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Applications and Constraints of Plant Beneficial Microorganisms in Agriculture

Sovan Debnath, Deepa Rawat, Aritra Kumar Mukherjee, Samrat Adhikary and Ritesh Kundu

Abstract

At present time, chemical fertilizers are more in practice for crop production, which failed to upkeep soil and environment quality and affected the sustainability of the agricultural production system. Conversely, biofertilizers are ecosystem friendly, one of the best modern tools for agriculture, and are used to improve soil fertility and quality. Biofertilizers have now emerged as a highly potent alternative to inorganic fertilizers and offer an ecologically sound and economically attractive route for augmenting nutrient supply and increasing crop production. These include live cells of diverse genera of microorganisms and have the potential to fix atmospheric nitrogen and solubilize and mobilize plant nutrients from insoluble form through microbiological process. It has also the potential to diminish the gap between nutrient supply through fertilizers and nutrient removal by crops. Hence, biofertilizers can be a feasible option to the farmers to increase crop productivity and should find greater acceptance from the extension workers and commercial biofertilizer manufacturers.

Keywords: N fixers, P-K mobilizers, biofertilizer formulation, current advances

1. Introduction

Biofertilizers, more appropriately microbial inoculants, are the preparations containing one or more species of microorganisms which have the ability to capture or mobilize nutritionally important plant nutrients from non-usable to usable form through the biological processes such as N fixation, P solubilization, excretion of plant growth enhancers, or cellulose degradation in soil, compost, and other environments [1–3]. Biofertilizers are low-cost and environment-friendly supplement to chemical fertilizers and manures. Recently, biofertilizers are gaining momentum due to its ability to maintain soil health, minimize environmental degradation, and cut down the use of inorganic fertilizers in agriculture. These inputs gained added importance in rainfed agriculture in view of their low cost, as small to marginal farmers across the globe cannot afford expensive chemical fertilizers [4]. Biofertilizers could be an ideal input for cutting the cost of production and for practicing organic and conservation farming [5]. These organisms can be engaged in maintaining long-term soil fertility and sustainability [6, 7]. For the generations to come, biofertilizers are indispensable to ensure healthy soils and food.

The emphasis on chemical fertilizers, which sometimes led to unscientific and non-judicious application, has meant that the soil be regarded as an inert substrate for plant roots, instead of a living biosphere, the rhizosphere, containing a myriad of organisms [3]. The blanket use of inorganic fertilizers has also led to pollution of the soils and surface water bodies in many regions of the world [5]. Nevertheless, the importance of fertilizers, essential for achieving increased crop production, will further increase because there is little scope for bringing more areas under cultivation and majority of soils are deficient in many macro- and micronutrients. It is now realized that in agricultural lands under intensive monoculture system, including rice, which receives heavy application of chemical fertilizers alone, productivity slowly is declining, and environmental quality is deteriorating [8]. Intensification of agriculture has also widened the gap between nutrient removal and supplies and, thus, soil fertility depletion [9]. The role of biofertilizers in agriculture, therefore, assumes special significance, particularly in the present context of increased cost of inorganic fertilizers and their hazardous effects on soil health. The success with biofertilizers is reported for more than 100 years in many parts of the world, and statistically significant increase in yields has been observed [2]. However, their response varies with crops, host cultivars, locations, seasons, agronomic practices, bacterial strains, soil fertility, and interaction with native soil microflora.

2. Types of biofertilizers

Biofertilizers may be broadly classified into nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and organic matter decomposers (**Figure 1**). Nevertheless, it also includes organic fertilizers (manure, etc.), which are rendered in an available form due to the interaction of microorganisms or due to their association with plants.

2.1 Nitrogen-fixing biofertilizer (NFB)

Nitrogen-fixing organisms are used in biofertilizer as a living fertilizer composed of microbial inoculants or groups of microorganisms which are able to fix

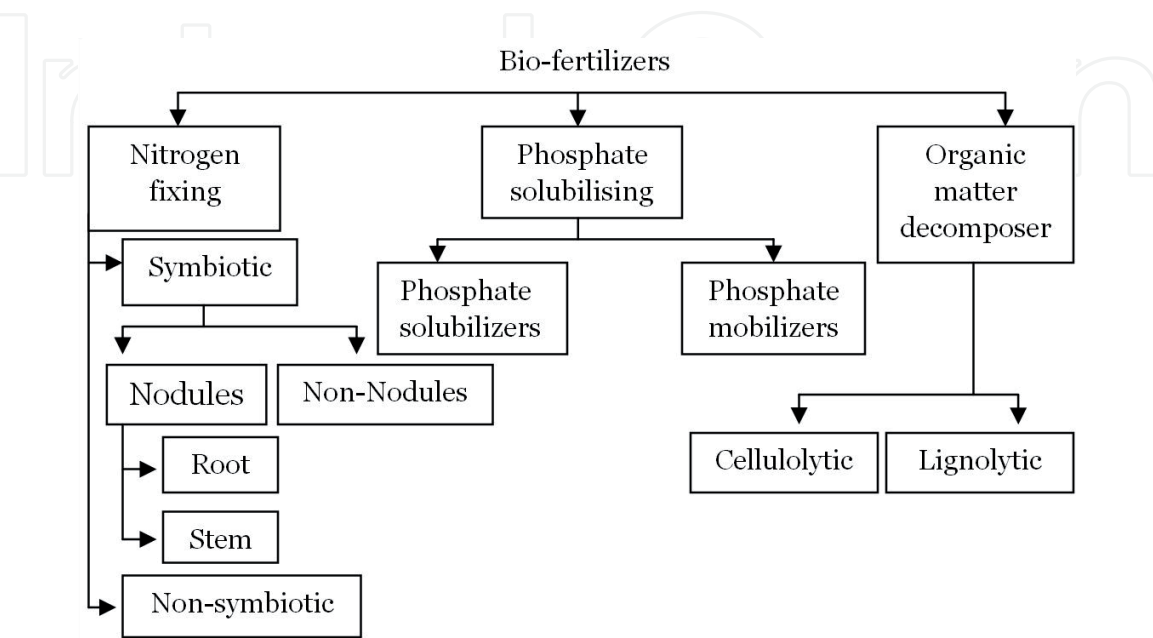


Figure 1.
A broad classification of biofertilizers.

