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Review

Plant Growth Promoting Rhizobacterial Biofertilizers for Sustainable Crop Production: The Past, Present, and Future

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Abstract: The world's population is increasing and so are agricultural activities to match the growing demand for food. Conventional agricultural practices generally employ artificial fertilizers to increase crop yields, but these have multiple environmental and human health effects. For decades, environmentalists and sustainability researchers have focused on alternative crop fertilization mechanisms to address these challenges, and biofertilizers have constantly been researched, recommended, and even successfully-adopted for several crops. Biofertilizers are microbial formulations made of indigenous plant growth-promoting rhizobacteria (PGPR) which can naturally improve plant growth either directly or indirectly, through the production of phytohormones, solubilization of soil nutrients, and production of iron-binding metabolites; siderophores. Biofertilizers, therefore, hold immense potential as tools for sustainable crop production especially in the wake of climate change and global warming. Despite the mounting interest in this technology, their full potential has not yet been realized. This review updates our understanding of the PGPR biofertilizers and sustainable crop production. It evaluates the history of these microbial products, assesses their present state of utilization, and also critically propounds on their future prospects for sustainable crop production. Such information is desirable to fully evaluate their potential and can ultimately pave the way for their increased adoption for crop production.

Keywords: biofertilizers; sustainable agriculture; plant growth-promoting rhizobacteria; microbial formulations

1. Introduction

It is approximated that by the year 2050, about 10 billion people will inhabit the earth and a lot of pressure will be mounted on the existing food resources [1]. The intensification of agricultural activities has greatly increased crop productivity all over the globe but has also increased our dependence on chemical inputs like fertilizers and pesticides [2–5]. The use of chemical fertilizers is a common practice around the globe [1] and is almost indispensable [6,7]. However, these chemicals have several negative effects on the environment as outlined by several workers [7–9]. Ironically, the long-term effects of chemical fertilizers also include the overall deterioration of soil quality and productivity [1] and soil acidification which ultimately reduces agricultural productivity [10,11].

Reports show that artificial fertilizers are widely associated with greenhouse gas (GHG) emissions [12–14] which greatly disturb environmental stability and affect both agriculture and natural systems [15], and are expected to rise as agricultural systems expand and to meet the rapidly and equally increasing demand for food. Cognizant of this, there is an urgent need for sustainable agricultural practices considerable strides have been made to investigate and implement various environmentally-friendly approaches as alternative crop fertilization mechanisms [16].

Biofertilizers are microbial formulations constituted of beneficial microbial strains immobilized or trapped on inert carrier materials that can be employed to enhance plant growth and increase soil fertility [9,17]. Research shows that the yield of various crops can be increased by about 25% and the use of inorganic N and P fertilizers be reduced by about 25–50% and 25% respectively through the application of biofertilizers [18,19]. Although the concept of biofertilizers is widely researched and there exist several practical applications globally, the utilization of this technology has not reached its full potential for several reasons. This chapter updates our understanding of biofertilizers by exploring their history, types, current status, and future prospects. We believe that such information will provide a good starting point for debate, and concerted global efforts to harness these bio-resources as biotechnological-based solutions for sustainable crop production systems.

2. What are biofertilizers?

The term 'biofertilizer' has earned several different definitions over the past decades (Table 1), reflecting the development of our understanding of them.

Table 1: Common definitions of biofertilizers from different literature

Literature	Provided definition
[20]	A biologically-active product or microbial inoculant/formulation containing one or more beneficial microbes, conserving and mobilizing crop nutrients in the soil
[21]	A preparation containing one or more species of microorganisms with the ability to mobilize important plant nutrients from non-usable form to usable forms
[22,23]	A formulated product containing one or more microbes enhancing the nutrient status of soil and promoting plant growth by availing nutrients and increasing plant access to nutrients
9[24]	A unique, eco-friendly, and cost-effective alternative to chemical fertilizers that improve crop productivity and soil health sustainably
[25]	A formulation or preparation containing latent or live microorganisms with effective and long-term storage, ease of handling, and delivery of the live microbes from the factory/lab to the field
[10]	A microbial inoculant which colonizes the rhizosphere and improves plant growth by enhancing nutrient accessibility to plants
[26]	A natural product containing a large population of specific beneficial microorganisms for enhancing soil productivity either by fixing atmospheric N, solubilizing P or stimulating plant growth through the synthesis of PGP substances
[27]	A mixture of an active ingredient with a formulated product with inactive or inert substances.
[28]	A formulation that contains microorganisms and/or a biological product that can fix atmospheric nitrogen, enhance the solubility of soil nutrients, and/or have the potential to enhance the yield of crop plants
[29]	A formulation based on beneficial microbes and/or biological product that either fixes atmospheric nitrogen or enhance the solubility of soil nutrients and have the potential to increase the yield of crops
[30]	A preparation containing beneficial microorganisms that enhance plant growth or fertilizers that meet a crop's nutritional requirements through microbiological means
[31]	The means of transporting beneficial microbes from the place of manufacture to the field for plant application

In this review, we define biofertilizers as active microbial agents that can stimulate plant growth by enhancing nutrient availability in the rhizosphere [21,32–34]. Other terminologies that are synonymous with biofertilizers include bioformulations or microbial inoculants [35], microbial cultures, bioinoculants, bacterial inoculants, or bacterial fertilizers [36]. Nevertheless, the major components of biofertilizers are the plant growth-promoting rhizobacteria (PGPR) whose activities in the plant rhizosphere contribute to the overall increment, accessibility, and concentration of plant nutrients [35,37,38], and are almost indispensable in sustainable agricultural practices [21]. Of all the plant-beneficial microorganisms in the rhizosphere, PGPR are the most promising and have widely been investigated [21,39,40]. The use of these microbiomes as biofertilizers in agriculture offers an effective and environmentally-friendly solution for achieving food security [39]. Consequently, biofertilizers and PGPR are well recognized as important components of integrated plant-nutrient management for sustainable agriculture [41].

