Review

Not peer-reviewed version

Microbial Biofertilizers in Plant Production and Resistance: A Review

Domenico Prisa *, Roberto Fresco, Damiano Spagnuolo

Posted Date: 26 July 2023

doi: 10.20944/preprints202307.1686.v1

Keywords: Microbial biofertilizers; microbial symbioses; plant interactions; crop resistance; plant stimulation; sustainable agriculture

Review

Microbial Biofertilizers in Plant Production and Resistance: A Review

Domenico Prisa [1*], Roberto Fresco [2] and Damiano Spagnuolo [3]

[1] CREA, Research Centre for Vegetable and Ornamental Crops, Via Dei Fiori 8, 51012 Pescia, Italy; domenico.prisa@crea.gov.it
[2] CREA, Research Centre for Engineering and Agri-food Transformation, Council for Agricultural Research and Economics, Via della Pascolare, 16, 00016 Monterotondo, Italy; roberto.fresco@crea.gov.it
[3] Department of Chemical, Biological, Pharmaceutical and Environmental Sciences,University of Messina, Salita Sperone 31, 98166 Messina, Italy; damiano.spagnuolo@unime.it
* Correspondence: domenico.prisa@crea.gov.it; Tel.: +39 0572 451033

Abstract: In sustainable agriculture, plant nutrients are the most important elements. Biofertilizers introduce microorganisms that improve the soil nutrients and increase their accessibility to crops. In order to meet the demands of a growing population, healthy crops need to be produced using the right type of fertilizers to provide them with all the major nutrients they require. However, an increasing dependency on chemical fertilizers is destroying the environment and negatively affecting the health of humans. Thus, using microbes as bioinoculants as the best replacement of chemical fertilizers as eco-friendly way for plant growth and soil fertility is believed to be the best method for improving plant growth and soil fertility. In sustainable agriculture, these microbes provide significant benefits to crops. In addition to colonizing plant systems (epiphytic, endophytic, and rhizospheric), beneficial microbes play a key role in absorbing nutrients from surrounding ecosystems. Plant associate microbes can promote plant growth regardless of natural and extreme conditions. Plant growth promoting microbes promote plant growth through a variety of direct and indirect methods, such as nitrogen fixation, plant growth hormone production, siderophores, HCN, several hydrolytic enzymes, and potassium, zinc, and phosphorus solubilization. Research on biofertilizers has been extensive and even available, which demonstrates how these microbes can deliver nutrients to crops in sufficient quantities to enhance their yield. This review examines in detail the direct and indirect mechanisms of PGPR action and their interaction in plant growth and resistance.

Keywords: microbial biofertilizers; microbial symbioses; plant interactions; crop resistance; plant stimulation; sustainable agriculture

1. Introduction

Rhizobacteria that supports plant growth are known as Plant Growth-Promoting Rhizobacteria (PGPR) [1,2]. The diversity of phenotypic and genotypic characteristics of soil microbiomes makes them complex and difficult to characterise [3]. However, as the rhizosphere has become increasingly important to the bio-sphere in recent years, several PGPRs have been identified that significantly have a great impact in plant growth, primarily because they act as an ecological unit [4]. The PGPRs affect plant growth by solubilising insoluble phosphates, fixing atmospheric nitrogen, and secreting hormones that control plant growth [5]. In addition, through induced systemic resistance (ISR), nutrient competition, antibiotics, parasitism, and suppression of rhizobacterial growth, PGPRs indirectly benefit plant growth [6]. These communities are very diverse, and their actions can take many forms, including antagonistic action against pathogens in the soil and inducing systemic resistance against pathogens throughout the plant [7]. Plants can be indirectly aided in growing by antagonistic rhizobacteria because they produce various substances that can control pathogens [8]. If the inducing bacteria and the challenging pathogen remain spatially separated, inducing systemic resistance (ISR) can be compared to pathogen-induced acquired systemic resistance (SAR). Different plant species have induced resistance that makes uninfected parts of the plant more resistant to

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 July 2023 doi:10.20944/preprints202307.1686.v1

pathogen attack [9]. Induction of resistance occurs by rhizobacteria either through salicylic acid-dependent SAR pathways or through the bacteria's perception of jasmonic acid and ethylene. Among the many characteristics of rhizobacteria are their antagonistic effects and ability to trigger inflammatory responses. Many studies have examined the use of PGPRs as a substitute for crop protection agents (fertilisers and pesticides) for plant growth promotion in recent years [10,11].The rhizobacteria can alter the soil structure, recycle essential elements, decompose organic matter, solubilise mineral nutrients, and serve as biocontrol agents for soil-borne and seed-borne pathogens [12–14]. A good understanding of rhizobacteria that promote plant growth and their interaction with bi-otic and abiotic factors is crucial to bioremediation techniques. This is also relevant for energy generation processes, and biotechnology industries, such as pharmaceutical, chemical and food industries [15]; rhizobacteria are also useful for reducing the use of chemical fertilisers. The main advantage of this approach is the increasing the productivity and sustainability of agricultural systems and soil fertility [16]. As a result, production costs are reduced, and the best soil and crop management practices are identified [17]. The aim of this review was to show the possible benefits of the application of rhizobacteria in plants, the direct and indirect mechanisms they influence, the possible applications of PGPR-based formulations in agriculture and the prospects of the use of rhizobacteria on crops.

2. Plant and Soil Effects of PGPRs

Rhizobacteria that promote plant growth are well known and essential, and this growth enhancement is due to rhizobacteria's characteristics [18]. PGPRs can enhance plant growth and development through various mechanisms [19]. In particular, rhizobacteria produce a variety of substances that alter the entire microbial community in the rhizosphere; and they are capable of supplying nutrients (nitrogen, phosphorus, potassium and essential minerals) or producing plant hormones [20]. For example, the inoculation of rhizobacteria in *Astrophytum* spp. grown in biochar-enriched substrates improves vegetative and root growth and plant flowering **(Figure 1)** [21]. By acting as biocontrol agents, environmental protectors, and root colonisers, PGPRs can also indirectly promote plant growth by reducing the effects of pathogens [22,23]. Sustainable agriculture and ecosystem stability are severely threatened by phytopathogenic microorganisms, which degrade soil fertility, alter the environment, and, ultimately, harm human health and contaminate groundwater [24]. By fixing nitrogen, mineralising organic compounds, solubilising mineral nutrients, and producing phytohormones, PGPRs also facilitate plant uptake of nutrients and increased the and increase resistance to biotic and abiotic stresses. Many species are able to survive particular environmental conditions, such as high temperatures and drought **(Table 1)** [25]. As an indirect means of achieving soil fertility and plant growth, PGPRs are crucial to a sustainable and ecological approach. This can be achieved through various mechanisms, including antibiotics, HCNs, siderophores, and hydrolytic enzymes, and as outlined before, PGPRs can be exploited to decrease the need for agrochemicals such as fertilisers and pesticides and increase soil fertility [26].

