## Chapter 15

# Status of biofertilizer research, commercialization, and practical applications: A global perspective

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## 15.1 Introduction

The greatest challenge in the world today and in the coming decades will be to increase the food production for food security without further degradation of the ecosystem (Ahmad et al., 2016). The global consensus supports and encourages the adoption of sustainable agricultural practices that can provide food for the populace while conserving the environment (Adeleke et al., 2017). One of the most popular technologies involves the use of beneficial plant-associated microbiome like the plant growth-promoting rhizobacteria (PGPR) ( Jain and Maheshwari, 2017). Beneficial plant-microbiome interactions represent a promising sustainable solution to improve the agriculture production (Timmusk et al., 2017). The symbiotic and free-living soil microorganisms inhabiting plant rhizospheres have diverse beneficial effects on their plant hosts (Raza et al., 2016) and hold a huge potential for producing plant growth-promoting (PGP) metabolites like siderophores, phytohormones, organic acids, and enzymes that catalyze nutrients solubilization for plant uptake (Glick, 2014; Vejan et al., 2016).

Beneficial rhizobacterial species have widely been utilized to produce commercial inoculants or biofertilizers for crop production (Ahemad and Kibret, 2014; Malusá et al., 2016). Although the term "biofertilizer" is a broad term that can include fungi, algae, and mycorrhiza, this chapter focuses on rhizobacterial biofertilizers. One of the well-known rhizobacterial biofertilizers are rhizobial inoculants (Lesueur et al., 2016), which have been used for legume production for more than a century (Arora et al., 2017; Sindhu et al., 2010). Literature suggests that harnessing these essential beneficial microbes for increased crop productivity is a viable strategy for achieving the objectives of sustainable agricultural production (Adeleke et al., 2017).

The application of biofertilizers is a very important component of integrated nutrient management systems that enhance agricultural productivity and sustainability simultaneously. Literature advances that biofertilizers are cost-effective and environmentally friendly (Mohammadi and Sohrabi, 2012) and can partially replace agrochemicals which are expensive and their development is in response to increasing demands for more environmentally friendly agricultural practices (Herrmann and Lesueur, 2013). Although reports on the enhancement of plant growth through PGPR as biofertilizers are widely available, there has been a paucity of information between their potential uses and their applications (Gouda et al., 2018). Although the vast body of research on microbial inoculants deals with their ability to promote plant growth, there has been limited success in developing commercially viable products. Similarly, despite a high number of patents, only a few have materialized in a register for agricultural application (Timmusk et al., 2017). The main aim of this chapter is to update our knowledge on biofertilizers and the current status of their research and application in the global perspective. Additionally, this chapter also evaluates the constraints facing biofertilizer research and global application and elucidates on some future prospects regarding their future research and practical application for sustainable agricultural systems. This kind of information is invaluable to the full evaluation and exploitation of the potential prospects of biofertilizers for sustainable agriculture, food security, and sustainable ecosystems globally.

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## 15.2 What are biofertilizers?

Biofertilizers are generally described as active biological agents like microorganisms that can stimulate plant growth through several biogeochemical processes that enhance nutrient availability in the rhizosphere (Herrmann and Lesueur, 2013; Lesueur et al., 2016; Singh et al., 2019; Vessey, 2003). They can sometimes be referred to as bioformulations or microbial inoculants (Arora et al., 2010). The PGPR act as direct growth enhancers to plants, as they have the tendency to increase the accessibility and concentration of nutrients by fixing or limiting their supply for plant growth and productivity (Arora et al., 2010; Bhattacharyya and Jha, 2012; Kumar, 2016). Due to their biological nature, and their beneficial aspects, biofertilizers are indispensable in sustainable agricultural practices (Vessey, 2003).

Of all the plant-beneficial microorganisms in the rhizosphere, the PGPR are the most promising for agricultural applications (Glick, 2014; Suyal et al., 2016; Vessey, 2003). The use of these microbiomes as biofertilizers in agriculture is a promising technology to provide effective and environmentally friendly solutions with the potential to ensure food security (Glick, 2014). Biofertilizers and PGPR are recognized as an important component of integrated plant-nutrient management for sustainable agriculture and they hold a great promise not only to improve crop yield but also to sustain soil health (Pérez-Montaño et al., 2014).

## 15.3 The global status of biofertilizer research

### 15.3.1 Nitrogen fixers

Plants absorb nitrogen (N) from the soil in the form of nitrate and ammonium ions (Gouda et al., 2018). However, these N forms are always limiting in soil and artificial N fertilizers are often heavily applied for plant N nutrition. Alarmingly, the global use of synthetic N fertilizers increased by 800% between the years 1960 and 2000, and recently, the anthropogenic N input was shown to be more than double the amount of N cycling in the biosphere (Canfield et al., 2010). The Food and Agriculture Organization (FAO) estimates that the demand for these fertilizers exceeds 130 million tons per year and is environmentally unsustainable especially since their production largely depends on the use of fossil fuels (Canfield et al., 2010).

Biological nitrogen fixation (BNF) is a largely investigated phenomenon where symbiotic or nonsymbiotic microbes fix N for plant use using the nitrogenase enzyme complex (Ahemad and Kibret, 2014). The $N_2$-fixing rhizobia in leguminous plants have been researched for decades (Santoyo et al., 2016). In India, the estimated amount of $N_2$ fixation by *Rhizobium*-legumes and cereal-bacterial associations is between 20 and 100 kg N $ha^{-1}$ and 10–30 kg N $ha^{-1}$, respectively (IARI, 2014).

Previous studies under controlled/greenhouse conditions involving the inoculation of soybean varieties in Kenya with selected commercial biofertilizers showed increased nodulation, N fixation, and biomass yield in the inoculated crops relative to the uninoculated controls (Thuita et al., 2012).

Other instances demonstrating BNF by rhizobacteria with the potential to be used for N biofertilization of different crops are shown in Table 15.1. Some of these have successfully been formulated into commercial biofertilizers but according to Timmusk et al. (2017), the N biofertilizers mostly contain inoculants like *Rhizobium*, *Actinorhizobium*, *Azotobacter*, and *Azospirillum* species which are widely applied to legume fields but can also be used on rice and sugarcane plantations.