2. History of plant growth-promoting rhizobacteria as biofertilizers for crop production

Whereas the use of microbial formulations is generally considered as a modern biotechnological and novel approach in sustainable agriculture. The inoculation of plants with PGPR to improve yields is a century-old practice [42]. The 1st attempts to this practice date back to as early as the late 18th century when a French scientist by the name Jean-Baptiste Boussingault (1801- 1887) recognized that plant growth was proportional to N quantities. This observation was later linked to the reduction of dinitrogen (N_2) to ammonium (NH_3) and the 1st commercial biological fertilizer Nitragin® made from laboratory rhizobial cultures [43,44] was the product of these findings. These were the earliest commercial preparations of PGPR and were patented and marketed close to a century ago [44].

The marketing of *Rhizobium* inoculants continued in the 19th century [45,46], and their commercial production and marketing expanded worldwide thereafter [47,48]. Since then, a lot of biofertilizers have been formulated and commercialized all over the globe. Soon after this, attempts were made to work to also formulate bacterial soil-fertilizing preparations for non-legume crops, and the 1st preparation ′Alinit′ was introduced by the German Albert Caron (1853-1933) based on *B. ellenbachensis* for enhancing the growth of cereals in Germany [49]. More on the history of these early attempts at bacterial inoculants and biofertilizers is comprehensively covered by Kolbe [50].

Due to the reliability of chemical fertilizers and the inconsistent performance of bioformulations, biofertilizers slowed down for some time but research in the following few decades yielded encouraging results in the greenhouse using root-colonizing Gram-negative *Pseudomonas spp.* [51–53]. By 1958, in the former Soviet Union, large scale field trials were performed using with Azotobacter and Bacillus spp. on more than 35 million hectares of land [54], but the impact of bacterization was relatively unsatisfactory [55].

The commercialization and application of N_2-fixing rhizobia for legumes production have especially been exploited for decades [42]. By the year 2000, the global area of legumes treated with commercial biofertilizers stood at more than 40 million hectares annually [56], and about ½ of this was used in soybean fields [47]. In Africa however, the use of rhizobial biofertilizers for legumes production is still negligible, mostly due to inadequate research, information, and markets [57]. The commercial production and utilization of rhizobial inoculants have thus been practices for many decades now, partially reducing the need for mineral fertilizers for legume production in many countries [58]. From the beginning of the 20th century, extensive research has been carried out for the development of state of the art rhizobial bioformulations, and advents of newer techniques have provided inputs in this direction [59].

3. Types of plant growth-promoting rhizobacterial biofertilizers

3.1. Nitrogen fixers

Plants take up N from the soil in the form of nitrates (NO^{3-}) and ammonium ions (NH^{4+}) [60] which are often limiting in soil

Table 2: Examples of nitrogen-fixing rhizobacteria and potential N biofertilizers

Crop	***Rhizobacteria***	***Reference(s)***
Potato (Solanum tuberosum)	*Azotobacter, Azospirillum*	[63]
	Serratia sp., Citrobacter sp., Klebsiella sp.,	[64]
	Azospirillum sp., Pseudomonas sp., Rhizobium sp.	[65]
Soybean (Glycine max)	*Rhizobium japonicum*	[66]
	Bradyrhizobium, Streptomyces griseoflavus	[67]
Sugarcane (Saccharum officinarum L)	*Kosakania sp. KB117*	[68]
	Gluconacetobacter diazotrophicus	[69]
	G. diazotrophicus	[70]
	P. agglomerans	[71]
	K. variicola DX120E	[72]
	Not specified	[73]
Rice (Oryza sativa)	*Lysinibacillus sphaericus, K. pneumoniae, B. cereus*	[74]
	P. stutzeri	[75]
	Rhizobium sp., Azospirillum sp	[76]
	Pantoea agglomerans, Rahnella aquatilis, P. orientalisj	[77]
	Not mentioned	[78]
	Microbacterium, Bacillus, Klebsiella spp. Paenibacillus	[79]
	kribbensi, B. aryabhattai, K. pneumoniae, B. subtilis, M. trichotecenolyticum	[80,81]
	Burkholderia, Herbaspirillum, Azospirillum, R. leguminosarum	
	Not specified	[73]
Maize (Zea mays)	*Klebsiella sp., K. pneumoniae, B. pumilus, Acinetobacter sp.*	[82]
	B. mojavensis, P. aeruginosa, Alcaligenes faecalis, P.	[83]
	syringiae, B. cereus	[84]
	P. protegens	[85]
	P. aeruginosa, E. asburiae, Acinetobacter brumalii	[86]
	Herbaspirillum species	[87]
	Bacillus sp., Enterobacter sp.	[88]
	P. pseudoalcaligenes, P. aeruginosa	
Green gram (Vigna radiate)	*Rhizobium sp.*	[89]
	Bradyrhizobium, Streptomyces griseoflavus	[67]
Groundnut (Arachis hypogaea)	*Enterobacter ludwigii*	[90]
	Bradyrhiziobium	[91]
Wheat (Triticum aestivum L.)	*P. protegens*	[84]
	Stenotrophomonas maltophilia, Chryseobacterium, Flavobacterium, P. Mexicana	[92]
	Achromobacter insolitus, Azospirillum brasisilense	[93]
	Azotobacter chroococcum	[94]
	Azospirillum brasilense	[95]
Tomato (Solanum lycopersicum L.)	*P. gessardi, P. koreensis, P. brassicacearum, P. marginalis, Acinetobacter calcoaceticus and Rahnella aquatica*	[96]
	Not specified	[73]
Banana (Musa sp.)	*Klebsiella sp., Bacillus sp., Microbacterium sp., Enterobacter sp.,*	[97]

Therefore, artificial N fertilizers are often heavily utilized to enhance N nutrition in plants. Alarmingly, the global use of synthetic N is rapidly expanding and the Food and Agriculture Organization (FAO) estimates that their demand exceeds 130 million tons per year which is environmentally unsuitable especially since their production largely depends on the use of fossil fuels [61,62].