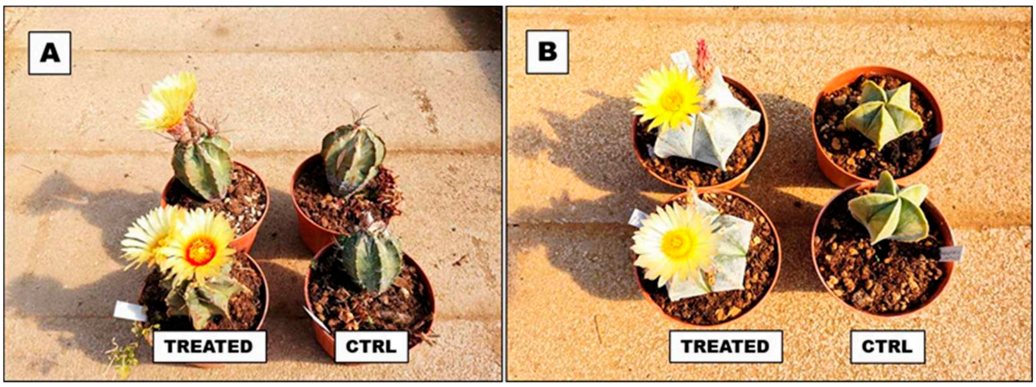

Figure 1. Increased vegetative growth and flowering in *Astrophytum capricorne* (A) and *Astrophytum myriostigma* (B) in plants supplemented with rhizobacteria on biochar substrate [21].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 July 2023 doi:10.20944/preprints202307.1686.v1

Table 1. Bacterial genera and species that are drought resistant [25].

Bacteria	Crop	Action Mechanism
Azospirillum sp.	Wheat	Highest amounts of N and auxin
Bacillus sp.	Grass	Responses of antioxidant system and early proline accumulation
Streptomyces sp.	*Tomato*	Increase the content of different sugars
Pseudomonas sp.	*Arabidopsis*	Higher ACC deaminase activity gibberellic acid, abscisic acid, indole acetic acid, and exopolysaccharide
Enterobacter sp.	*Bean*	Enhance proline, malondialdehyde, and antioxidant enzymes
Azospirillum brasilense	*Wheat*	Less accumulation of H_2O_2 with less enhanced production of proline and activities of catalase and peroxidase

3. Mechanisms Activated Directly by Plant Growth Promoting Rhizobacteria

In terms of plant growth, phytohormones play a critical role. These are plant hormones that affect the plant's response to its environment. These hormones are produced at one point in the plant and then transferred to another part of the plant, where they are used to promote the growth [1]. Roots and leaves grow due to the physical responses caused by these hormones [27]. Some essential plant hormones are auxins, gibberellins, ethylene, cytokinins, and abscisic acid [28]. Rhizobacteria produce these phytohormones. In addition to auxins and gibberellins, ethylene, cytokinins and abscisic acid are important phytohormones [29]. In plant roots and shoots, cytokinins (CKs) play a role in cell division [30]. Among their benefits, there is the growth of cells, differentiation of cells, apical dominance, axillary bud development, and leaf senescence [31,32]. Plants synthesise this hormone, but yeast strains and PGPR strains can also prepare it. As well as phytopathogens, some phytopathogens can synthesise cytokinins. It has been reported that *Azotobacter* species, *Pantoea agglomerans* strains, *Rhizobium* species, *Rhodospirillum rubrum* strains, *Bacillus subtilis* strains, *Pseudomonas fluorescens* strains, and *Paenibacillus polymyxa* species all produce the cytokinin hormone [33,34]. Some rhizobacteria are able by their action to mitigate the effect of different types of stress such as water, salt and heat stress **(Table 2)** [35]. A class of important plant hormones, gibberellins (GA) control various developmental processes in plants. Their functions include stem elongation, dormancy, germination, flowering, and flower development. Several cytokinin-producing polymeric protein receptors synthesise gibberellin, a phytohormone involved in breaking dormancy and other aspects of germination. Gibberellin is the most crucial phytohormone synthesised by some PGPRs. Production and regulation of gibberellin and cytokinin are extremely important [36]. PGPRs and plants produce a variety of phytohormones, including indoloacetic acid. In addition to cell division, other proprieties like gene expression, organogenesis, pigmentation, root development, seed germination, stress resistance, tropical responses, and photosynthesis, play an essential role in plant cellular responses [37]. Plants and bacteria influence the amount of IAAs required to promote plant growth vigorously. The amount of IAA required to promote plant growth depends on the plant and bacterial species. PGPRs produce indole-3-acetic acid, which is responsible for root elongation and the formation of roots. Nearly all plants produce ethylene as a growth hormone, which is key in many physiological changes [38]. Plants respond to biotic and abiotic stresses negatively, affecting root growth and plant growth [39]. The PGPR enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase can regulate ethylene production. Inoculation with PGPRs can maintain plant growth and development under stressful conditions, such as drought, salinity, cold, and soil pollution, plants synthesise abscisic acid [25]. This growth hormone activates stress-resistance genes. Abscissic acid producing strains, such as *Bacillus licheniformis* Rt4M10, *Azospirillum brasilense* sp. 245, and *Pseudomonas fluorescens* Rt6M10, increase the internal ABA content of plants. As a result, the plants

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 July 2023 doi:10.20944/preprints202307.1686.v1

become more resilient to drought. The unavailability of nitrogen can limit plant growth, but phosphorus is also essential for life [40]. There are large quantities of phosphate in soil, but they are in an insoluble form that plants cannot utilise for growth since they are insoluble. PGPRs can solubilise phosphate in soil via acidification, chelation or enzyme action [41]. For example, the PGPR *Gluconacetobacter diazotrophicus*, found in sugar cane, can solubilise phosphate by acidification [7].

Table 2. Application of Rhizobacteria in mitigating heat stress in plants [35].

Microbes	Plant	Parameters	Stress
Enterobacter SA187	*Arabidopsis thaliana*, Wheat plant	Increased Biomass, height, seed weight	Long term
Septoglomus deserticola	*Solanum Lycopersicum*	Improved stomatal conductance, water content	Heat Drought
Pseudomonas fluorescens, Pantoea agglomerans	*Triticum aestivum*	Increased Antioxidant enzymes	High Temp.
B. phytofirmans	*Solanum tuberosum*	Increased Proline and glycine betaine	High Temp.
B. cereus	*Soybean*	Increased Chlorophyll and Carotenoid	High Temp.