The inoculation of crops and agricultural with PGPR capable of BNF can help to maintain the N levels (Daman et al., 2016). Literature shows that rhizobial $N_2$ fixation rates of 1–2 kg N $ha^{-1}$ $day^{-1}$ can be obtained in all legumes (Lesueur et al., 2016). However, the presence, level, and diversity of native rhizobia in the soil are critical for inoculant performance (Lesueur et al., 2016). In Vietnam, Herridge (2008) estimated that the annual cost of N fertilization could be reduced to US$1 million from about US $30 million per annum if chemical fertilizers were replaced by rhizobial inoculants. These examples illustrate the importance of symbiotic and associative $N_2$-fixing rhizobacteria. However, it is important to evaluate the symbiotic performance of new/proposed strains in the field for suitability and adaptability before being recommended for use in an inoculant (Lesueur et al., 2016).

Although it is advanced that indigenous rhizobacterial populations are better plant-growth promoters, research in Eastern, Western, and Southern African countries by the International Institute of Tropical Agriculture (IITA) has shown poor soybean yields grown without *Bradyrhizobium* inoculations or N fertilizers, an indication that indigenous strains despite effecting nodulations do not always meet the soybean N requirements (Thuita et al., 2012). For decades, considerable efforts have been made to illustrate endophytic and associative $N_2$ fixation in cereals and other nonlegume crops using free-living diazotrophs like *Azotobacter*, *Azospirillum*, *Gluconacetobacter*, and *Burkholderia* (da Silva et al.,

**TABLE 15.1 Rhizobacterial biological nitrogen fixation and nitrogen bio-fertilization potential in different plants.**

| Crop | Rhizobacteria | Experimental conditions | Study location | References |
|---|---|---|---|---|
| Potato (*Solanum tuberosum*) | *Azotobacter, Azospirillum* | Field | Egypt | Abdel-Salam and Shams (2012) |
| Soybean (*Glycine max*) | *Rhizobium japonicum* | Filed | Pakistan | Yousaf et al. (2019) |
| | *Bradyrhizobium, Streptomyces griseoflavus* | Pot | Japan | Htwe et al. (2019) |
| Sugarcane (*Saccharum officinarum* L.) | *Kosakania* sp. KB117 | Potted | Brazil | Kleingesinds et al. (2018) |
| | *Gluconacetobacter diazotrophicus* | In vitro | Egypt | Ahmed et al. (2016) |
| Rice (*Oryza sativa*) | *Lysinibacillus sphaericus, Klebsiella pneumoniae Bacillus cereus* | Plate | India | Shabanamol et al. (2018) |
| | *Pseudomonas stutzeri* | Greenhouse | Belgium | Pham et al. (2017) |
| | *Rhizobium* sp., *Azospirillum* sp. | In vitro | Myanmar/ Burma | Sev et al. (2016) |
| | *Pantoea agglomerans, Rahnella aquatilis, Pseudomonas orientalis* | Pot and Field | Iran | Yaghoubi et al. (2018) |
| Maize (*Zea mays*) | *Klebsiella* sp., *Klebsiella pneumoniae, Bacillus pumilus, Acinetobacter* sp. | Greenhouse | Malaysia | Kuan et al. (2016) |
| | *Bacillus mojavensis, Pseudomonas aeruginosa, Alcaligenes faecalis, P. syringae, B. cereus* | Laboratory | Nigeria | Akintokun et al. (2019) |
| | *Pseudomonas protegens* | Field | Argentina | Fox et al. (2016) |
| | *Pseudomonas aeruginosa, E. asburiae, Acinetobacter brumalii* | In vitro | India | Sandhya et al. (2017) |
| | *Herbaspirillum species* | Controlled and field | Brazil | Alves et al. (2015) |
| Green gram (*Vigna radiata*) | *Rhizobium* sp. | Field | India | Choudhary et al. (2019) |
| | *Bradyrhizobium, Streptomyces griseoflavus* | pot | Japan | Htwe et al. (2019) |
| Wheat (*Triticum aestivum* L.) | *Pseudomonas protegens* | Field | Argentina | Fox et al. (2016) |
| | *Stenotrophomonas maltophilia, Chryseobacterium, Flavobacterium, Pseudomonas mexicana* | Greenhouse | Egypt | Youseif (2018) |
| | *Achromobacter insolitus, Azospirillum brasiliense* | Greenhouse | Brazil | Silveira et al. (2016) |
| | *Azotobacter chroococcum* | Glasshouse | Colombia | Romero-Perdon et al. (2017) |
| | *Azospirillum brasilense* | Field | Iran | Karimi et al. (2018) |
| Banana (*Musa* sp.) | *Klebsiella* sp., *Bacillus* sp., *Microbacterium* sp., *Enterobacter* sp. | Greenhouse | India | Patel et al. (2017) |

2012). For example, studies by Hungria et al. (2006) and Melchiorre et al. (2011) illustrated that grain yields in Brazil, Argentina, and the United States of America (USA), respectively, can reach up to 4 t $ha^{-1}$ per growing season through BNF and by rhizobial inoculants. In Australian soils, $N_2$ fixation rates of up to 40 kg N $ha^{-1}$ $year^{-1}$ have also been documented (Unkovich and Baldock, 2008). However, the contribution of symbiotically fixed N to plants remains largely unestablished and wanting.

## 15.3.2 Nutrient solubilizers

### *15.3.2.1 Phosphate solubilizers*

Phosphorus is the second most essential nutrient for optimum plant growth (Goswami et al., 2016). Plants can only take P either as monobasic ($H_2PO_4^-$) or dibasic ($HPO_4^{-2}$) ions but up to 95–99% of P occurs as insoluble, immobilized, or precipitated forms (Gouda et al., 2018; Verma et al., 2019). Consequently, although the average P-content in most soils is 0.05%, only about 0.1% of this is available for crop uptake (Alori et al., 2017; Jorquera et al., 2011), which is rarely sufficient for plant growth (Malhorta et al., 2018).