Biological nitrogen fixation (BNF) is a widely-investigated phenomenon where certain microbes fix N for plant use using the nitrogenase enzyme complex [98]. For instance, the N_2-fixing rhizobia in leguminous plants have been researched for several decades [99]. Several controlled studies involving the inoculation of different crop plants have shown N fixation and biomass yield in plants inoculated with N-fixers relative to un-inoculated controls. Several instances demonstrating BNF by rhizobacteria with the potential to be used as biofertilizers for different crops are displayed in Table 2. Some of these have successfully been formulated into commercial biofertilizers but the commercially available N biofertilizers mostly consist of *Rhizobium,* and a few other bacteria such as *Azotobacter,* and *Azospirillum* species and are widely applicable to legume crops [100].

Inoculating crops and agricultural fields with PGPR capable of BNF can help to provide the required N levels [101]. Evidence shows that rhizobial N_2 fixation rates of 1–2 kg N ha^{-1} day^{-1} can be obtained in legume fields [33]. Herridge proposed that the replacement of chemical fertilizers with rhizobial inoculants would reduce the annual cost of N fertilization to about US$1 million from US$30 million per year. The provided examples illustrate the importance of symbiotic and associative N_2-fixing rhizobacteria. Nevertheless, there is need to perform field trials of new strains for suitability and adaptability before application as inoculants [33].

For decades, several efforts have been made to demonstrate endophytic and associative N_2 fixation in non-leguminous crops using free-living diazotrophs like *Azotobacter, Azospirillum, Gluconaceotobacter,* and *Burkholderia* [102]. For instance, studies by Hungria et al. [103] and Melchiorre et al. [104] respectively demonstrated that grain yields in Brazil, Argentina, and the United States of America (USA) could reach up to 4 t ha^{-1} per growing season through BNF by rhizobial inoculants. Similarly, in Australian soils, N_2 fixation rates of up to 40 kg N ha^{-1} $year^{-1}$ are documented [105]. However, the contribution of symbiotically-fixed N to plants remains largely unestablished and wanting. More research in this area is definitely necessary especially for crops like cereals, vegetables, and tubers, considering they contribute to the bulk of human food.

3.2. Nutrient solubilizers

3.2.1. Phosphate solubilizers

Phosphorus is the 2nd most essential plant macronutrient [106]. However, plants can only take it up as monobasic ($H_2PO_4^-$) or dibasic (HPO_4^{-2}) ions yet between 95 and 99% of soil P occurs in insoluble, immobilized, or precipitated forms that are not plant-available [60,107]. Consequently, only a small percentage of the total soil P is utilizable by crops and is rarely sufficient [108–110]. Many PGPR have attracted the attention of researchers as plant inoculants due to their P solubilization abilities [60,111]. Since P deficiency is inherent in many agricultural soils, such organisms are largely proposed as prospective P biofertilizers [112]. Literature shows that P-solubilizing bacteria (PSB) secrete various enzymes and metabolites that solubilize P [113], but the solubilization of P is largely advanced to occur by acidification [113,114]. For instance, recent studies by Zeng et al. [115] successfully demonstrated that the P solubilizing activities of *Pseudomonas frederiksbergensis* positively correlated with the production of organic acids.

There are numerous reports concerning the growth stimulation of crops owing to inoculation with PSB, examples of which are provided in Table 3. Similarly, several reviews have also highlighted the importance, potential, and mechanisms of P solubilization by PSB [116–119]. Despite the growing volume of literature, studies regarding their use as biofertilizers are still limited [60].

Table 3: Examples of phosphates solubilizing rhizobacteria and potential P biofertilizers

Crop	*Rhizobacteria*	*Reference(s)*
Potato (Solanum tuberosum)	*B. megaterium*	[63]
	Bacillus spp., Pseudomonas spp., Serratia spp.	[123]
	Serratia sp., Citrobacter sp., Klebsiella sp.	[64]
	Pseudomonas sp., B. subtilis	[124]