4. Mechanisms Indirectly Activated by Plant Growth-Promoting Rhizobacteria

Microorganisms compete for nutrients and colonisation sites in their natural environment fiercely. Various mechanisms of PGPR species have evolved that allow them to reduce competition by releasing antibiotics, lytic enzymes, or weak organic acids into their environments **(Figure 2)** [21,42]. As a result, PGPRs are valuable tools that can be used against plant pathogens. However, there is a possibility of the development of resistant pathogens if antibiotic-producing bacteria are used more frequently. It was shown that PGPR enzymes secreted by these PGPRs could eliminate pathogens such as *Botrytis cinerea*, *Fusarium oxysporum*, *Sclerotium rolfsii*, *Phytophthora* spp, *Pythium ultimum* and *Rhizoctonia solani* [43,44]. They include cellulases, chitinases, lipases and proteases secreted by the plant. Plants respond to pathogens in two ways: acquired systemic resistance and induced systemic resistance. Induced systemic resistance is the same as Systemic Acquired Resistance (SAR) [45]. Acquired systemic resistance is triggered by the infection of a plant by a pathogen, whereas PGPR triggers acquired systemic resistance. The application of PGPR inoculum induces systemic resistance in the plant against many bacterial pathogens. Plants also need iron as a nutrient. Under aerobic conditions, iron is found as Fe3+, which is not soluble for use by microorganisms and plants [46]. Therefore, microbes produce and secrete iron chelators, known as siderophores. The chelators are highly iron-adjacent. They function as iron solubilising agents under limiting conditions. In the cell, Fe^{3+} is transformed into Fe^{2+}, which is then released by the siderophores [47]. Rhizobacteria steal iron from other microorganisms by producing siderophores. In addition, PGPRs use siderophores to remove other heavy metals from soil and prevent the heavy metals from causing toxicity in plants. They can also be used for the bioremediation of heavy metal toxic soils [48]. As well as helping plants grow and ripen fruit, ethylene acts as a phytohormone in response to salt, drought or pathogenic bacteria. However, high amounts of ethylene can also cause plant harm. Many PGPR synthesises an ACC deaminase enzyme [49,50]. This enzyme destroys 1-aminocyclopropane-1-carboxylate, the precursor of ethylene. It relieves plant stress by reducing ethylene levels. Plant root surfaces can be colonised by harmful rhizobacteria that act as biocontrol agents for weeds. They produce toxic compounds known as cyanides, produced by many microorganisms, such as bacteria, algae, fungi and plants [51]. Biological weed control agents can be derived from host-specific rhizobacteria, which compete with their counterparts to survive. It has no negative impact on host plants when inoculated with cyanide-producing bacterial strains that produce cyanide [52]. In addition, weed biocontrol agents, such as hydro-gen cyanide, are produced, which inhibits the electron transport chain and energy supply to cells. Many harmful microbes compete with PGPRs for nutrients, but these nutrients are present only in trace amounts so that they can limit the disease's causative agent [53]. In fertile soils with abundant non-pathogenic microbes, they colonise plant surfaces quickly and utilise nutrients. These mechanisms can be challenging to study in the system because they inhibit pathogenic microbes from growing. One essential interaction that indirectly supports plant growth is the competition for nutrients between PGPR and pathogens [54].

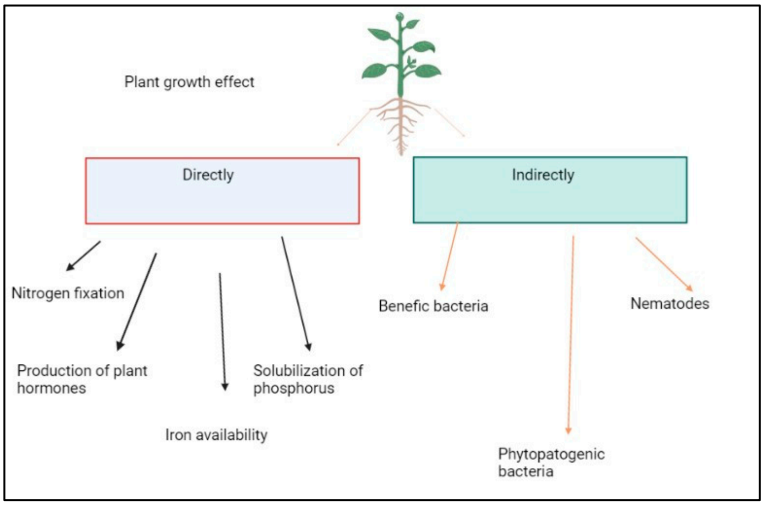

Figure 2. PGPB promotes plant growth through the production of siderophores, increasing iron availability, and producing hormones such as auxins, gibberellins, and cytokinin that modulate the hormone balance of the host plant. The direct mechanism includes biological nitrogen fixation (BNF) by the activity of the nitrogenase enzyme complex; the solubilization of inorganic phosphate in the soil; and the production of siderophores. The indirect mechanisms are attributed to PGPB's occupation of niches and the production of substances that repel phytopathogens and nematodes [21].

5. Preparation and Application of Commercial Biofertilizers

The use of sustainable technologies to improve the plant health has become a necessity due to a number of environmental issues, and biofertilizers play a crucial role in overcoming those issues. In light of this, it becomes apparent that biofertilizers are microbes that are vital to sustainable agriculture and play a crucial role in maintaining plant health by acting against pathogens as well as supporting plant growth by providing various nutrients and phytohormones. As a result of the preparation of these formulations, they remain viable while simultaneously enhancing soil fertility and productivity. The formulations are found to increase in number and activity more after being inoculated in the host plant [55]. Biofertilizer formulations that are effective should possess the following desirable characteristics, such as being environmentally friendly, not toxic to the environment, and biodegradable. In addition to permitting the addition of nutrients and pH adjustments, it should consist of low-cost raw materials that are readily available and easy to access, should have a long shelf life, and should be capable of maintaining metabolically viable high numbers under unfavorable conditions. In addition to liquid biofertilizers, peat-based formulations, granules, and freeze-dried powders, there are several types of commercial biofertilizers. As liquid formulations have been developed recently, they have gained popularity due to their ease of handling and ease of application on seeds and in soil [56]. As a result of their longer shelf life and ease of application compared to conventional solid carriers based inoculants, liquid biofertilizers offer a lot of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 July 2023 doi:10.20944/preprints202307.1686.v1

advantages over conventional solid carrier inoculants. These formulations allow the manufacturer to include adequate amounts of nutrients. Additionally, certain inducers can be added to help the formation of cells, spores, or cysts, thereby ensuring a longer shelf life [57], purity, easy identification, application, and maintenance [58]. In comparison to carrier-based powder fertilizers, liquid fertilizers require fewer doses and have a high export potential.