Many PGPR have attracted the attention of researchers as inoculants to improve plant growth through their P solubilization abilities (Gouda et al., 2018; Oteino et al., 2015). Due to P-deficiency in many agricultural soils, such organisms are largely considered as prospective biofertilizers (Emami et al., 2018). Literature shows that these P-solubilizing microorganisms secrete various enzymes and metabolites that solubilize nutrients (Rafi et al., 2019), and there are many reports concerning growth enhancement of crops inoculated with phosphate-solubilizing bacteria (PSB) examples of which are displayed in Table 15.2.

**TABLE 15.2 Studies involving phosphate-solubilizing rhizobacteria in different crops**

| Crop | Bacteria | Experimental conditions | Study location | References |
|---|---|---|---|---|
| Potato (*Solanum tuberosum*) | *Bacillus megaterium* | Field | Egypt | Abdel-Salam and Shams (2012) |
| Maize (*Zea mays* | *Bacillus mojavensis, Pseudomonas aeruginosa, Alcaligenes faecalis, P. syringae, B. cereus* | Laboratory | Nigeria | Akintokun et al. (2019) |
| | *Lysinibacillus fusiformis* | Greenhouse | Pakistan | Rafique et al. (2017) |
| | *Pseudomonas fluorescens* | Field | Spain | Krey et al. (2013) |
| Soybean (*Glycine max*) | *Rhizobium japonicum* | Filed | Pakistan | Yousaf et al. (2019) |
| Wheat (*Triticum aestivum* L.) | *Pseudomonas putida, Azospirillum* | Pot, greenhouse and field | Iran | Zabihi et al. (2011) |
| | *Serratia marcescens* | Pot and net-house | India | Sood et al. (2018) |
| | *Pseudomonas* sp., *Pseudomonas mosselii* | Greenhouse | Iran | Emami et al. (2018) |
| | *P. mosselii* | In vitro and greenhouse | Iran | Emami et al. (2019) |
| Poplar (*Populus* spp.) | *Pseudomonas frederiksbergensis* | Pot | China | Zeng et al. (2017) |
| Cowpea (*Vigna unguiculata*) | *Bradyrhizobium japonicum* | Field and pot house | Tanzania | Nyoki and Ndakidemi (2014) |
| Mung bean (*Vigna radiata*) | *Pantoea agglomerans, Burkholderia anthina* | Greenhouse | Korea | Walpola and Yoon (2013) |
| | *B. circulans, Cladosporium herbarum* | Pot | Ireland | Oteino et al. (2015) |
| Rice (*Oryza sativa*) | *Serratia marcescens, Pseudomonas* sp. | Pot | India | Kolekar et al. (2017) |
| | *Rahnella aquatilis, Enterobacter* sp., *Pseudomonas fluorescens* and *Pseudomonas putida* | Pot and field | Iran | Bakhshandeh et al. (2015) |
| | *Pantoea agglomerans, Rahnella aquatilis and Pseudomonas orientalis* | Pot and field | Iran | Yaghoubi et al. (2018) |
| Cotton (*Gossypium hirsutum*) | *Azotobacter chroococcum* | Glasshouse | Colombia | Romero-Perdon et al. (2017) |

Many reviews have also highlighted the importance and mechanisms of P solubilization employed by PSB (Chhabra and Dowling, 2017; Shrivastava et al., 2018; Varma et al., 2017; Walia et al., 2017). Despite the burgeoning volume of literature on PSB, studies regarding their use as biofertilizers are still limited and very few reports exist on this (Gouda et al., 2018). The solubilization of P is advanced to occur mostly by acidification (Bakhshandeh et al., 2017; Rafi et al., 2019). For instance, very recent studies by Zeng et al. (2017) successfully demonstrated that the P-solubilizing activities of *Pseudomonas frederiksbergensis* strains are correlated positively with the production of organic acids.

Economically mineable P deposits are finite and better management of the P cycle is becoming increasingly important (Cordell et al., 2009). The world's main source of P is rock phosphate, a nonrenewable resource, and the mining and trading of rock phosphate contribute to global energy consumption, which is extremely inefficient and harmful to the environment (Lesueur et al., 2016). There is no doubt that bacterial biofertilizers can increase the yield of various crops significantly also through improved P acquisition (Hinsinger et al., 2018). The use of P-solubilizing bacteria as bioinoculants can be critical in the maintenance of soil nutrient status and opens a new horizon for better crop productivity (Ingle and Padole, 2017). However, field results are generally inconsistent despite some recent encouraging field inoculation studies.

### *15.3.2.2 Potassium solubilizers*

Potassium is the third major macronutrient required for plant growth (Ahmad et al., 2016; Gouda et al., 2018; Proença et al., 2017). However, more than 90% of soil K exists as insoluble rocks and silicate minerals and the concentration of soluble K is usually very low for plant growth (Bahadur et al., 2019; Parmar and Sindhu, 2013). Therefore, K deficiency is a major limiting factor in crop production worldwide (Bhattacharyya et al., 2016; Gouda et al., 2018). Artificial K fertilizers are often used for K augmentation in agricultural soils, but these are costly and reduce profit margins for farmers (Ahmad et al., 2016; Mohammadi and Sohrabi, 2012). It is therefore essential to find alternative ways of improving K availability to sustain crop production (Kumar and Dubey, 2012; Mohamed et al., 2017).

The ability of PGPR to solubilize K from K-bearing rocks by secretion of organic acids has widely been investigated (Bahadur et al., 2019; Gouda et al., 2018), and the K-solubilizing bacteria (KSB) have been shown to have prominent roles in improving crop growth, yield, and quality (Basak and Biswas, 2012). For instance, it is well documented that they can significantly improve the germination, growth, yield, and nutrient uptake of crops under both gnotobiotic and field conditions (Basak and Biswas, 2012; Zhang et al., 2013). In Table 15.3, we summarize some studies that have successfully demonstrated the effectiveness of K-solubilizers for improving growth and K-uptake in different plants.