Bananas (Musa spp.)	*B. subtilis, Agrobacterium tumefaciens, Streptomyces sp., B. thuringiensis, B. amyloliquefaciens, Micrococcus luteus*	[125]
Maize (Zea mays)	*B. mojavensis, P. aeruginosa, Alcaligenes faecalis, P. syringiae, B. cereus* *Lysinibacillus fusiformis* *P. fluorescens* *Bacillus spp., Klebsiella sp., E. ludwigii, Pantoea spp.* *P. aeruginosa, E. asburiae, Acinetobacter brumalii* *Klebsiella sp., K. pneumoniae, B. pumilus* *Acinetobacter sp. and B. subtilis*	[83] [126] [127] [128] [85] [82]
Soybean (Glycine max)	*R. japonicum* *E. sakazakii, P. straminae, Acinetobacter calcoaceticus* *B. acidiceler, B. megaterium, B. pumilus, B. safensis, B. simplex, Lysinibacillus fusiformis, Paenibacillus cineris and P. graminis* *P. plecoglossicida*	[66] [129] [130] [131]
Wheat (Triticum aestivum L.)	*P. putida, Azospirillum* *Serratia marcescens* *Pseudomonas* sp., *P. mosselii* *P. mosselii* *Stenotrophomonas maltophilia, Chryseobacterium, Flavobacterium, P. mexicana* *Non-identified strains*	[132] [133] [112] [134] [92] [135]
Poplar (Populus spp.)	*P. frederiksbergensis*	[115]
Cowpea (Vigna unguiculata)	*Bradyrhizobium japonicum*	[136]
Sugarcane (Saccharum officinarum L)	*Herbaspirillum spp., Bacillus spp.* *Burkholderia mallei, B. cepacia, Proteus vulgaris, Pasteurella multocida, K. pneumoniae, K. oxytoca, E. cloacae, C. freundii* *G. diazotrophicus* *Not identified*	[137] [138] [139] [73]
Chickpea (Cicer arietinum)	*B. subtilis, B. licheniformis* *Bacillus sp., Klebsiella sp., Pseudomonas sp.* *P. agglomerans, B. cereus, B. sonorensis*	[140] [141] [142]
Mungbean (Vigna radiate)	*P. agglomerans, Burkholderia anthina* *B. circulans, Cladosporium herbarum* *B. subtilis, B. licheniformis*	[143] [111] [140]
Tomato (Solanum lycopersicum L.)	*P. gessardi, P. koreensis, P. brassicacearum, P. marginalis, Acinetobacter calcoaceticus and Rahnella aquatica* *Not specified*	[96] [73]
Rice (Oryza sativa)	*S. marcescens, Pseudomonas sp.* *Rahnella aquatillis, Enterobacter* sp., *P. fluorescens* and *P. putida* *P. agglomerans, Rahnella aquatilis and P. orientalis* *Not mentioned* *Paenibacillus kribbensi, B. aryabhattai, K. pneumoniae, B. subtilis, Microbacterium trichotecenolyticum* *Not speciied*	[144] [145] [77] [78] [79] [73]
Coffee (*Coffea arabica L.)*	*Pseudomonas sp., Bacillus sp., Enterobacter sp. and Stenotrophomonas sp.*	[146]

	P. chlorophis, Erwinia rapontici, Bacillus sp., Serratia marcescens	[147]
Cotton (Gossypium hirsutum)	*Azotobacter chroococcum*	[94]
	B. megaterium, P. putida, P. fluorescens	[148]
Various leguminous and non-leguminous plants	*Azotobacter sp., Mesorhizobium sp., Pseudomonas sp., Bacillus sp., Rhizobium sp.*	[149]

The economically-mineable P deposits are limited [120]. The world's main P source; rock phosphate is a non-renewable resource whose mining also contributes largely to global energy consumption, and therefore extremely unsustainable environmentally [33]. There is no doubt that through P solubilization, bacterial biofertilizers can significantly increase crop yields [121], and that the use of PSB as bioinoculants can open up a new horizon for maintaining soil P levels and by large, sustainable crop productivity [122]. However, despite several encouraging field inoculation studies, field results are still generally inconsistent, calling for more research.

3.2.2. Potassium solubilizers

Potassium is the 3rd major plant macronutrient [60,150,151], but > 90% of soil K exists in insoluble complexes and the available quantities are usually insufficient for plant growth [152,153]. Reports show that K deficiency is a major challenge in crop production worldwide [60,154]. Artificial K fertilizers are often used to supplement K in agricultural soils, but these are costly and condense profit margins for farmers [150,155]. It is therefore essential to find alternative ways of improving K availability to sustain crop production [156,157].

The ability of PGPR to solubilize K from K-bearing rocks through the secretion of organic acids has widely been investigated [60,152], and K solubilizing bacteria (KSB) have been demonstrated to have prominent roles in improving crop growth and yield [158]. For instance, reports show that these bacteria can significantly improve the germination, nutrient uptake, growth, and yield of crops under both controlled and field conditions [158,159]. In Table 4, we summarize some examples of KSB that have been associated with improved K-uptake in different plants.

Although the solubilization of K-bearing rocks may not entirely fulfill the total plant K requirements like the commercial fertilizers, studies show that this novel approach may significantly enhance K availability in agricultural soils [174]. Furthermore, literature strongly progresses that the application of KSB to agricultural soils as biofertilizers can greatly cut the use of chemical fertilizers [175,176], and are eco-friendly approaches to crop production [165,173,177]. Indigenous KSB are especially in the limelight and emerging as some of the viable technologies for mitigating K deficiency in agricultural soils [178].

The diversity, solubilizing abilities, and mechanisms of KSB are extensively reviewed by Sattar et al. [174], Ahmad et al. [150], and Sindhu et al. [179]. Despite this burgeoning volume of literature, little is still known about the efficacy of KSB and how they can influence plant growth under different agro-climatic conditions [180].

Table 4: Examples of potassium solubilizing rhizobacteria and potential K solubilizers

Bacteria	***Crop***	***Reference***
Potato (Solanum tuberosum)	*B. circulans*	[63]
	Klebsiella sp., Citrobacter sp., Serratia sp.	[64]
Wheat (Triticum aestivum)	*Paenibacillus kribbensis*	[159]
	Pseudomonas, Bacillus, Stenotrophomonas, Methylobacterium, Arthrobacter, Pantoea, Achromobacter, Acinetobacter, Exiguobacterium, Staphylococcus	[160]
	Not identified	[161]