6. Formulated Biofertilizers: Application Methods

Biofertilizers that have been formulated can be applied to soil in a variety of ways, including inoculating seeds with dry fertilizer or liquid fertilizer [59]. The stimulation of plant growth and crop yield by beneficial plant growth promoting microbiomes either to decrease the use of agrochemicals or pollution caused by them has been assessed in a variety of studies both in greenhouses as well as in fields. As far as PGPR go, *Azospirillum* has been evaluated in several studies and is the top choice [60]. *Azospirillum* inoculants can be found in Europe and South Africa. It sells a variety of products, including barley, maize, sorghum, and wheat, based on *Azospirillum brasilense*. It is becoming increasingly common for companies to develop new products based on *Azospirillum* and other benefits. The positive results of *Azospirillum* are emphasized, but certain limitations remain to commercialize it, which may be the result of variations in results in field experiments. There are several reasons for the inconsistency of the results, including the physical and chemical conditions of the soil, fluctuations in pH, and the inoculated strain's inability to colonize roots. In addition, fluctuating temperatures and low rainfall during growing may also affect such variable results [61–63]. The support of crop management by beneficial microorganisms is an environmentally friendly alternative to the conventional techniques that are based on chemical inputs, with respect to the increasing consumer expectations of healthy products and current policies towards the implementation of environmentally friendly cropping systems [64]. Besides biotic stresses, useful microorganisms in agriculture have been shown to increase plant tolerance to abiotic stresses such as flooding, water shortages, and excess salinity [65]. Plant growth regulators of microbial origin are of great agrarian and ecological interest, since they offer significant opportunities for eco-friendly agronomic applications. As a result of selected strains, these regulators can also be used in the open field today, thus overcoming certain limitations. It is difficult to colonize the rhizosphere of an adult plant that is already well colonized by resident microorganisms due to high competition [66]. Soil type, temperature, introduced strains, inoculant density, and plant species can all influence the immediate response to PGPR soil administration. After inoculation, the introduced population typically drops rapidly, and it is possible that the number of PGPR colonizing roots is insufficient to achieve the desired results [67]. Other times, the introduced microorganisms cannot find a free ecological niche in the soil. As well as maintaining the desired character characteristics, the strains used must be capable of surviving the stresses associated with concentration and stabilisation processes during production. Agricultural crops can be inoculated in a variety of ways:

- covering the seed at the time of sowing;
- using confected seed, i.e. covered with matrices that have included beneficial microorganisms;
- distributing the product directly in the furrows at the time of sowing;
- performing covering treatments during plant growth.

Using seed inoculation allows farmers to sow and inoculate at the same time, thus saving time and money. Another option is to encapsulate microbial cells in polymers, particularly alginate, which protect them from environmental stress and allow them to be released into the soil slowly and in large quantities [68]. For example, alginate preparations have been proposed for *Pseudomonas fluorescens* as a biocontrol and biostimulating agent, and for *Azospirillum brasilense* as a biofertilizing and biostimulating agent [69].

7. The Role of Microbial Biofertilizers in Photosynthesis

Approximately 90% of plant biomass is derived from CO_2 assimilation [70], so plant growth depends on the rate of photosynthesis. According to Mia and Shamsuddin [71], rice plants inoculated with certain strains of *Rhizobia* showed a notable increase in their overall photosynthetic rate. Reactive oxygen species (ROS) are produced as a result of water deficits [72], which damage the photosynthetic apparatus. Under water stress conditions, Heidari and Golpayegani [72] evaluated the effect of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 July 2023 doi:10.20944/preprints202307.1686.v1

Pseudomonas sp., *Bacillus lentus*, and *Azospirillum brasilensis* on basil plant photosynthetic capacity and antioxidant activity. Researchers found that these strains decreased water stress by increasing the antioxidant, photosynthetic pigment, and chlorophyll content of leaves. Inoculating potatoes with Bacillus sp. under salt, drought, and heavy metal stress was studied by Gururani et al. [73]. It was clear from the study that these bacterial strains influenced the photochemistry of the plants positively, as indicated by the photosynthetic performance indices of inoculated plants. According to Cohen et al. [74], *Azospirillum brasilense* sp. 245 strain was used to inoculate *Arabidopsis thaliana* aba2-1 and Col-0 mutant plants with morphophysiological and biochemical responses. In addition to other parameters observed, the strain stimulated the formation of photosynthetic and photoprotective pigments. The photosynthetic machinery of the plants is boosted by biofertilizers so that they can grow and survive under stress conditions.

8. Biofortification with Microbial Biofertilizers

Micronutrients, such as iron, zinc, and magnesium, are crucial to improving productivity and human health in food crops. A lack of micronutrients in the soil, particularly Zn, is a major limiting factor in achieving maximum yields [75]. In developing countries, cereals are a major source of calories, but they also have a low zinc content because they are mostly grown in soils that lack zinc. Health problems related to zinc deficiency can result from cereal-based diets. There is evidence that most micronutrient deficiencies are associated with wheat and rice, which are dominantly consumed in many countries [75,76]. One strategy that may be effective in enhancing Fe and Zn uptake in the grains is the application of chemical fertilizers, but the disadvantage of using chemical fertilizers is that their micronutrient utilization effectiveness is very small (only 2–5%) [77]. Another advantageous strategy would be to utilize potential microbes for improving the nutrient efficiency of genotypes and fortifying the grains of different crops. The utilization of plant and soil microbiomes to increase micronutrient gaining has been demonstrated in several studies [78].

9. Perspectives on the Use of Microbial Biofertilizers in Agriculture

An essential and safe method to increase yield is PGPR. In terms of increasing productivity, it is a promising solution [79,80]. In addition, it protects plants from chemicals used to control pests, which can also have a negative impact on the environment. Plant diseases and pests can also be controlled with PGPRs, improving yields. In laboratory and greenhouse experiments, PGPR strains are advantageous [81,82]. The field of genetic engineering is emerging as a means to improve PGPR strains and explore their potential applications. Besides all these advances, some environmental barriers and adverse conditions greatly influence the activity of PGPRs [83]. Mixing of strains, use of improved inoculation techniques and transfer of the active gene source of antagonists to the host plant can improve the variable efficacy of PGPRs [84]. Furthermore, biocontrol agents need a specific ecological environment to grow and survive, so different conditions may influence their efficacy and use [58,85]. The efficacy of biocontrol agents can be modified by using compatible mixed inocula in different ecological niches. Besides these advantages, PGPRs face several challenges [86]. Due to natural variations, it is difficult to predict the behaviour of bacteria in the laboratory and on the farm. These variations can have a significant effect on the entire experiment. Plant type and season can also influence the propagation of PGPRs to recover their viability and biological activity [87,88]. According to the notion that these bacteria can be applied as biofertilisers in agriculture and forestry [89,90], monitoring their activity under stress conditions such as salinity, soil pollution and other environmental conditions that alter crop productivity and yield is essential to understand their applications in different sectors of agriculture. Soil moisture, electrical conductivity and N, P and K concentrations must be monitored under different climatic conditions and bacterial concentrations. This is important in order to develop real, concrete microbial application protocols suitable for different geographical locations.

