sci. Proc.* **2016**, *9*, 108–117. [CrossRef]
40. Prajapati, K.; Sharma, M.; Modi, H. Growth promoting effect of potassium solubilizing microorganisms on Abelmoscus esculantus. *Int. J. Agric. Sci.* **2013**, *3*, 181–188.
41. Khan, N.; Bano, A.; Rahman, M.A.; Guo, J.; Kang, Z.; Babar, M.A. Comparative physiological and metabolic analysis reveals a complex mechanism involved in drought tolerance in chickpea (*Cicer arietinum* L.) induced by PGPR and PGRs. *Sci. Rep.* **2019**, *9*, 2097. [CrossRef] [PubMed]
42. Tian, F.; Ding, Y.; Zhu, H.; Yao, L.; Du, B. Genetic diversity of siderophore-producing bacteria of tobacco rhizosphere. *Brazil. J. Microbiol.* **2009**, *40*, 276–284. [CrossRef]

43. Khoshru, B.; Mitra, D.; Khoshmanzar, E.; Myo, E.M.; Uniyal, N.; Mahakur, B.; Das Mohapatra, P.K.; Panneerselvam, P.; Boutaj, H.; Alizadeh, M.; et al. Current scenario and future prospects of plant growth-promoting rhizobacteria: An economic valuable resource for the agriculture revival under stressful conditions. *J. Plant Nutr.* **2020**, *43*, 3062–3092. [CrossRef]
44. Shanmugaiah, V.; Nithya, K.; Harikrishnan, H.; Jayaprakashvel, M.; Balasubramanian, N. Biocontrol mechanisms of siderophores against bacterial plant pathogens. *Sustain. Approach. Control. Plant Pathog. Bact.* **2015**, *24*, 167–190.
45. Goswami, D.; Thakker, J.N.; Dhandhukia, P.C. Portraying mechanics of plant growth promoting rhizobacteria (PGPR): A review. *Cogent Food Agric.* **2016**, *2*, 1127500. [CrossRef]
46. Rezanka, T.; Palyzová, A.; Sigler, K. Isolation and identification of siderophores produced by cyanobacteria. *Folia Microbiol.* **2018**, *63*, 569–579. [CrossRef] [PubMed]
47. Czarnes, S.; Mercier, P.; Lemoine, D.G.; Hamzaoui, J.; Legendre, L. Impact of soil water content on maize responses to the plant growth-promoting rhizobacterium *Azospirillum lipoferum* CRT1. *J. Agron. Crop. Sci.* **2020**, *206*, 505–516. [CrossRef]
48. Goteti, P.K.; Emmanuel, L.D.A.; Desai, S.; Shaik, M.H.A. Prospective Zinc Solubilising Bacteria for Enhanced Nutrient Uptake and Growth Promotion in Maize (*Zea mays* L.). *Int. J. Microbiol.* **2013**, *2013*, 869697. [CrossRef]
49. Vaid, S.K.; Kumar, B.; Sharma, A.; Shukla, A.; Srivastava, P. Effect of Zn solubilizing bacteria on growth promotion and Zn nutrition of rice. *J. Soil Sci. Plant Nutr.* **2014**, *14*, 889–910. [CrossRef]
50. UmairHassan, M.; Aamer, M.; UmerChattha, M.; Haiying, T.; Shahzad, B.; Barbanti, L.; Nawaz, M.; Rasheed, A.; Afzal, A.; Liu, Y.; et al. The critical role of zinc in plants facing the drought stress. *Agriculture* **2020**, *10*, 396. [CrossRef]
51. FAO. *Human Vitamin and Mineral Requirements. Bangkok: Food and Agriculture Organization of the United Nations*; FAO: Rome, Italy, 2002.
52. Lopes, M.J.S.; Dias-Filho, M.B.; Gurgel, E.S.C. Successful Plant Growth-Promoting Microbes: Inoculation Methods and Abiotic Factors. *Front. Sustain. Food Syst.* **2021**, *5*, 606454. [CrossRef]
53. Kamran, S.; Shahid, I.; Baig, D.N.; Rizwan, M.; Malik, K.A.; Mehnaz, S. Contribution of Zinc Solubilizing Bacteria in Growth Promotion and Zinc Content of Wheat. *Front. Microbiol.* **2017**, *8*, 2593. [CrossRef] [PubMed]
54. Vejan, P.; Abdullah, R.; Khadiran, T.; Ismail, S.; Nasrulhaq, B.A. Role of plant growth promoting rhizobacteria in agricultural sustainability—A review. *Molecules* **2016**, *21*, 573. [CrossRef]
55. Baharlouei, J.; Pazira, E.; Khavazi, K.; Solhi, M. Evaluation of inoculation of plant growth-promoting rhizobacteria on cadmium uptake by canola and barley. *Int. Conf. Environ. Sci. Techol.* **2011**, *2*, 28–32.