Common bean (Phaseolus vulgaris)	*Acinetobacter sp., Bacillus sp., Enterobacter sp., Micrococcus sp., Pseudomonas sp.*	[162]
Maize (Zea mays)	*B. mojavensis, P. aeruginosa, Alcaligenes faecalis, P. syringiae, B. cereus* *B. licheniformis, B. subtilis* *K. oxytoca*	[83] [163] [164]
Sorghum (Sorghum bicolor) and Chilli (Capsicum sp.)	*Bacillus, Pseudomonas sp.*	[165]
Tomato (Solanum lycopersicum L.)	*P. gessardi, P. koreensis, P. brassicacearum, P. marginalis, Acinetobacter calcoaceticus and Rahnella aquatica* *Not specified*	[96] [73]
Black pepper (Piper nigrum)	*Paenibacillus glucanolyticus* *B. megaterium var phosphaticum, B. mucilaginosus*	[166] [167]
Chickpea (Cicer arietinum)	*P. jessenii, Mesorhizobiumciceri*	[168]
Fava/faba bean (Vicia faba)	*Rhizobium sp.*	[169]
Apples (Malus domestica)	*B. subtilis, B. licheniformis, B. pumilus, B. methylotrophicus, B. firmus, B. altitudinus* *Paenibacillus mucilaginosus*	[170] [171]
Orange (Citrus sinensis)	*B. circulans*	[172]
Rice (Oryza sativa)	*P. agglomerans, Rahnella aquatilis, P. orientalis* *Pantoea ananatis, Rahnella aquatilis, Enterobacter sp.* *Not identified* *Not specified*	[77] [114] [161] [73]
Sugarcane (Saccharum officinarum L)	*Not mentioned* *Not specified*	[173] [73]
Various leguminous and non-leguminous plants	*Azotobacter sp., Mesorhizobium sp., Pseudomonas sp., Bacillus sp., Rhizobium sp.*	[149]

According to Meena et al. [176], KSB are precious resources for mitigating K-deficiencies in agricultural soils but experimental evidence on their efficacy at the field level is still grossly inadequate. Certainly, more research is needed to increase their usability. This and related information will certainly help in understanding their use as bioinoculants for practical purposes under actual field conditions [180].

3.2.3. Zinc solubilizers

Zinc is a major plant micronutrient that drives several primary and secondary metabolic processes [181]. Existing reports worldwide show that Zn deficiency is a common problem in most agricultural soils due to nutrient mining during crop harvesting and increased use of NPK fertilizers containing lesser amounts of these micronutrients [182,183]. Synthetic Zn fertilizers are often employed to augment these deficiencies at the recommended rates of approximately 25 kg ha^{-1} ZnSO4 heptahydrate, (equivalent to 5 kg ha^{-1} Zn). Nevertheless, these artificial fertilizers are not cost-effective and readily get converted into insoluble and non-accessible forms to plants [183,184].

Recent literature advances rhizobacterial Zn solubilization [149,185–187]. In a study by Naz et al. [188], species of *Azospirillum*, *Azotobacter*, *Pseudomonas*, and *Rhizobium* species have been shown to significantly increase Zn uptake in wheat plants relative to un-inoculated controls. Similarly, Sharma et al. [189] who isolated 134 *Bacillus* strains from soybean (*G. max*) rhizosphere soils to select for effective Zn solubilizers showed that the isolates significantly increased the Zn concentration of inoculated crops relative to the un-inoculated controls. Similarly, several Zn solubilizing bacteria (ZSB) including *P. fragi, Pantoea dispersa*, *P. agglomerans*, *E. cloacae*, and *Rhizobium* sp. isolated from wheat and sugarcane were recently shown to improve the Zn contents and growth of pot-grown wheat [190]. In another study, Dinesh et al. [191] several promising ZSB isolated from soil were evaluated for their effects on soil Zn release rates, soil-available Zn and plant Zn contents in a greenhouse experiment and the results showed that Zn concentration in soil and plants was higher in the treated plants than the non-treated controls. In another study in India by Goteti et al. [181], the bacterization of maize seeds with a Zn-solubilizing *Pseudomonas* strain significantly enhanced the uptake and concentration of Zn in pot experiments.

Prospective ZSB for enhanced Zn uptake in maize, Zn solubilizing *Bacillus* strains that modulate the growth, yield, and Zn biofortification in soybean and wheat have also been reported in India [192]. In a study by Sunithakumari et al. [193], several rhizobacteria isolated from banana, chilli, bean, groundnuts, maize, sorghum, and tomato plants among them, species of *Stenotrophomonas, Mycobacterium, Enterobacter, Pseudomonas,* and *Xanthomonas* also demonstrated excellent *in vitro* Zn solubilization abilities. *Agrobacterium tumefaciens* and *Rhizobium* sp. isolated from barley and tomato have also been demonstrated to solubilize Zn in vitro [194]. Zinc solubilizing abilities and increased Zn uptake following inoculation of rice plants by *Pseudomonas* strains [195], soybean and wheat by *B. aryabhattai* [196], maize by *Bacillus* strains [197], wheat by *Serratia liquefaciens, S. marcescens*, and *B. thuringiensis* [198] and recently in rice by several ZSB [199] have similarly been demonstrated. It is proposed that the use of such ZSB in the field can result in increased Zn uptake by plants, and subsequently, improved growth and yield [200].

3.2.4. Iron sequesters

Iron is the 4th most abundant nutrient element in soil and an important micronutrient needed for plant growth [201]. Most agricultural soils are however Fe-deficient especially since the element occurs in the insoluble ferric (Fe^{3+}) form that is unavailable for plant-uptake [202]. Thus, the unavailability of Fe is a major plant-growth limiting factor in many agricultural systems [34,203].

Some microorganisms have developed special mechanisms for Fe-acquisition by synthesizing low molecular weight metabolites known as siderophores [142] with high affinity for Fe in low-Fe environments [204,205]. This way, the siderophores function as Fe-chelators and bind most of the available Fe in the rhizosphere [34]. Furthermore, literature advances that siderophore-producing bacteria and the subsequent Fe-unavailability in plant rhizospheres may also prevent the proliferation of plant pathogens [206,207].