7. Conclusions

There has been substantial progress in the field of using PGP microbes as biofertilizers and biopesticides worldwide. When members of different microbial types interact directly, various key processes occur that ultimately benefit plant growth and soil health. Number issues will, however, need to be addressed if PGP microbes are extensively utilized. Firstly, moving from laboratory and

 doi:10.20944/preprints202307.1686.v1

greenhouse to field trials will require a number of novel approaches, such as how to grow, store these microbes, as well as the proper facilities for shipping, formulating, and applying them. Furthermore, there is a well-known myth that microbes cause disease, so educating the public about the use of these microbes in agriculture on a large scale is essential. In order to make these beneficial microbes useful in the environment on a large scale, these misconceptions must be eliminated. Moreover, plants are exposed to various pathogens that lead to crop loss and the use of chemical pesticides for fighting diseases, which pose an array of environmental and health problems. In order to feed the emerging population, it is imperative to find alternative strategies that are eco-friendly. In the near future, biofertilizers will not only improve productivity and support the growth of plants during stressful conditions, but also provide a potential alternative to feed the emerging population. As a result, biofertilizers play a crucial role in modern agriculture, and it is crucial to recognize their importance. Rather than growing plants, sustainable agriculture should cultivate plant-microbial communities, which will ultimately result in high productivity with little energy and chemical investment and minimal environmental impact. In order to achieve sustainable microbial-based agro technologies, much more efforts and collaboration between experts in genetics, molecular biology, and ecology are needed.

Author Contributions: Conceptualization, D.P.; methodology, writing—original draft preparation D.P. and D.S.; software and investigation, R.F.; writing—review and editing, D.P.; funding acquisition, D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the CREA Research Centre for Vegetable and Ornamental Crops.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, tables, and figures in this manuscript are original.

Acknowledgments: The author would like to express his heartfelt gratitude to his colleagues at CREA Research Centre for Vegetable and Ornamental Crops in Pescia and to all other sources for their cooperation and guidance in writing this article.

Conflicts of Interest: The authors declare no conflict of interest

References

1. Basu, A.; Prasad, P.; Das, S.N.; Kalam, S.; Sayyed, R.Z. Plant Growth Promoting Rhizobacteria (PGPR) as Green Bioinoculants: Recent Developments, Constraints, and Prospects. Sustainability. **2021**, 13, 1140.
2. Camaille, M.; Fabre, N.; Clément, C.; Ait Barka, E. Advances in Wheat Physiology in Response to Drought and the Role of Plant Growth Promoting Rhizobacteria to Trigger Drought Tolerance. Microorganisms. **2021**, 9, 687.
3. Di Salvo, L.P.; Cellucci, G.C.; Carlino, M.E.; De Salamone, I.E.G. Plant growth-promoting rhizobacteria inoculation and nitrogen fertilization increase maize (*Zea mays* L.) grain yield and modified rhizosphere microbial communities. Appl. Soil Ecol. **2018**, 126, 113–120.
4. Ekinci, M.; Kocaman, A.; Argin, S.; Turan, M.; Dadaso-Glu, F. Rhizobacteria alleviate the adverse effects of salt stress on seedling growth of *Capsicum annuum* L. by modulating the antioxidant enzyme activity and mineral uptake. Taiwania. **2021**, 66, 287–297.
5. El-Sawah, A.; El-Keblawy, A.; Ali, D.; Ibrahim, H.; El-Sheikh, M. Arbuscular Mycorrhizal Fungi and Plant Growth-Promoting Rhizobacteria Enhance Soil Key Enzymes, Plant Growth, Seed Yield, and Qualitative Attributes of Guar. Agriculture. **2021**, 11, 194.
6. Emmanuel, O.C.; Babalola, O.O. Productivity and quality of horticultural crops through coinoculation of arbuscular mycorrhizal fungi and plant growth promoting bacteria. Microbiol. Res. **2020**, 239, 126569–126569.
7. Enebe M.C.; Babalola O.O. The influence of plant growth-promoting rhizobacteria in plant tolerance to abiotic stress: a survival strategy. Appl Microbiol Biotechnol. **2018**, 102, 7821–7835.
8. Forni, C.; Duca, D.; Glick, B.R. Mechanisms of plant response to salt and drought stress and their alteration by rhizobacteria. Plant Soil. **2017**, 410, 335–356.
9. Gouda, S.; Kerry, R.G.; Das, G.; Paramithiotis, S.; Shin, H.S. Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiol. Res. **2018**, 206, 131–140.
10. Grover, M.; Bodhankar, S.; Sharma, A.; Sharma, P.; Singh, J. PGPR mediated alterations in root traits: way toward sustainable crop production. Front Sustain. Food Syst. **2021**, 4, 39.
11. Kalsoom, M.; Rehman, F.; Shafique, T.; Junaid, S.; Khalid, N. Biological importance of microbes in Agriculture, Food and Pharmaceutical Industry: A Review. Innove. J. Life Sci. **2020**, 8, 1–4.