Although the solubilization of K-bearing minerals may not entirely fulfill the total plant K requirements compared to commercial K fertilizers, these novel approaches may significantly enhance K release from K-bearing minerals (Sattar et al., 2019). Literature strongly advances that the use of KSB as biofertilizers for improving agriculture productivity can reduce the use of chemical fertilizers (Liu et al., 2012; Meena et al., 2018), and are eco-friendly approaches to crop production (Archana et al., 2013; Setiawati and Mutmainnah, 2016; Sindhu et al., 2010). Indigenous KSB are especially in the limelight and are emerging as one of the viable technologies for mitigating K deficiency in soils (Meena et al., 2015).

The K-solubilizing abilities, mechanisms, and diversity are extensively reviewed by Sattar et al. (2019), Ahmad et al. (2016), and Sindhu et al. (2016) among others. Despite the numerous reports on K-solubilizing microorganisms (KSM), reports still maintain that little is still known about their efficacy and mechanisms of K solubilization and how they affect plant growth under different agroclimatic conditions (Teotia et al., 2016). According to Meena et al. (2018), KSM are precious resources for K-deficiency mitigation in agricultural soils but experimental evidence on their performance is still inadequate especially at the field level. This definitely calls for more research to increase its usability. This and related information will certainly help in understanding the use of these bioinoculants that would be needed for practical purposes under actual field conditions (Teotia et al., 2016).

### *15.3.2.3 Zinc solubilizers*

Zinc is an important micronutrient required for primary and secondary metabolism in plants (Goteti et al., 2013). However, reports show that most agricultural soils in the world are deficient in Zn and other micronutrients due to nutrient mining by high-yield crops, and increased use of NPK fertilizers containing lesser amounts of micronutrients (Sharifi and Paymozd, 2016; Sindhu et al., 2019). In some instances, chemical Zn fertilizers are often applied to overcome these nutritional constraints, and the impact of artificial Zn application on increasing crop yields has been recorded on most crops. Generally, the addition of $25\,\mathrm{kg\,ha^{-1}}$ $ZnSO_4$ heptahydrate, (equivalent to $5\,\mathrm{kg\,ha^{-1}}$ Zn), is recommended for every year or alternate years for soil application. Nevertheless, Zn fertilizers are not cost-effective and most of the applied Zn readily get converted into nonaccessible insoluble form to plants (Sindhu et al., 2019), and only about 20% remains available for plant use (Bapiri et al., 2012).

**TABLE 15.3 Potassium-solubilizing activities and abilities of various rhizobacteria in different plants.**

| Crop | Bacteria | Experimental conditions | Study location | References |
|---|---|---|---|---|
| Potato (*Solanum tuberosum*) | *Bacillus circulans* | Field | Egypt | Abdel-Salam and Shams (2012) |
| Wheat (*Triticum aestivum*) | *Paenibacillus kribbensis* | In vitro | China | Zhang et al. (2013) |
| Common bean (*Phaseolus vulgaris*) | *Acinetobacter* sp., *Bacillus* sp., *Enterobacter* sp., *Micrococcus* sp., *Pseudomonas* sp. | In vitro | India | Kumar et al. (2012) |
| Maize (*Zea mays*) | *Bacillus mojavensis, Pseudomonas aeruginosa, Alcaligenes faecalis, P. syringae, B. cereus* | Laboratory | Nigeria | Akintokun et al. (2019) |
| | *B. licheniformis, B. subtilis* | Laboratory | Navsari | Parmar et al. (2016) |
| Sorghum (*Sorghum bicolor*) and Chili (*Capsicum* sp.) | *Bacillus, Pseudomonas* sp. | In vitro | India | Archana et al. (2013) |
| Black pepper (*Piper nigrum*) | *Paenibacillus glucanolyticus* | Greenhouse pot | India | Sangeeth et al. (2012) |
| Chickpea (*Cicer arietinum*) | *Pseudomonas jessenii, Mesorhizobium ciceri* | Greenhouse and field | Spain | Valverde et al. (2006) |
| Apples (*Malus domestica*) | *B. subtilis, B. licheniformis, B. pumilus, B. methylotrophicus, B. firmus, B. altitudinis* | Laboratory | India | Mehta et al. (2015) |
| Orange (*Citrus sinensis*) | *Bacillus circulans* | Field | Egypt | Shaaban et al. (2012) |
| Rice (*Oryza sativa*) | *Pantoea agglomerans, Rahnella aquatilis, Pseudomonas orientalis* | Pot and field | Iran | Yaghoubi et al. (2018) |

Rhizobacterial Zn solubilization abilities are a widely reported phenomenon (Mishra et al., 2013; Shaikh and Saraf, 2017; Zamana et al., 2018). In Pakistan, studies showed that *Azospirillum*, *Azotobacter*, *Pseudomonas*, and *Rhizobium* species significantly increased Zn uptake in wheat relative to uninoculated controls (Naz et al., 2016). In Madhya Pradesh, India, Sharma et al. (2012) isolated 134 *Bacillus* isolates from soybean rhizosphere soils to select effective Zn solubilizers for increased assimilation of Zn in soybean (*Glycine max*) seeds and inoculation of *Bacillus* isolates significantly increased the Zn concentration in inoculated crops relative to the uninoculated control (47.14 µg/g). In yet another study in Pakistan, several Zn-solubilizing bacteria (ZSB) among them, *Pseudomonas fragi*, *Pantoea dispersa*, *Pantoea agglomerans*, *Enterobacter cloacae*, and *Rhizobium* sp. isolated from wheat and sugarcane were also demonstrated to improve the growth and Zn content of pot-grown wheat plants (Kamran et al., 2017). In another study by Dinesh et al. (2018) in India, six promising ZSB, among them, *Bacillus megaterium* 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 nontreated ones. In yet another study in India, Goteti et al. (2013) showed that maize seed bacterization with a Zn-solubilizing *Pseudomonas* sp. strain significantly enhanced the Zn concentrations (278.8 ppm) of inoculated plants relative to the uninoculated control in pot cultures.