56. Haggag, W.M.; Abouziena, H.F.; Abd-El-Kreem, F.; El Habbasha, S. Agriculture biotechnology for management of multiple biotic and abiotic environmental stress in crops. *J. Chem. Pharm. Res.* **2015**, *7*, 882889.
57. Kumar, H.; Bajpai, V.K.; Dubey, R.C. Wilt disease management and enhancement of growth and yield of *Cajanus cajan* (L) var. Manak by bacterial combinations amended with chemical fertilizer. *Crop Protect.* **2010**, *29*, 591–598. [CrossRef]
58. Santoro, M.V.; Bogino, P.C.; Nocelli, N.; Cappellari, L.R.; Giordano, W.F.; Banchio, E. Analysis of plant growth-promoting effects of fluorescent Pseudomonas strains isolated from Mentha piperita rhizosphere and effects of their volatile organic compounds on essential oil composition. *Front. Microbiol.* **2016**, *7*, 198824. [CrossRef] [PubMed]
59. Sanlibaba, P.; Cakmak, G.A. Exopolysaccharides production by lactic acid bacteria. *Appl. Microbiol.* **2016**, *2*, 1–5. [CrossRef]
60. Mahmood, S.; Daur, I.; Al-Solaimani, S.G.; Ahmad, S.; Madkour, M.H.; Yasir, M.; Hirt, H.; Ali, S.; Ali, Z. Plant growth promoting rhizobacteria and silicon synergistically enhance salinity tolerance of mung bean. *Front. Plant Sci.* **2016**, *7*, 876. [CrossRef] [PubMed]
61. Ulloa-Ogaz, A.L.; Munoz-Castellanos, L.N.; Nevarez-Moorillon, G.V. Biocontrol of phytopathogens: Antibiotic production as mechanism of control, the battle against microbial pathogens. In *Basic Science, Technological Advance and Educational Programs 1*; Mendez Vilas, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 305–309.
62. Fouzia, A.; Allaoua, S.; Hafsa, C.; Mostefa, G. Plant growth promoting and antagonistic traits of indigenous *fluorescent pseudomonas* spp. isolated from wheat rhizosphere and *A. halimus endosphere*. *Eur. Sci. J.* **2015**, *11*, 129–148.
63. Damam, M.; Kaloori, K.; Gaddam, B.; Kausar, R. Plant growth promoting substances (phytohormones) produced by rhizobacterial strains isolated from the rhizosphere of medicinal plants. *Int. J. Pharm. Sci. Rev.* **2016**, *37*, 130–136.
64. Antar, M.; Gopal, P.; Msimbira, L.A.; Naamala, J.; Nazari, M.; Overbeek, W.; Backer, R.; Smith, D.L. Inter-organismal signaling in the rhizosphere. In *Rhizosphere Biology: Interactions Between Microbes and Plants*; Springer: Singapore, 2021; pp. 255–293. [CrossRef]
65. Nath, D.; Maurya, B.R.; Meena, V.S. Documentation of five potassium-and phosphorus-solubilizing bacteria for their K and P-solubilization ability from various minerals. *Biocatal. Agric. Biotechnol.* **2017**, *10*, 174181. [CrossRef]
66. Etesami, H.A.; Alikhani, H.A.; Akbari, A.A. Evaluation of plant growth hormones production (IAA) ability by Iranian soils rhizobial strains and effects of superior strains application on wheat growth indexes. *World Appl. Sci. J.* **2009**, *6*, 15761584.
67. Kumar, A.; Kumar, A.; Pratush, A. Molecular diversity and functional variability of environmental isolates of *Bacillus* species. *SpringerPlus* **2014**, *3*, 312. [CrossRef]
68. Fenta, L.; Assefa, F. Isolation and characterization of phosphate solubilizing bacteria from tomato rhizosphere and their effect on growth and phosphorus uptake of the host plant under greenhouse experiment. *Int. J. Adv. Res.* **2017**, *3*, 2320–5407.
69. Lemessa, F.; Zeller, W. Screening rhizobacteria for biological control of *Ralstonia solanacearum* in Ethiopia. *Biol. Cont.* **2007**, *42*, 336–344. [CrossRef]
70. Council, I.G. *Five-Year Baseline Projections of Supply and Demand for Wheat, Maize (Corn), Rice and Soyabeans to 2023/24*; International Grains Council: London, UK, 2019.