 doi:10.20944/preprints202307.1686.v1

12. Kenneth, O.C.; Nwadibe, E.C.; Kalu, A.U.; Unah, U.V. Plant growth promoting rhizobacteria (PGPR): A novel agent for sustainable food production. J. Agric. Biol. Sci. **2019**, 14, 35–54.
13. Khan, N.; Bano, A.; Shahid, M.A.; Nasim, W.; Babar, M.A. Interaction between PGPR and PGR for water conserva-tion and plant growth attributes under drought condition. Biologia. **2018**,73, 1083–1098.
14. Kumari, B.; Mallick, M.A.; Solanki, M.K.; Solanki, A.C.; Hora, A. Plant Growth Promoting Rhizobacteria (PGPR): Modern Prospects for Sustainable Agriculture. In Plant Health Under Biotic Stress, Springer: Singapore. 2019; pp. 109–127.
15. Oleńska, E.; Małek, W.; Wójcik, M.; Swiecicka, I.; Thijs, S. Beneficial features of plant growth-promoting rhizobacteria for improving plant growth and health in challenging conditions: A methodical review. Sci. Total Environ. **2020**, 743, 140682.
16. Poveda, J.; Gonzalez-Andres, F. *Bacillus* as a source of phytohormones for use in agriculture. Appl. Microbiol. Biotechnol. **2021**,105, 8629–8645.
17. Prasad, M.; Srinivasan, R.; Chaudhary, M.; Choudhary, M.; Jat, L.K. Plant growth promoting rhizobacteria (PGPR) for sustainable agriculture: perspectives and challenges. In PGPR Amelioration in Sustainable Agriculture, Woodhead Publishing. **2019**, 129–157.
18. Rehman, F.; Kalsoom, M.; Adnan, M.; Toor, M.D.; Zulfiqar, A. Plant Growth Promoting Rhizobacteria and their Mechanisms Involved in Agricultural Crop Production: A Review. -SunText Rev Biotechnol. **2020**, 1, 110.
19. Rehman, F.; Kalsoom, M.; Nasir, T.A.; Adnan, M.; Anwar, S. Chemistry of Plant–Microbe Interactions in Rhizosphere and Rhizoplane. Ind. J. Pure App. Biosci. **2020**, 8, 11–19.
20. Song, Q.; Song, X.S.; Deng, X.; Luo, J.Y.; Song, R.Q. Effects of plant growth promoting Rhizobacteria microbial on the growth, rhizosphere soil properties, and bacterial community of Pinus sylvestris var. mongolica seedlings. Scand J For Res. **2021**, 36, 249–262.
21. Prisa, D. Biochar effects in the growing and control of biotic and abiotic stress in *Astrophytum myriostigma* and *Astrophytum capricorne*. GSC Biological and Pharmaceutical Sciences. **2021**, 16, 186–194.
22. Tariq, M.; Noman, M.; Ahmed, T.; Hameed, A.; Manzoor, N. Antagonistic features displayed by plant growth promoting rhizobacteria (PGPR): a review. J. Plant Sci. Phytopathol. **2017**, 1, 38–43.
23. Ullah, N.; Ditta, A.; Imtiaz, M.; Li, X.; Jan, A.U. Appraisal for organic amendments and plant growth-promoting rhizobacteria to enhance crop productivity under drought stress: A review. J. Agron. Crop Sci. **2021**, 207, 783–802.
24. Wang, H.; Liu, R.J.; You, M.P.; Barbetti, M.J.; Chen, Y.L. Pathogen biocontrol using plant growth-promoting bacteria (PGPR): role of bacterial diversity. Microorganisms. **2021**, 9, 1988.
25. Abdelaal, K.; Alkahtani, M.; Attia, K.; Hafez, Y.; Király, L.; Künstler, A. The role of plant growth-promoting bacteria in alleviating the adverse effects of drought on plants. Biology. **2021**, 10, 520.
26. Zeng, Q.; Ding, X.; Wang, J.; Han, X.; Iqbal, H.M.N. Insight into soil nitrogen and phosphorus availability and agricultural sustainability by plant growth-promoting rhizobacteria. Environ. Sci. Pollut. Res. **2022**, 29, 45089–45106.
27. Dar, S.A.; Bhat, R.A.; Dervash, M.A.; Dar, Z.A. Azotobacter as biofertilizer for sustainable soil and plant health under saline environmental conditions. Microbiota and Biofertilizers. Springer. **2021**,4, 231–254.
28. Ghaffari, M.R.; Mirzaei, M.; Ghabooli, M.; Khatabi, B.; Wu, Y.; Zabet-Moghaddam, M.; Mohammadi-Nejad, G.; Haynes, P.A.; Hajirezaei, M.R.; Sepehri, M.; Salekdeh, G.H. Root endophytic fungus *Piriformospora indica* improves drought stress adaptation in barley by metabolic and proteomic reprogramming. Environ. Exp. Bot. **2019**, 157, 197–210.
29. Liu, G.Y.; Chen, L.L.; Shi, X.R.; Yuan, Z.Y.; Yuan, L.Y.; Lock, T.R.; Kallenbach, R.L. Changes in rhizosphere bacterial and fungal community composition with vegetation restoration in planted forests. Land Degrad. Dev. **2019**, 30, 1147–1157.
30. Dubey, A.; Malla, M.A.; Khan, F.; Chowdhary, K.; Yadav, S.; Kumar, A.; Sharma, S.; Khare, P.K.; Khan, M.L. Soil microbiome: a key player for conservation of soil health under changing climate. Biodivers. Conserv. **2019**, 28, 2405–2429.
31. Diagne, N.; Ndour, M.; Djighaly, P.I.; Ngom, D.; Ngom, M.C.N.; Ndong, G.; Svistoonoff, S.; Cherif-Silini, H. Effect of plant growth promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) on salt stress tolerance of *Casuarina obesa* (Miq.). Front. Sustain. Food Syst. **2020**, 4, 266.
32. Fadiji, A.E.; Babalola, O.O.; Santoyo, G.; Perazzolli, M. The potential role of microbial biostimulants in the amelioration of climate change-associated abiotic stresses on crops. Front. Microbiol. **2022**, 12, 829099.
33. Ramakrishna, W.; Yadav, R.; Li, K. Plant growth promoting bacteria in agriculture: Two sides of a coin. Appl. Soil Ecol. **2019**, 138, 10–18.
34. Chiappero, J.; Del Rosario Cappellari, L.; Alderete, L.G.S.; Palermo, T.B.; Banchio, E. Plant growth promoting rhizobacteria improve the antioxidant status in *Mentha piperita* grown under drought stress leading to an enhancement of plant growth and total phenolic content, Ind. Crops Prod. **2019**, 139, 111553.