Prospective ZSB for enhanced Zn uptake in *Zea mays* L., Zn-solubilizing *Bacillus* strains that modulate the growth, yield, and Zn biofortification of soybean and wheat have also been studied in India (Khande et al., 2017). A study by Sunithakumari et al. (2016), on several rhizobacteria isolated from of banana, chili, bean, groundnut, maize, sorghum, and tomato among them, *Stenotrophomonas maltophilia*, *Mycobacterium brisbanense*, *Enterobacter aerogenes*, *Pseudomonas aeruginosa*, and *Xanthomonas retroflexus* demonstrated excellent Zn solubilization abilities under in vitro studies. *Agrobacterium tumefaciens* and *Rhizobium* sp. isolated from barley and tomato have also been demonstrated to solubilize Zn in laboratory experiments (Yaghoubi et al., 2017). Zinc-solubilizing abilities and increased Zn uptake have also been demonstrated following inoculation of wheat by *Pseudomonas* strains ( Joshi et al., 2013), soybean and wheat by *Bacillus aryabhattai* (Ramesh et al., 2014), maize by *Bacillus* strains (Hussain et al., 2015), wheat by *Serratia liquefaciens*, *Serratia* *marcescens*, and *Bacillus thuringiensis* (Abaid-Ullah et al., 2015) and recently in rice by several ZSB (Perumal et al., 2019). It is proposed that the use of such ZSB in the field might result in increased Zn uptake by plants, and subsequently, improved growth and yield (Suman et al., 2016).

### 15.3.3 Iron chelators

Iron is the fourth most abundant nutrient element in soil and an important micronutrient required for plant growth (Saha et al., 2016). Most agricultural soils, however, are Fe-deficient because the element occurs in the insoluble ferric ($Fe^{3+}$) form that is unavailable for plant-uptake (Rajkumar et al., 2010). Thus, the unavailability of Fe is a major plant-growth limiting factor in many agricultural systems (Arora and Verma, 2017; Singh et al., 2019).

Some microorganisms have developed special Fe-acquisition mechanisms through the production of siderophores (Maheshwari et al., 2019) which are low molecular weight (500–1000 Da) Fe-binding metabolites synthesized in low-Fe environments (Mhlongo et al., 2018; Tank et al., 2012). These siderophores act as Fe-chelators and bind most of the available Fe in the rhizosphere (Singh et al., 2019). Literature advances that siderophore-producing bacteria and the subsequent Fe-unavailability in plant rhizospheres may also prevent the proliferation of plant pathogens (Mitter et al., 2013; Olanrewaju et al., 2017).

A lot of studies have shown the ability of different rhizobacterial species to produce siderophores and enhance Fe nutrition in plants. In a recent study in Iran by Emami et al. (2019), several rhizobacterial isolates from the wheat among them, *Stenotrophomonas* sp., *S. marcescens*, *Pseudomonas* sp., *Nocardia fluminea*, *S. maltophilia*, *Bacillus zhangzhouensis*, *Pseudomonas mosselii*, and *Microbacterium* sp. showed very good siderophore production abilities in vitro and significantly enhanced the Fe uptake in greenhouse-grown wheat plants. In quite a recent study in India, the use of siderophore-producing bacteria was also shown to significantly enhance Fe uptake and transport in grains (Sah et al., 2017). In earlier studies by Vendan et al. (2010) in Korea, a number of endophytic rhizobacteria such as *Bacillus cereus*, *Bacillus flexus*, *B. megaterium*, *Lysinibacillus fusiformis*, *Lysinibacillus sphaericus*, *Microbacterium phyllosphaerae*, and *Micrococcus luteus* isolated from maize also exhibited excellent siderophore production abilities. Siderophore-producing rhizobacteria have also been isolated from maize and canola in Iran (Ghavami et al., 2017), peach and pear roots in Turkey (Liaqat and Eltem, 2016), corn in Brazil (Szilagyi-Zecchin et al., 2014), and banana in Kenya (Ouma et al., 2014), among others.

## 15.4 The global commercialization and practical applications of biofertilizers

A large volume of literature supports and demonstrates the use of microbial products as biofertilizers agricultural inputs (Timmusk et al., 2017), and the inoculation of plants with PGPR to improve yields is a century-old practice (Bashan et al., 2014). The earliest commercial preparations of PGPR were patented and marketed close to a century ago in 1986 when Nobbe and Hiltner launched “Nitrigan” from laboratory rhizobial cultures (1986). The marketing of *Rhizobium* inoculants continued in the 19th century (Fages, 1992; Tang and Yang, 1997), and their commercial production and marketing expanded worldwide thereafter (Catroux et al., 2001; Deaker et al., 2004). Since then, a lot of biofertilizers have been formulated and commercialized all over the globe.

The commercialization and application of $N_2$-fixing rhizobia for legumes production have especially been exploited for decades (Bashan et al., 2014). By the year 2000, the global area of legumes treated with commercial biofertilizers stood at more than 40 million hectares annually (Phillips, 2004), and about half of this was used in soybean fields (Catroux et al., 2001). In Africa however, the use of rhizobial biofertilizers for legumes production is still negligible, mostly due to inadequate research, information, and markets ( Jansa et al., 2011).

The commercial production and utilization of rhizobial inoculants have thus been practiced for many decades now, partially reducing the need for mineral fertilizers for legume production in many countries (Rodríguez-Navarro et al., 2011). However, the full potential of several beneficial rhizobacteria as biofertilizers still 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 few thousand hectares are treated annually with nonrhizobial biofertilizers (Lesueur et al., 2016). Most of the nonrhizobial PGPR inoculants currently available contain bacteria from the genus *Azospirillum* (free-living $N_2$-fixing bacteria) or *Bacillus* (PSB) (Herrmann and Lesueur, 2013). *Azospirillum*-based products have been commercialized in places like Cuba, Mexico, and Brazil (Saikia et al., 2010). According to Lesueur et al. (2016), the application of commercial nonrhizobial biofertilizers does not significantly affect the global food production. This indicates the existence of bottlenecks in the uptake and use of these products in contrast to their well-documented PGP roles. The global agricultural crop production including legumes is estimated at some 1.6 billion hectares (FAO, 2013), but there is an obvious lack of market penetration and application of nonrhizobial biofertilizers in spite of decades of research (Lesueur et al., 2016).