71. FAOSTAT Food Balance Sheets. 2020. Available online: http://www.fao.org/faostat/en/#data/FBS (accessed on 24 April 2020).
72. Kuan, K.B.; Othman, R.; Rahim, K.A.; Shamsuddin, Z.H. Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilisation of maize under greenhouse conditions. *PLoS ONE* **2016**, *11*, e0152478. [CrossRef]
73. Pereira, P.; Ibàñez, F.; Rosenblueth, M.; Etcheverry, M.; Martínez-Romero, E. Analysis of the bacterial diversity associated with the roots of maize (*Zea mays* L.) through culture-dependent and culture-independent methods. *ISRN Ecol.* **2011**, *10*, 938546. [CrossRef]
74. Bevivino, A.; Sarrocco, S.; Dalmastri, C.; Tabacchioni, S.; Cantale, C.; Chiarini, L. Characterization of a free-living maize-rhizosphere population of Burkholderia cepacia: Effect of seed treatment on disease suppression and growth promotion of maize. *FEMS Microbiol. Ecol.* **1998**, *27*, 225–237. [CrossRef]
75. Zhao, D.L.; Li, Y.R. Climate change and sugarcane production: Potential impact and mitigation strategies. *Int. J. Agron.* **2015**, *2015*, 1–10. [CrossRef]
76. Zuo, Y.; Zhang, F. Soil and crop management strategies to prevent iron deficiency in crops. *Plant Soil* **2011**, *339*, 83–95. [CrossRef]
77. Mohanram, S.; Kumar, P. Rhizosphere microbiome: Revisiting the synergy of plant-microbe interactions. *Ann. Microbiol.* **2019**, *69*, 307–320. [CrossRef]
78. Zhang, X.; Baars, O.; Morel, F.M. Genetic, structural, and functional diversity of low and high-affinity siderophores in strains of nitrogen fixing *Azotobacter chroococcum*. *Metallomics* **2019**, *11*, 201–212. [CrossRef] [PubMed]
79. Lucy, M.; Reed, E.; Glick, B.R. Applications of free living plant growth-promoting rhizobacteria. *Antonie Van Leeuwenhoek* **2004**, *86*, 1–25. [CrossRef] [PubMed]
80. Hashami, S.Z.; Nakamura, H.; Ohkama-Ohtsu, N.; Kojima, K.; Djedidi, S.; Fukuhara, I.; Haidari, M.D.; Sekimoto, H.; Yokoyama, T. Evaluation of immune responses induced by simultaneous inoculations of soybean (Glycine max [L.] Merr.) with soil bacteria and rhizobia. *Microbes Environ.* **2019**, *34*, 64–75. [CrossRef] [PubMed]
81. Abdeljalil, N.O.B.; Vallance, J.J.; Gerbore, J.; Rey, P.P.; Daami-Remadi, M. Bio-suppression of Sclerotinia stem rot of tomato and biostimulation of plant growth using tomato-associated rhizobacteria. *J. Plant. Pathol. Microbiol.* **2016**, *7*, 2. [CrossRef]
82. Tahir, H.A.; Gu, Q.; Wu, H.; Raza, W.; Hanif, A.; Wu, L.; Gao, X. Plant growth promotion by volatile organic compounds produced by Bacillus subtilis SYST2. *Front. Microbiol.* **2017**, *8*, 171. [CrossRef]
83. Sharma, S.; Chen, C.; Navathe, S.; Chand, R.; Pandey, S.P. A halotolerant growth promoting rhizobacteria triggers induced systemic resistance in plants and defends against fungal infection. *Sci. Rep.* **2019**, *9*, 4054. [CrossRef]
84. Cheng, K.Y.; Karthikeyan, R.; Wong, J.W. Microbial electrochemical remediation of organic contaminants: Possibilities and perspective. *Microb. Electrochem. Technol.* **2019**, *25*, 613–640. [CrossRef]
85. Manzoor, M.; Gul, I.; Ahmed, I.; Zeeshan, M.; Hashmi, I.; Amin, B.A.Z.; Kallerhoff, J.; Arshad, M. Metal tolerant bacteria enhanced phytoextraction of lead by two accumulator ornamental species. *Chemosphere* **2019**, *227*, 561–569. [CrossRef] [PubMed]
86. Syers, J.; Johnston, A.; Curtin, D. Efficiency of soil and fertilizer phosphorus use. *FAO Fertil. Plant Nutr. Bull.* **2008**, *18*, 5–50.