35. Shaffique, S.; Khan, M.A.; Wani, S.H.; Pande, A.; Imran, M.; Kang, S.M.; Rahim, W.; Khan, S.A.; Bhatta, D.; Kwon, E.H. A Review on the Role of Endophytes and Plant Growth Promoting Rhizobacteria in Mitigating Heat Stress in Plants. Microorganisms. **2022**, 10, 1286.
36. Vorholt, J.A.; Vogel, C.; Carlström, C.I.; Müller, D.B. Establishing causality: Opportunities of synthetic communities for plant microbiome research. Cell Host Microbe. **2017**, 22, 142–155.
37. Kaminsky, L.M.; Trexler, R.V.; Malik, R.J.; Hockett, K.L.; Bell, T.H. The inherent conflicts in developing soil microbial inoculants. Trends Biotechnol. **2019**, 37, 140–151.
38. Naylor, D.; Degraaf, S.; Purdom, E.; Coleman-Derr, D. Drought and host selection influence bacterial community dynamics in the grass root microbiome. ISME J. **2017**, 11, 2691–2704.
39. Ahluwalia, O.; Singh, P.C.; Bhatia, R. A review on drought stress in plants: Implications, mitigation and the role of plant growth promoting rhizobacteria. Resour. Environ. Sustain. **2021**, 5, 100032.
40. Akhtar, N.; Ilyas, N.; Hayat, R.; Yasmin, H.; Noureldeen, A.; Ahmad, P. Synergistic effects of plant growth promoting rhizobacteria and silicon dioxide nanoparticles for amelioration of drought stress in wheat. Plant Physiol. Biochem. **2021**, 166, 160–176.
41. Bhat, M.A.; Kumar, V.; Bhat, M.A.; Wani, I.A.; Dar, F.L.; Farooq, I.; Bhatti, F.; Koser, R.; Rahman, S.; Jan, A.T. Mechanistic insights of the interaction of plant growth-promoting rhizobacteria (PGPR) with plant roots toward enhancing plant productivity by alleviating salinity stress. Front. Microbiol. **2020**, 11, 1952.
42. Saleem, M.; Law, A.D.; Sahib, M.R.; Pervaiz, Z.H.; Zhang, Q. Impact of root system architecture on rhizosphere and root microbiome. Rhizosphere. **2018**, 6, 47–51.
43. Niu, X.; Song, L.; Xiao, Y.; Ge, W. Drought-tolerant plant growth-promoting rhizobacteria associated with foxtail millet in a semi-arid agroecosystem and their potential in alleviating drought stress. Front. Microbiol. **2018**, 8, 2580.
44. Narayanasamy, S.; Thangappan, S.; Uthandi, S. Plant growth-promoting *Bacillus* sp. cahoots moisture stress alleviation in rice genotypes by triggering antioxidant defense system. Microbiol. Res. **2020**, 239, 126518.
45. Rashid, U.; Yasmin, H.; Hassan, M.N.; Naz, R.; Nosheen, A.; Sajjad, M.; Ilyas, N.; Keyani, R.; Jabeen, Z.; Mumtaz, S. Drought tolerant Bacillus megaterium isolated from semi-arid conditions induces systemic tolerance of wheat under drought conditions. Plant Cell Rep. **2022**, 41, 549–569.
46. Vandana, U.K.; Rajkumari, J.; Singha, L.P.; Satish, L.; Alavilli, H.; Sudheer, P.D.; Chauhan, S.; Ratnala, R.: Satturu, V.; Mazumder, P.B. The endophytic microbiome as a hotspot of synergistic interactions, with prospects of plant growth promotion. Biology. **2021**, 10, 101.
47. Carlson, R.; Tugizimana, F.; Steenkamp, P.A.; Dubery, I.A.; Hassen, A.I.; Labuschagne, N. Rhizobacteria-induced systemic tolerance against drought stress in *Sorghum bicolor* (L.) Moench. Microbiol. Res. **2020**, 232, 126388.
48. Barnawal, D.; Bharti, N.; Pandey, S.S.; Pandey, A.; Chanotiya, C.S.; Kalra, A. Plant growth-promoting rhizobacteria enhance wheat salt and drought stress tolerance by altering endogenous phytohormone levels and TaCTR1/TaDREB2 expression. Physiol. Plant. **2017**, 161, 502–514.
49. Khan, M.A.; Asaf, S.; Khan, A.L.; Ullah, I.; Ali, S.; Kang, S.-M.; Lee, I.-J. Alleviation of salt stress response in soy-bean plants with the endophytic bacterial isolate *Curtobacterium* sp. SAK1. Ann. Microbiol. 2019, 69, 797–800.
50. Orozco-Mosqueda, M.; Flores, A.; Rojas-Sánchez, B.; Urtis-Flores, C.A.; Morales-Cedeño, L.R.; Valencia-Marin, M.F.; Chávez-Avila, S.; Rojas-Solis, D.; Santoyo, G. Plant growth-promoting bacteria as bioinoculants: Attributes and challenges for sustainable crop improvement. Agronomy**.** **2021**, 11, 1167.
51. Gadhave, K.R.; Devlin, P.F.; Ebertz, A.; Ross, A.; Gange, A.C. Soil inoculation with *Bacillus* spp. modifies root endophytic bacterial diversity, evenness, and community composition in a context-specific manner. Microb. Ecol. **2018**, 76, 741–750.
52. Hafez, E.M.; Alsohim, A.S.; Farig, M.; Omara, A.E.D.; Rashwan, E.; Kamara, M.M. Synergistic effect of biochar and plant growth promoting rhizobacteria on alleviation of water deficit in rice plants under salt-affected soil. Agronomy. **2019**, 9, 847.
53. Azmat, A.; Yasmin, H.; Hassan, M.N.; Nosheen, A.; Naz, R.; Sajjad, M.; Ilyas, N.; Akhtar, M.N. Co-application of biofertilizer and salicylic acid improves growth, photosynthetic pigments and stress tolerance in wheat under drought stress. PeerJ. **2020**, 8, e9960.
54. Lally, R.D.; Galbally, P.; Moreira, A.S.; Spink, J.; Ryan, D.; Germaine, K.J.; Dowling, D.N. Application of endophytic Pseudomonas fluorescens and a bacterial consortium to Brassica napus can increase plant height and biomass under greenhouse and field conditions. Front. Plant Sci. **2017**, 8, 2193.
55. Arora, N.K.; Khare, E.; Maheshwari, D.K. Plant growth promoting rhizobacteria: constraints in bioformulation, commercialization, and future strategies. Springer Berlin Heidelberg, Berlin, Heidelberg. 2010; pp. 97–116
56. Herrmann, L.; Lesueur, D. Challenges of formulation and quality of biofertilizers for successful inoculation. Appl. Microbiol. Biotechnol. **2013**, 97, 8859–8873.
57. Brar, S.; Sarma, S.; Chaabouni, E. Shelf-life of biofertilizers: an accord between formulations and genetics J. Biofert. Biopestic. **2021**, 3, 1–2.