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 (BCC Research, 2014). In the developed world where agricultural chemicals remain relatively inexpensive, the use of PGPR occupies a small but growing niche (Timmusk et al., 2017). The global biofertilizer market is currently largely dominated by legume and $N_2$-fixing inoculants (Grand View Research, 2015). Literature suggests that the rhizobia-based inoculants occupy approximately 78% of the global biofertilizer market, while phosphate solubilizers and other bioinoculants have 15% and 7% shares, respectively (Owen et al., 2015; Transparency Market Research, 2017). Recent reports show that P-, Zn-, and K-based biofertilizers are also emerging as important bioinoculants to address deficiencies in soils (Khatibi, 2011; Shaikh and Saraf, 2017). According to Teotia et al. (2016), KSM are widely employed as bioinoculants in most countries, where agricultural soils are K-deficient. For instance, reports show that India 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 (Investing News Network, 2015).

Geographically, North America had the highest demand for biofertilizers in 2013 and it was projected that Asia-Pacific would show the most upward growth market for biofertilizers from 2014 to 2019. Market trends also indicated that this would increase further in the near future. Expectations were that North America would also dominate the global biofertilizer market in terms of demand over the forecast period (Markets and Markets, 2014). It is clear that the biofertilizer market continues to expand globally due to the need to increase food production sustainably (Verma et al., 2019).

Forecasts predict that the biofertilizer market share will reach US $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 (2019), the current global market of microbial inoculants was estimated at US $396.07 million in 2018 and expected to rise at an annual growth rate of 9.5% to approximately US $623.51 million by the year 2023. The revenue for the North American biofertilizer market was also expected to reach $205.6 million with a CAGR of 6.4% between 2011 and 2018 (Timmusk et al., 2017).

In the USA and Canada alone, legume biofertilizers were the largest revenue earners, accounting for 72.5% of the total revenue collection from biofertilizers in the year 2011, with expected growth at a CAGR around 5.3%, between 2011 and 2018. This advancement has also stimulated the isolation and selection of biofertilizers with the best PGP abilities (Timmusk et al., 2017). Some examples of biofertilizers that have been formulated and commercialized in some countries across the globe are displayed in Table 15.4. Most of these products are commercialized and used in Europe, Asia, and the USA but in Africa, only South Africa conspicuously has the most application of biofertilizers but Zimbabwe has also invested considerably in biofertilizer usage in soybean production (Mpepereki et al., 2000). Literature suggests that for most developing countries, the PGPR inoculant technology has little or no impact on productivity since it is either not practiced or the inoculants are of poor quality (Bashan, 1998). 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.

## 15.5 Constraints facing global biofertilizer research, commercialization, and practical application

Although decades of research have demonstrated the effectiveness of biofertilizers and microbial inoculants for enhancing plant growth and reducing the usage of artificial fertilizers, their commercialization and utilization remain largely untapped partly because of their inadequate shelf lives (Arora et al., 2010). Additionally, the formalities involved in registration of microbial formulations by environmental protection agencies in both developed and developing countries are very stringent and the costs involved are also high. This is often prohibitive to industrialists to venture into their commercialization and most often, research from laboratories do not end up as practical field applications. Closely related to this, commercialization and application of biofertilizers is largely hampered by quality assurance issues. According to Bashan et al. (2014), there are no international inoculant quality standards and quality issues are mostly governed by individual country regulations, for example, in Netherlands, Thailand, Russia, Canada, France, and Australia, or left to the discretion of manufacturers as in, Mexico, Argentina, the United Kingdom, and the USA.

The use of PGPR's is also seriously limited due to variability and inconsistency of results observed under laboratory, greenhouse, and field trials (Gouda et al., 2018). According to several reports, inconsistent field performance is actually the major obstacle to the marketing and use of biofertilizer formulations from a global perspective (Cho, 2013; Shaikh and Sayyed, 2015; Trivedi et al., 2017). Soil is an unpredictable environment and climatic variations relating to pH, humidity,

**TABLE 15.4** Examples of commercial biofertilizer products in some countries.

| Country | Manufacture | Product | Organisms | Crop | References |
|---|---|---|---|---|---|
| Argentina | Laboratorios BioAgro S.A. | Liquid PSA | *Pseudomonas aurantiaca* | Wheat | Celador-Lera et al. (2018) |
| | Semillera Guasch SRL | Zadspirillum | *Azospirillum brasilense* | Maize | Celador-Lera et al. (2018) |
| | Rhizobacter | Rhizo Liq | *Bradyrhizobium* sp., *Mesorhizobium ciceri*, *Rhizobium* spp. | Green gram, common bean, soybean, groundnut, chickpea | Adeleke et al. (2019) |
| Australia | Nutri-Tech solution | Bio-N | *Azotobacter* spp. | Not mentioned | Adeleke et al. (2019) |
| | Nutri-Tech solution | Myco-Tea | *Azotobacter chroococcum*, *Bacillus polymyxa* | Tea | Adeleke et al. (2019) |
| | Mapleton Int. Ltd | Twin N | *Azorhizobium* sp., *Azoarcus* sp., *Azospirillum* sp. | Not mentioned | Adeleke et al. (2019) |
| Brazil | Embrafros Ltda | Bioativo | PGPR consortia | Beans, maize, sugarcane, rice, cereals | Odoh et al. (2019) |
| Canada | Lallen and plant care BASF Inc. | Rhizocell GC Nodulator | *B. amyloliquefaciens* IT 45 *B. japonicum* | Beans, maize, carrot, rice, cotton | Odoh et al. (2019) |
| | BASF | Vault HP | *Bradyrhizobium* sp. | Not mentioned | Adeleke et al. (2019) |
| China | China Bio-Fertilizer AG | CBF | *Bacillus mucilaginosus*, *B. subtilis* | Various cereal plants | Celador-Lera et al. (2018) |
| Colombia | Agri Life Bio Solutions | Fe Sol B | Not mentioned | Not mentioned | Mishra and Arora (2016) |
| Germany | AbiTEP GmbH | FZB 24 fl, BactofilA 10 | *B. amyloliquefaciens*, *B. megaterium*, *P. fluorescens* | Vegetables, cereals | Odoh et al. (2019) |
| Hungary | AGRObio | BactoFil A10 | *A. brasilense*, *Azotobacter vinelandii*, *B. megaterium* | Maize | Mustafa et al. (2019) |
| India | Ajay Biotech | Ajay Azospirillum | *Azospirillum* | Cereals | Celador-Lera et al. (2018) |
| | Biomax | Greenmax AgroTech Life Biomix, Biodinc, *G. max* PGPR | *Azotobacter*, *P. fluorescens* | Various crops | Odoh et al. (2019) |
| | Agri Life Bio Solutions | Fe Sol B | Not mentioned | Not mentioned | Mishra and Arora (2016) |
| | T. stanes and Co. Ltd | Symbion van plus | *B. megaterium* | Not mentioned | (Sekar et al., 2016) |
| Kenya | MEA Fertilizer Ltd | Biofix | Rhizobia | Not mentioned | Adeleke et al. (2019), Martínez-Romero (2009) |
| Nigeria | IITA | Nodumax | *Bradyrhizobia* | Not mentioned | Adeleke et al. (2019), Tairo and Ndakidemi (2014) |
| Russia | JSC Industrial Innovations | Azobacterium | *Azospirillum brasilense* | Wheat, barley, maize, | Celador-Lera et al. (2018) |
| South Africa | Amka Products (Pty) Ltd | Organico | *Bacillus* spp. *Enterobacter* spp., *Pseudomonas*, *Stenotrophomonas*, *Rhizobium* | Not mentioned | Adeleke et al. (2019) |
| | Soygro (Pty) Ltd, S.A | Mazospirflo, Rhizostim | *A. brasiliense* | Not mentioned | Rodrigues et al. (2008) |