87. Spolaor, L.T.; Gonçalves, L.S.A.; Santos, O.J.A.P.D.; Oliveira, A.L.M.D.; Scapim, C.A.; Bertagna, F.A.B.; Kuki, M.C. Plant growth-promoting bacteria associated with nitrogen fertilization at topdressing in popcorn agronomic performance. *Bragantia* **2016**, *75*, 33–40. [CrossRef]
88. Rosa, P.A.L.; Mortinho, E.S.; Jalal, A.; Galindo, F.S.; Buzetti, S.; Fernandes, G.C.; BarcoNeto, M.; Pavinato, P.S.; TeixeiraFilho, M.; Carvalho, M. Inoculation with growth-promoting bacteria associated with the reduction of phosphate fertilization in sugarcane. *Front. Environ. Sci.* **2020**, *8*, 32. [CrossRef]
89. Santos, R.M.; Kandasamy, S.; Rigobelo, E.C. Sugarcane growth and nutrition levels are differentially affected by the application of PGPR and cane waste. *Microbiologyopen* **2018**, *7*, e00617. [CrossRef]
90. Rani, R.; Bernela, M.; Malik, P.; Mukherjee, T. Chapter 9—Nanofertilizers Applications and Future Prospects. In *Nanotechonlogy: Principles and Applications*; Sindhu, R.K., Chitkara, M., Sandhu, S.I., Eds.; Jenny Stanford Publishing: Dubai, United Arab Emirates, 2020. [CrossRef]
91. Nayana, A.R.; Joseph, B.J.; Jose, A.; Radhakrishnan, E.K. Nanotechnological Advances with PGPR Applications. *Sustain. Agric. Rev.* **2020**, *41*, 163–180. [CrossRef]
92. Khanm, H.; Vaishnavi, B.A.; Shankar, A.G. Raise of Nano-fertilizer ERA: Effect of nano scale zinc oxide particles on the germination, growth and yield of tomato (*Solanum lycopersicum*). *Int. J. Curr. Microbiol. Appl. Sci.* **2018**, *7*, 1861–1871. [CrossRef]
93. Mishra, J.; Prakash, J.; Arora, N.K. Role of beneficial soil microbes in sustainable agriculture and environmental management. *Clim. Change Environ. Sustain.* **2016**, *4*, 137–149. [CrossRef]
94. Reichman, S.M. Probing the plant growth-promoting and heavy metal tolerance characteristics of *Bradyrhizobium japonicum* CB1809. *Eur. J. Soil Biol.* **2014**, *63*, 7–13. [CrossRef]
95. Sriprang, R.; Hayashi, M.; Ono, H.; Takagi, M.; Hirata, K.; Murooka, Y. Enhanced Accumulation of Cd^{2+} by a *Mesorhizobium* sp. Transformed with a Gene from Arabidopsis thaliana Coding for Phytochelatin Synthase. *Appl. Environ. Microbiol.* **2003**, *69*, 1791–1796. [CrossRef] [PubMed]
96. Wu, S.C.; Cheung, K.C.; Luo, Y.M.; Wong, M.H. Effects of inoculation of plant growth-promoting rhizobacteria on metal uptake by *Brassica juncea*. *Environ. Pol.* **2006**, *140*, 124–135. [CrossRef] [PubMed]
97. Siddiqui, M.H.; Al-Whaibi, M.H.; Mohammad, F. Nanotechnogy and Plant Sciences: Nanoparticles and Their Impact on Plants. *Nanotechnol. Plant Sci. Nanopart Impact Plants* **2015**, *10*, 1–303. [CrossRef]

98. Pacheco, A.; Moel, M.; Segrè, D. Costless metabolic secretions as drivers of interspecies interactions in microbial ecosystems. *Nat. Commun.* **2019**, *10*, 103. [CrossRef]
99. Shalaby, T.A.; Bayoumi, Y.; Abdalla, N.; Taha, H.; Alshaal, T.; Shehata, S.; Amer, M.; Domokos-Szabolcsy, É.; El-Ramady, H. Nanoparticles, soils, plant sand sustainable agriculture. In *Nanoscience in Food and Agriculture 1*; Springer: Cham, Switzerland, 2016; pp. 283–312.
100. Buzea, C.; Pacheco, I. Nanomaterials and their classification. In *EMR/ESR/EPR Spectros-Copy for Characterization of Nanomaterials*; Springer: New Delhi, India, 2017; pp. 3–45.
101. Yadav, T.P.; Yadav, R.M.; Singh, D.P. Mechanical milling: A Top down approach for synthesis of nanoparticles and nanocomposites. *Nanosci. Nanotechnol.* **2012**, *2*, 22–48. [CrossRef]