A lot of studies have shown the ability of different rhizobacterial species to produce siderophores and the enhancement of plant Fe nutrition. In a recent study by Emami et al. [134], several rhizobacterial isolates from the wheat including *Stenotrophomonas sp., Serratia marcescens, Pseudomonas sp., Nocardia fluminea, Stenotrophomonas maltophilia, Bacillus zhangzhouensis, Pseudomonas mosselii,* and *Microbacterium sp*. were shown to have very good siderophore production abilities *in vitro* and significantly enhanced the Fe uptake in greenhouse-grown wheat plants. In another recent study by Verma and Pal [149], various rhizobacteria including Bacillus sp., Pseudomonas sp., Rhizobium sp., MEsorhizobium sp., and Azotobacter sp. were isolated from various leguminous and non-leguminous plants and shown tom possess siderophore producing capabilities. In yet another recent study, the use of siderophore-producing bacteria was also shown to significantly enhance Fe uptake and transport in grains [208]. In earlier studies by Vendan et al. [209], several endophytic rhizobacteria such as *Bacillus cereus, B. flexus, B. megaterium, Lysinibacillus fusiformis, L. sphaericus, Microbacterium phyllosphaerae, Micrococcus luteus* isolated from maize also exhibited excellent siderophore production abilities. Siderophore-producing rhizobacteria have also been isolated from maize and canola in Iran [210], peach, and pear roots in Turkey [211], corn in Brazil [87], and banana in Kenya [212], among others.

The Fe^{3+} and microbial siderophores form a complex in the membrane in which the former is reduced to $Fe^{2+}$and released into the cell through an input mechanism that links the outer and inner cell membranes. During this process, the siderophores can be destroyed or recycled [213] and the plants can access and assimilate the Fe^{2+} from bacterial siderophores by direct up-take of the Fe-siderophore complexes or by exchange reactions using appropriate ligands [214,215]. Siderophore production is a classic example of how rhizobacterial inoculants in biofertilizers can establish themselves in the plant rhizosphere and enhance Fe nutrition and due to its indisputable importance, should be given more attention [216].

4. The current state of plant growth-promoting rhizobacterial biofertilizers and crop production

There is a burgeoning volume of literature demonstrating the application of microbial products as biofertilizers and agricultural inputs [100]. Around 170 organizations in 24 countries are engaged in the commercial production of biofertilizers and many countries have industries that produce, market, and distribute microbe-based fertilizers at both large and small scales [217]. The commercial production and utilization of rhizobial inoculants have been practiced for many decades now, partially reducing the need for mineral fertilizers in many countries [58]. However, the full potential of several beneficial rhizobacteria as biofertilizers remains largely unexplored.

Unlike the rhizobial inoculants, PSB like *Bacillus* and *Pseudomonas*, and diazotrophs like *Azospirillum* have less frequently been used and on a much lesser scale than the rhizobial inoculants and it is estimated that no more than a few thousand hectares are treated annually with non-rhizobial biofertilizers [33]. Most of the currently available non-rhizobial PGPR inoculants consist of *Azospirillum* as free-living N2 fixers or *Bacillus* as PSB [32]. According to Lesuer [33], the application of commercial non-rhizobial biofertilizers does not significantly affect global food production. This is probably because of the several bottlenecks that exist in their uptake and use in contrast to their well-documented PGP roles. The global agricultural crop production was estimated at 1.6 billion hectares [218], but there is an obvious lack of market penetration and application of non-rhizobial biofertilizers despite decades of research [33].

Generally, the commercialization of biofertilizers remains low globally but is steadily expanding. By the year 2014, the biofertilizer market represented only about 5% of the total chemical fertilizer market [219]. In the developed world where agricultural chemicals remain relatively inexpensive, the use of PGPR occupies a smaller niche, but this is also growing [100]. The global biofertilizer market is currently largely dominated by legume and N_2-fixing inoculants [220]. Literature suggests that the rhizobia-based inoculants occupy approximately 78% of the global biofertilizer market, while P solubilizers and other bioinoculants occupy about 15 and 7% respectively [221,222]. Recent reports show that P, Zn, and K based biofertilizers are also emerging as important bioinoculants to address nutrient deficiencies in soils [186,223]. According to Teotia et al. [180], KSM are widely employed as bioinoculants in most countries, where crop fields are K-deficient.

Table 5: Examples of commercial biofertilizer products in some countries around the world

Country	Product	Organisms	Manufacturer	Crop	Reference
Argentina	Liquid PSA	*P. aurantiaca*	Laboratorios BioAgro S.A.	Wheat	[224]
	Zadspirillum	*Azospirillum brasilense*	Semillera Guasch SRL	Maize	[224]
	Rhizo Liq	*Bradyrhizobium sp., Mesorhizobium ciceri, Rhizobium spp.*	Rhizobacter	Green gram, Common bean, Soybean, Groundnut, Chickpea	[225]
Australia	Bio-N	*Azotobacter spp.*	Nutri-Tech solution	Not mentioned	[225]
	Myco-Tea	*Azotobacter chrococcum, B. polymyxa*	Nutri-Tech solution	Tea	[225]