*Continued*

**TABLE 15.4 Examples of commercial biofertilizer products in some countries—cont'd**

| Country | Manufacture | Product | Organisms | Crop | References |
|---|---|---|---|---|---|
| | Biocontrol Products Ltd | Azo-N, Azo-N-Plus | *A. brasiliense, A. lipoferum* | Not mentioned | Raimi (2018), Rodrigues et al. (2008) |
| | Microbial solution (Pty) Ltd | Lifeforce, Firstbase, Biostart, Landbac, Composter, Waterbac | *Bacillus* spp. | Not mentioned | Mohammadi and Sohrabi (2012), Parmar and Sindhu (2013) |
| | BASF | Histick | *B. japonicum* | Not mentioned | Tairo and Ndakidemi (2014) |
| | Biocontrol Products Ltd | N-Soy | *B. japonicum* | Not mentioned | Tairo and Ndakidemi (2014) |
| | Biocontrol Products Ltd | Soilfix | *Brevibacillus laterosporus, Paenibacillus chitinolyticus* | Not mentioned | Grady et al. (2016) |
| | Amka Products | Organico | *Bacillus* sp. | Not mentioned | Raimi (2018) |
| | Biocontrol Products Ltd | Bac-up | *B. subtilis* | Not mentioned | Adeleke et al. (2019) |
| Spain | Lab (Labiotech) | InomixR | *B. polymyxa, B. subtilis* | Cereals | Odoh et al. (2019) |
| | Symborg | Vita Soil | PGPR consortia | Not mentioned | Sekar et al. (2016) |
| Thailand | Artemis & Angelio Co. Ltd. | BioPlant | *Clostridium, Achromobacter, Streptomyces, Aerobacter, Nitrobacter, Nitrosomonas, Bacillus* | Not mentioned | Adeleke et al. (2019) |
| United Kingdom | Cleveland biotech | Ammnite A 100 | *Azetobacter, Bacillus, Rhizobium, Pseudomonas* | Cucumber, tomato, pepper | Odoh et al. (2019) |
| | Legume Technology | Legume Fix | *Rhizobium* sp., *B. japonicum* | Common bean, soybean | Adeleke et al. (2019) |
| | Mapleton Int. Ltd | Twin N | *Azorhizobium* sp., *Azoarcus* sp., *Azospirillum* sp. | Not mentioned | Adeleke et al. (2019) |
| Uruguay | Lage y Cia | Nitrasec | *Rhizobium* sp. | Not mentioned | Adeleke et al. (2019) |
| USA | FLozyme Corporation | Inogro | 30 bacterial species | Rice | Celador-Lera et al. (2018) |
| | Becker Underwood | Vault NP | *B. japonicum* | Not mentioned | Adeleke et al. (2019) |
| | Becker Underwood | Chickpea Nodulator | *Mesorhizobium ciceri* | Chickpea | Adeleke et al. (2019) |
| | Becker Underwood | Cowpea Inoculant | *Rhizobia* | Cowpea | Adeleke et al. (2019) |
| | Plant Health Care Inc. | PHC Biopak | *B. azotofixans, B. licheniformis, B. megaterium, B. polymyxa, B. subtilis, B. thuringiensis* | Not mentioned | Adeleke et al. (2019) |
| | Plant Health Care | Complete Plus | *Bacillus strains* | Various crops | Mustafa et al. (2019) |
| | Monsanto | Quickroots | *Bacillus amyloliquefaciens* | Wheat and common bean | Celador-Lera et al. (2018) |

and temperature greatly impact the effectiveness of PGPR inoculants (Lucy et al., 2004; Zaidi et al., 2009). As a result, biofertilizers that function optimally under laboratory conditions may fail to replicate the desired results under field conditions (Nehra and Choudhary, 2015). Inconsistency of results may also occur for different plant cultivars (Remans et al., 2008), and fields (Hilali et al., 2001).

Lack of adequate formulations and low inoculant quality also constrain the successful and widespread use of biofertilizers (Stephens and Rask, 2000). For most formulations, bacterial populations often decline rapidly and shortly after soil inoculation. This phenomenon, combined with poor rhizosphere competitiveness and colonization can prevent the sufficient buildup of PGPR populations in the rhizosphere for effective crop bio-fertilization (Bashan et al., 2014). Other constraints relate to formulating products that are acceptable to farmers who do not readily accept alternative farming technologies especially on small-scale farms and in developing countries (Bashan et al., 2014), and especially due to their variable efficacy in the field compared to the conventional synthetic fertilizers (Arora et al., 2010). To increase their acceptance, biofertilizer formulations should be compatible with conventional products, applicable to standard/traditional machinery and not be associated with additional work (Catroux et al., 2001). Because chemical agro-products set high standards for long shelf life and ease of use, the greatest challenge is to formulate microbial biofertilizers that can match them. Additionally, inoculants must overcome the possible loss of viability and stability during storage and distribution. Considering the distribution of inoculants to remote farms, it is obvious that inoculants cannot always be stored under ideal conditions (Herrmann and Lesueur, 2013).