58. Bresson, J.; Vasseur, F.; Dauzat, M.; Labadie, M.; Varoquaux, F.; Touraine, B.; Vile, D. Interact to survive: Phyllobacterium brassicacearum improves *Arabidopsis* tolerance to severe water deficit and growth recovery. PLoS One. **2014**, 9, e107607.
59. Bashan, Y.; De-Bashan, L.E. Chapter two-how the plant growth-promoting bacterium *Azospirillum* promotes plant growth—a critical assessment. Adv. Agron. **2010**, 108, 77–136.
60. Burdman, S.; Jurkevitch, E.; Okon, Y. Recent advances in the use of plant growth promoting rhizobacteria (PGPR) in agriculture. Microbial Interactions in Agriculture and Forestry, vol. II, Science Publishers, Inc., USA. 2000; pp. 229–250.
61. Broek, A.V.; Dobbelaere, S.; Vanderleyden, J.; Vandommelen, A.; Triplett, E. *Azospirillum*-plant Root Interactions: Signaling and Metabolic Interactions. Prokaryotic Nitrogen Fixation: a Model System for the Analysis of a Biological Process. 2000; pp. 761–777.
62. Lucy, M.; Reed, E.; Glick, B.R. Applications of free living plant growth-promoting rhizobacteria Antonie Van Leeuwenhoek. **2004**, 86, pp. 1–25.
63. Vessey, J.K. Plant growth promoting rhizobacteria as biofertilizers. Plant Soil. **2003**, 255, pp. 571–586.
64. Głodowska, M.; Schwinghamer, T.; Husk, B.; Smith, D. Biochar based inoculants improve soybean growth and nodulation. Agric. Sci. **2017**, 8, 1048–1064.
65. Finkel, O.M.; Salas-González, I.; Castrillo, G.; Con-Way, J.M.; Law, T.F.; Teixeira, P.J.P.L.; Wilson, E.D.; Fitz-Patrick, C.R.; Jones, C.D.; Dangl, J.L. A single bacterial genus maintains root growth in a complex microbiome. Nature. **2020**, 587, 103–108.
66. Vurukonda, S.S.K.P.; Giovanardi, D.; Stefani, E. Plant growth promoting and biocontrol activity of *Streptomyces* spp. as endophytes. Int. J. Mol. Sci. **2018**, 19, 952.
67. Meena, K.K.; Sorty, A.M.; Bitla, U.M.; Choudhary, K.; Gupta, P.; Pareek, A.; Singh, D.P.; Prabha, R.; Sahu, P.K.; Gupta, V.K. Abiotic stress responses and microbe-mediated mitigation in plants: The omics strategies. Front. Plant Sci. **2017**, 8, 172.
68. del Carmen Orozco-Mosqueda, M.; Fadiji, A.E.; Babalola, O.O.; Glick, B.R.; Santoyo, G. Rhizobiome engineering: Unveiling complex rhizosphere interactions to enhance plant growth and health. Microbiol. Res. **2022**, 16, 127137.
69. Meena, M.; Swapnil, P.; Zehra, A.; Aamir, M.; Dubey, M.; Goutam, J.; Upadhyay, R. Beneficial Microbes for Disease Suppression and Plant Growth Promotion. In Plant-Microbe Interactions in Agro-Ecological Perspectives; Springer: Singapore. **2017**, 395–432.
70. Long, S.P.; ZHU, X.G.; Naidu, S.L.; Ort, D.R. Can improvement in photosynthesis increase crop yields? Plant Cell Environ. **2006**, 29, 315–330.
71. Mia, M.B.; Shamsuddin, Z. Nitrogen fixation and transportation by rhizobacteria: a scenario of rice and banana. Int. J. Bot. **2010**, 6, 235–242.
72. Heidari, M.; Golpayegani, A. Effects of water stress and inoculation with plant growth promoting rhizobacteria (PGPR) on antioxidant status and photosynthetic pigments in basil (*Ocimum basilicum* L.) J. Saudi Soc. Agric. Sci. **2012**, 11, 57–61.
73. Gururani, M.A.; Upadhyaya, C.P.; Baskar, V.; Venkatesh, J.; Nookaraju, A.; Park, S.W. Plant growth-promoting rhizobacteria enhance abiotic stress tolerance in Solanum tuberosum through inducing changes in the expression of ROS-scavenging enzymes and improved photosynthetic performance J. Plant Growth Regul. **2013**, 32, 245–258.
74. Cohen, A.C.; Bottini, R.; Pontin, M., Berli, F.J., Moreno, D.; Boccanlandro, H.; Travaglia, C.N.; Piccoli, P.N. *Azospirillum brasilense* ameliorates the response of Arabidopsis thaliana to drought mainly via enhancement of ABA levels Physiol. Plant. **2015**, 153, 79–90.
75. White, P.J.; Broadley, M.R. Biofortification of crops with seven mineral elements often lacking in human diets–iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytol. **2009**, 182, 49–84.
76. Velu, G.; Ortiz-Monasterio, I.; Cakmak, I.; Hao, Y.; Singh, R. Biofortification strategies to increase grain zinc and iron concentrations in wheat. J. Cereal Sci. **2014**, 59, 365–372.
77. Xin-chun, T.X.-h.L.; Xi-wen, M.W.-x.Y.; Sheng-xiu, L. Effect of calcium carbonate content on availability of zinc in soil and zinc and iron uptake by wheat plants. Soils. **2008**, 3, 0–18.
78. Yadav, A.N.; Kumar, R.; Kumar, S.; Kumar, V.; Sugitha, T.; Singh, B.; Chauhan, V.S.; Dhaliwal, H.S.; Saxena, A.K. Beneficial microbiomes: biodiversity and potential biotechnological applications for sustainable agriculture and human health. J. Appl. Biol. Biotechnol. 2017, 5, 1–13.
79. Tabassum, B.; Khan, A.; Tariq, M.; Ramzan, M.; Khan, M.S.I.; Shahid, N.; Aaliya, K. Bottlenecks in commercialisation and future prospects of PGPR. Appl. Soil Ecol. **2017**, 121, 102–117.
80. Thakur, M.P.; Van Der Putten, W.H.; Apon, F.; Angelini, E.; Vreš, B.; Geisen, S. Resilience of rhizosphere microbial predators and their prey communities after an extreme heat event. Funct. Ecol. **2021**, 35, 216–225.
81. Lugtenber, B.J.; Malfanova, N.; Kamilova, F.; Berg, G. Plant growth promotion by microbes. Mol. Microb. Ecol. Rhizosphere. **2013**, 2, 561–573.
82. Naik, K.; Mishra, S.; Srichandan, H.; Singh, P.K.; Sarangi, P.K. Plant growth promoting microbes: Potential link to sustainable agriculture and environment. Biocatal. Agric. Biotechnol. **2019**, 21, 101326.

 doi:10.20944/preprints202307.1686.v1

83. Ghosh, S.K.; Bera, T.; Chakrabarty, A.M. Microbial siderophore a boon to agricultural sciences. Biol. Control. **2020**, 144, 104214.
84. Saha, M.; Sarkar, S.; Sarkar, B.; Sharma, B.K.; Bhattacharjee, S.; Tribedi, P. Microbial siderophores and their potential applications: A review. Environ. Sci. Pollut. Res. **2016**, 23, 3984–3999.
85. Trivedi, P.; Batista, B.D.; Bazany, K.E.; Singh, B.K. Plant–microbiome interactions under a changing world: Responses, consequences and perspectives. New Phytol. **2022**, 234, 1951–1959.
86. Zia, R.; Nawaz, M.S.; Siddique, M.J.; Hakim, S.; Imran, A. Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. Microbiol. Res. **2021**, 242, 126626.
87. Berg, G. Plant–microbe interactions promoting plant growth and health: Perspectives for controlled use of microorganisms in agriculture. Appl. Microbiol. Biotechnol. **2009**, 84, 11–18.
88. Anli, M.; Baslam, M.; Tahiri, A.; Raklami, A.; Symanczik, S.; Boutasknit, A.; Ait-El-Mokhtar, M.; Ben-Laouane, R.; Toubali, S.; Rahou, Y.A. Biofertilizers as strategies to improve photosynthetic apparatus, growth, and drought stress tolerance in the date palm. Front. Plant Sci. **2020**, 11, 516818.
89. García-Fraile, P.; Menéndez, E.; Rivas, R.L. Role of bacterial biofertilizers in agriculture and forestry. AIMS Bioen-gineering. **2015**, 2, 183–205.
90. Basu, S.; Kumar, G.; Chhabra, S.; Prasad, R. Role of soil microbes in biogeochemical cycle for enhancing soil fertility, New and Future Developments in Microbial Biotechnology and Bioengineering. Elsevier. **2021**, 3, 149–157.