	Twin N	*Azorhizobium sp., Azoarcus sp., Azospirillum sp*	Mapleton Int. Ltd	Not mentioned	[225]
Brazil	Bioativo	PGPR consortia	Embrafros Ltda	Beans, maize, sugarcane, rice, cereals	[226]
Canada	Rhizocell GC Nodulator	*B. amyloliquefaciens IT 45* *B. japonicum*	Lallen and plant care BASF Inc.	Beans, maize, carrot, rice, cotton	[226]
	Vault HP	*Bradyrhizobium sp.*	BASF	Not mentioned	[225]
China	CBF	*Bacillus mucilaginosus, B. subtilis*	China Bio-Fertilizer AG	Various cereals	[224]
Colombia	Fe Sol B	*Not mentioned*	Agri Life Bio Solutions	Not mentioned	[227]
Germany	FZB 24 fl, BactofilA 10	*B. amyloliquefaciens, B. megaterium, P. fluorescens*	AbiTEP GmbH	Vegetables, cereals	[226]
Hungary	BactoFil A10	*A. brasilense, Azotobacter vinelandii, B. megaterium*	AGRObio	Maize	[228]
India	Ajay Azospirillum	*Azospirillum*	Ajay Biotech	Cereals	[224]
	Greenmax AgroTech Life Biomix, Biodinc, G max PGPR	*Azotobacter, P. fluorescens*	Biomax	Various crops	[226]
	Fe Sol B	*Not mentioned*	Agri Life Bio Solutions	Not mentioned	[227]
	Symbion van plus	*B.megaterium*	T. stanes and Co. Ltd	Not mentioned	[229]
Kenya	Biofix	Rhizobia	MEA Fertilizer Ltd	Not mentioned	[225,230]
Nigeria	Nodumax	*Bradyrhizobia*	IITA	Not mentioned	[225,231]
Russia	Azobacterium	*Azobacterium brasilense*	JSC Industrial Innovations	Wheat, barley, maize,	[224]
South Africa	Organico	*Bacillus spp. Enterobacter spp., Pseudomonas, Stenotrophomonas, Rhizobium*	Amka Products (Pty) Ltd	Not mentioned	[225]
	Azo-N, Azo-N-Plus	*A.brasiliense, A. lipoferum*	Biocontrol Products Ltd	Not mentioned	[232,233]
	Lifeforce, Firstbase, Biostart, Landbac, Composter, Waterbac	*Bacillus spp.,*	Microbial solution (Pty) Ltd	Not mentioned	[153,155]
	Histick	*B. japonicum*	BASF	Not mentioned	[231]
	N-Soy	*B.japoniucm*	Biocontrol Products Ltd	Not mentioned	[231]
	Soilfix	*Brevibacillus laterosporus, Paenibacillus chitinolyticus*	Biocontrol Products Ltd	Not mentioned	[234]
	Organico	*Bacillus sp.*	Amka Products	Not mentioned	[232]

	Bac-up	*B. subtilis*	Biocontrol Products Ltd	Not mentioned	[225]
Spain	InomixR	*B. polymyxa, B. subtilis*	Lab (Labiotech)	Cereals	[226]
	Vita Soil	*PGPR consortia*	Symborg	Not mentioned	[229]
Thailand	BioPlant	*Clostridium, Achromobacter, Streptomyces, Aerobacter, Nitrobacter, Nitrosomonas, Bacillus*	Artemis & Angelio Co. Ltd.	Not mentioned	[225]
United Kingdom	Ammnite A 100	*Azotobacter, Bacillus, Rhizobium, Pseudomonas*	Cleveland biotech	Cucumber, tomato, pepper	[226]
	Legume Fix	*Rhizobium sp., B. japonicum.*	Legume Technology	Common bean, Soybean	[225]
	Twin N	*Azorhizobium sp., Azoarcus sp., Azospirillum sp*	Mapleton Int. Ltd	Not mentioned	[225]
Uruguay	Nitrasec	*Rhizobium sp.*	Lage y Cia	Not mentioned	[225])
USA	Inogro	*30 bacterial species*	FLozyme Corporation	Rice	[224]
	Vault NP	*B. japonicum*	Becker Underwood	Not mentioned	[225]
	Chickpea Nodulator	*Mesorhizobium cicero*	Becker Underwood	Chickpea	[225]
	Cowpea Inoculant	*Rhizobia*	Becker Underwood	Cowpea	[225]
	PHC Biopak	*B. azotofixans, B. licheniformis, B. megaterium, B. polymyxa, B. subtilis, B. thuringiensis*	Plant Health Care Inc.	Not mentioned	[225]
	Complete Plus	*Bacillus strains*	Plant Health Care	Various crops	[228]
	Quickroots	*B. amyloliquefaciens*	Monsanto	Wheat and common bean	[224]

In this regard, India is reportedly the fourth-largest consumer of K bioinoculants in the world, whereas countries like the USA, China, and Brazil top the list in total consumption of these microbial products [235].

In 2013, North America had the highest demand for biofertilizers geographically and projections were that the entire Asia-Pacific biofertilizer market would show the maximum growth from 2014 to 2019 and dominate the global biofertilizer market in terms of demand [236]. The biofertilizer market is clearly undergoing a global expansion due to the need to increase food production sustainably [107]. Forecasts predict that the biofertilizer market share will reach USD 1.66 billion by 2022 and will rise at a compounding annual growth rate (CAGR) of 13.2% from 2015 to 2022 and according to Market Data Forecast [237], the current global market of microbial inoculants was estimated at USD 396.07 million in 2018 and expected to rise at an annual growth rate of 9.5% to approximately USD 623.51 million by 2023. $205.6 million with a CAGR of 6.4% between 2011 and 2018 [100].

In the USA and Canada alone, legume biofertilizers were the largest revenue earners in 2011, accounting for 72.5% of the total revenue collection from biofertilizers, with an expected CAGR of approximately 5.3% up to 2018. This advancement has also stimulated the isolation and selection of biofertilizers with the best PGP abilities [100]. Table 5 displays examples of commercially-available biofertilizers used to improve crop productivity in various countries across the globe. Although many reports exist on the formulation, commercialization, and application of rhizobacteria in other continents, very few reports indicate their commercialization and applications in African countries. Most of these products are commercialized and used in Europe, Asia, and the USA but in Africa, only South Africa conspicuously has the widest commercialization and application. Previous research documents that in most developing countries, the PGPR inoculant technology has little or no impact on crop productivity since it is either not practiced or the available inoculants are of poor quality [238].

The most advanced and prevalent biofertilizer market is Europe, and growth from $2566.4 million in 2012 to $4582.2 million was observed in this region 2017, at an annual growth rate of 12.3% from 2012 to 2017 [239]. In 2012, the biofertilizer market was highest in North America and was expected to grow at a rate of 14.4% from 2013–2018 [240]. The N_2-fixing biofertilizers were used in maximum as compared to all other biofertilizers, and in 2012 their worldwide demand increased over 78% [241]. Several biofertilizer formulations are already in use on a commercial level.