The lack of clarity in distinguishing biofertilizers from related opportunistic pathogens also hugely contributes to the acceptability of bottlenecks and challenges in convincing policy-makers, environmental protection agencies, and other stakeholders to promote the acceptance, registration, technology transfer, and adoption of biofertilizers (Nakkreen et al., 2005). It is obvious that farmers prefer products which are easy to handle and affordable and in this regard, the numerous disadvantages associated with biofertilizers such as low shelf life, temperature-sensitive storage conditions, bulkiness, low scope of export, high chances of contamination are possibly the main reasons as to why this promising technology is not yet popular as alternative soil fertilization means (Verma et al., 2011). All these challenges remain to be overcome before the biofertilizer technology can widely and successfully be commercialized and used on a global scale.

## 15.6 Future prospects concerning global biofertilizer research, commercialization, and practical applications

The future is bright for rhizobacterial biofertilizers and the global biofertilizer market potential is already considerable in size (Bhattacharyya and Jha, 2012; Malusá et al., 2012). The prospects are massive for different crops in different countries. For instance, Pereg and McMillan (2015) advanced that the potential use of beneficial microorganisms can greatly increase productivity in cotton cropping systems in Australia and pointed out that Australian cotton industry could greatly benefit from research into the isolation of crop-specific beneficial microbes. While commercial biofertilizers are currently available for different crops, they are not systematically applied because of inconsistent results. There is a need to carefully consider indigenous microbes because they are more effective and adapted to their respective environmental conditions. It would be necessary to carry out more studies on the ecology and colonization of microorganisms in the rhizosphere at different conditions to optimize them for different cultivars, climates, and soil conditions. Although field experiments with nonsymbiotic biofertilizers have shown real potential, it is still unclear as to whether these products can reliably substitute chemical fertilizers (Lesueur et al., 2016). Furthermore, relatively little is known about the conditions under which the potential inoculants work and there is insufficient information about their quality and application practices in published studies (Lesueur et al., 2016).

Gram-negative PGPR have better effects on plant growth and can make good biofertilizers. However, commercial-based Gram-negative PGPR formulations have short shelf lives because the bacteria do not sporulate like their Gram-positive counterparts and are easily killed by desiccation (Berg, 2009). To overcome this challenge, there is a need to develop mechanisms of maintaining sufficient numbers of viable bacterial inoculants for an acceptable period of time (Tabassum et al., 2017). There is a wealth of information on several plant PGPR, but there is still opportunity to isolate, screen, and culture more PGPR for development of biofertilizers. It is proposed that this biotechnology not only improves crop yield and quality but also environmental quality by decreasing the use of agrochemicals. However, the application of such fertilizers is limited because of their relatively short shelf lives and unpopularity. Therefore, for the efficient use of such biofertilizers, special emphasis should be put on improving their shelf lives and acceptability (Ahmad et al., 2016). Intensive efforts on research, legislative support, and awareness creation for these products will together increase their credibility, acceptance, and widespread application (Wezel, 2014).

Finding suitable carrier materials for formulations is a huge bottleneck in biofertilizer commercialization. Modern techniques like nano-biotechnological approaches, nanoencapsulation and microencapsulation can be explored to address this problem (Gouda et al., 2018). The use of KSM in cropping systems will certainly solve the deficiency of this macroelement in many agricultural soils, and further research in this area is definitely required. According to recent literature, KSM have not been formulated into biofertilizers to a huge extent due to inconsistent field performances, but molecular biology approaches are likely to lead to the development of better K solubilization abilities in the near future (Teotia et al., 2016). To establish the biofertilizer potential of PGPR, effective strains are often tested and established under controlled designs. However, the degree of plant growth stimulation by the commercially available microbial strains, their persistence in the rhizosphere and their PGP abilities under field conditions remains largely ambiguous and vague and the laboratory and controlled experiments must be followed by field trials to authenticate the efficiency of biofertilizers.

While nature offers an incredible diversity of microbes with awesome PGP traits and functions, new gene-editing technologies and synthetic biology tools can help engineer microbes with more efficiency (Hutchison et al., 2016). This is a relatively new field and can definitely bear fruits in the near future with more intensive research. Most available PGPR formulations comprise of single microbial strains that may not perform well in the field and for consortia formulations, the compatibility of different bacteria remains a bottleneck (Tabassum et al., 2017). Biofertilizer developers face problems with PGPR-cultivar specificity and the field performance of one given formulation can vary extensively with a multiplicity of climatic and environmental conditions of a crop (Tabassum et al., 2017). The commercialization of PGPR can be fastened if formulations with a broad spectrum of action, consistent field performance, and increased shelf lives can be developed. Time-consuming and expensive registration procedures for new products are also a huge obstruction for the market expansion of bacterial biocontrol products (Berg, 2009) which should be easened for biofertilizer success. The patent protection rights for effective products should also be strengthened to encourage the identification of efficient PGPR strains for development of biofertilizers. Within the context of climate change and increasing population, these alternative methods of crop fertilization offer an important potential for achieving sustainable food production (Le Mire et al., 2016), and meeting the sustainable development goals (SDGs).

## 15.7 Conclusions

Agricultural activities are definitely important for sustaining life on earth. However, the indiscriminate and continued use of artificial fertilizers is no longer sustainable. The use of biofertilizers has proven effective in promoting the growth of several crop plants but there is still an opportunity to study and exploit them for the many other crops. Modern tools and techniques can be used to enhance the activities of PGPR as biofertilizers for different crops. However, further research is still necessary to select more suitable microbes and microbial consortia that can together provide new formulations and opportunities with immense potential with regards to biofertilizers. With intensive research, commercialization, and utilization, biofertilizers could be the ultimate resources for sustainable agricultural practices and important tools for food security, environmental protection, and a sustainable world.

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