5. Future prospects and perspectives of plant growth-promoting rhizobacterial biofertilizers and crop production

The use of biofertilizers as an integral component of agricultural practices is quickly gaining momentum worldwide. These microbial products are already in use successfully in some countries their use is expected to expand [242]. There is an increasing number of studies aiming to isolate, identify, and evaluate the capacity of PGPR with the potential of being transformed into inoculants for a variety of crops [243–246]. It is, therefore, reasonable to expect that soon, the extensive use of biofertilizers will offer various strategies for the overall development of sustainable crop production systems [11]. However, more widespread utilization of biofertilizers will require proper regulatory and legal frameworks that are currently stringent and a hindrance to their proper utilization [247]. Fortunately, the regulatory authorities are of late increasingly encouraging the implementation of alternative crop fertilization mechanisms to promote the development of sustainable agricultural technologies [100]. For instance, acknowledging the need for a specific legislative framework for biofertilizers/biostimulants in Europe, the European Commission subsequently issued a proposal to amend existing regulations [248]. Such initiatives will eventually relax the stringent regulatory frameworks and enable the widespread adoption of these microbial resources.

While a number of the existing biofertilizers are likely to be composed of non-transformed rhizobacterial strains selected for their positive traits, the invention of genetically modified rhizobacterial inoculants which are likely to be more efficient in stimulating plant growth is required. However, the biggest huddle will be for scientists to prove to the general public and regulatory authorities worldwide that genetically-engineered organisms do not present any new hazards or risks [11].

Our current ability to harness the plant microbiome in agriculture and manipulate plant microbiomes *in situ* remain largely limited, and more trials are needed in this area to increase our understanding and enable their application and commercialization at large scale [249]. The inoculant industry is faced with various challenges in making formulations with prolonged shelf lives. The development of formulations with increased shelf lives, broad spectra of action, and consistent field performance could pave the way for the commercialization of this technology at a faster rate [250]. In this regard, new biotechnological approaches should be evaluated to develop formulations with longer shelf lives. Micro-encapsulation is one viable approach but most of the experiments on this have been restricted only to laboratories and the technology should be standardized for the industrial and field applications [217]. The future of biofertilizer technology depends a lot on developing efficient PGP strains. This is quite challenging but continued research in this area will eventually pave way for this [251].

Research on N-fixation and Pm solubilization by PGPRs is progressing well, but research on K solubilization is not progressing as fast yet this is the 3rd most important macronutrient for plant development [252]. Research in this area will not only promote the use of bioinoculants but also create confidence in their utilization. Apart from this, future research should focus on the optimization of cost-effective growth conditions, can tolerate unfavorable environmental situations, and achieve higher productivity [253]. The potential benefits of microbial biofertilizers in stressful soil environments should especially be explored for applicability especially in the wake of climate change and global warming. More research is needed on the practical aspects of mass production and formulation to develop effective, stable, safer, cheap, and novel bioformulations. The use of consortia of multi-trait PGP strains may be useful in obtaining novel biofertilizers that can offer inexpensive substitutes for agrochemicals [252,254,255].

The use of nano-factories is an emerging technique in bioformulation development in which engineered bioinoculants are used to enhance communication with plants through quorum sensing that leads to biofilm formation. Biofilm formation not only maintains a sufficient bacterial population in soil but also protects the bioinoculant from fluctuating environmental conditions and provides them a competitive advantage [256]. The interactions among plants, and microorganisms as biofertilizers may need further studies [36], and future strategies also are needed to focus on understanding the interactions of biofertilizers from bacteria with nanoparticles, which also serve as useful micronutrients for microorganisms and plants [36].

Future research should also include careful isolation of the rhizosphere microbiota, and their *in situ* testing for use as plant inoculants [249]. It is prospected that the identification of effective microbiomes in different soil types and climates will extremely be helpful in this regard [257]. To improve this strategy, establishing a global database of effective plant microbiomes will be an important milestone towards successful translational research [249]. The present international market for organically produced food is approximately US$30 billion and is increasing at about 8% annually with approximately 37.2 million hectares of land being under organic-based agriculture technology [258]. However, only about 1% of the world's agriculture comprises organic methods, an indication of the remarkable prospects and capacity in the growth of biofertilizers [217]. A lot of obstacles still remain to be overcome before this can fully be realized. For instance, numerous formulations based on such microorganisms have been developed, with applications for different crops around the world (Saleem and Khan, 2017). However, the inconsistency in the results obtained, dependent on autochthonous microbiota, available nutrients and crop characteristics, makes it necessary to optimize each particular system [254].

The use of biotechnological tools and improvement in regulations can go a long way in designing a rhizobial bioformulation that will be more reliable and effective. To design a tailor-made state of the art rhizobial formulation, it is very important to further our knowledge on plant-microbe interactions by using the latest tools and techniques. Use of omics-based approaches (genomics and proteomics) can also be very useful in enhancing our understanding of plant-microbial symbioses and omics-based techniques including genomics, proteomics and metabolomics can go a long way in designing state of the art bioformulation for a particular soil and crop [59].

3. Conclusions

The greatest global challenge in the 21st century is to develop and implement sustainable agricultural practices. This can only be achieved if we accommodate changing and advanced technologies such as the use of efficient rhizobacterial biofertilizers. The discussion in this chapter will definitely be useful for the development of sustainable agro-ecosystems. The use of these bio-resources though has been practiced in several parts of the globe is still low but the results are encouraging and there is room for improvement to enhance their efficacy. With time, the practice will certainly grow and projections are that in the coming years, the bioformulations demand will have huge market potential. Researchers, agricultural institutions, and universities can fast-track biofertilizer development and promote their usage and adaptation for sustainable agricultural practices. In addition to these emerging approaches, if issues linked to regulatory and policy development, and social acceptability of microbial/ microbiome products can be simultaneously addressed, these bio-based tools can potentially contribute significantly to the sustainable increase in agricultural productivity

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