atmospheric nitrogen, which is transformed into organic nitrogenous compound. The nitrogen-fixing bacteria work under two conditions, symbiotically (*Rhizobium*, *Frankia*) and as free-living bacteria (nonsymbiotic) such as *Azotobacter* and *Azospirillum*. The N₂-fixing bacteria associated with nonlegumes include species of *Achromobacter*, *Alcaligenes*, *Arthrobacter*, *Acetobacter*, *Azomonas*, *Beijerinckia*, *Bacillus*, *Clostridium*, *Enterobacter*, *Erwinia*, *Derxia*, *Desulfovibrio*, *Corynebacterium*, *Campylobacter*, *Herbaspirillum*, *Klebsiella*, *Lignobacter*, *Mycobacterium*, *Rhodospirillum*, *Rhodopseudomonas*, *Xanthobacter*, *Mycobacterium*, and *Methylosinus* [10].

2.1.1 Symbiotic

The most exploited symbiotic N₂-fixing bacteria are those belonging to the family *Rhizobiaceae*. *Rhizobium* inoculants are of greatest importance because of their ability to fix atmospheric N₂ in association with certain legumes [11]. It is estimated that N₂ fixation by *Rhizobium* in root nodules of legumes is of the order of 14 million tons on a global scale and is almost 15% of the industrial N fixation. Yield of many legumes can be increased substantially by the use of appropriate *Rhizobium* cultures. For successful nodulation each legume requires a specific species of *Rhizobium* to form effective nodules. Many legumes may be modulated by diverse strains of rhizobia, but growth is enhanced only when nodules are produced by effective strains of rhizobia [12]. *Rhizobium* can be used for legumes crop and trees (e.g., lucerne) and is a crop-specific inoculant, for example, *Rhizobium trifolii* for berseem, *Rhizobium meliloti* for lucerne, *Rhizobium phaseoli* for green gram and black gram, *Rhizobium japonicum* for soya bean, *Rhizobium leguminosarum* for pea and lentil, *Rhizobium lupini* for chickpea, and *Rhizobium* spp. for cowpea. *Rhizobium* is however limited by cross-inoculation group, and only certain legumes are benefited by this symbiosis.

Similar to the *Rhizobium*, other filamentous bacteria of genus *Frankia* belonging to the family *Frankiaceae* are found in the root nodules of nonlegumes such as trees and shrubs. These bacteria live in symbiosis with actinorhizal plants. These actinorhizal plants are used for timber and fuel wood production, for wind breaks, and for shelterbelts in coastlines and desert, as well as for land reclamation [13]. In arid areas where actinorhizal plants are not present, inoculation of *Frankia* (*Frankia alni*) can be advantageous [13]. Despite their potential importance, very limited information is available for inoculation practice and their use for *Frankia* symbiosis. However, their potential could be harnessed in agroforestry system.

2.1.2 Nonsymbiotic

In nonsymbiotic or free-living nitrogen, fixation does not require host plant, and bacteria do not form nodules. An example of such free-living bacteria is *Azotobacter*. They fix atmospheric N₂ nonsymbiotically, and the extent of fixation is directly depends upon the amount of carbohydrates utilized by them [14, 15]. *Azotobacter* comprises seven species: *A. chroococcum*, *A. vinelandii*, *A. beijerinckii*, *A. paspali*, *A. armeniacus*, *A. nigricans*, and *A. salinestri* [16]. Soils containing poor organic matter and antagonistic relationship with other soil microorganism adversely affect the population of *Azotobacter*. Besides nitrogen fixation, it can also synthesize growth-promoting substances, viz., auxins, gibberellins, and to some extent the vitamins. It also helps to improve seed germination and crop growth due to positive response of B vitamins, naphthalene acetic acid (NAA), gibberellic acid (GA), and chemical produced during the biochemical process showing antagonistic relationship with root pathogen [17].

2.1.3 Associative

Apart from symbiotic and nonsymbiotic nitrogen fixers, some bacteria form a close associative symbiosis with the higher plants. These bacteria live on the root surface and sometimes also penetrate into the root tissues but do not produce any visible nodule or outgrowth on the root tissue. *Acetobacter diazotrophicus* and *Herbaspirillum* spp. associated with sorghum, maize, and sugarcane [18–20] and *Azospirillum*, *Bacillus*, *Enterobacter*, *Herbaspirillum*, *Klebsiella*, *Pseudomonas*, and *Rhizobium* associated with rice and maize [21] are examples of associative nitrogen-fixing microorganism.

Azospirillum produces growth-regulating substances, which help to protect from soilborne diseases. It improves leaf area index and ultimately crop yield. Apart from many species across the globe, the major species under this genus are *A. lipoferum* and *A. brasilense*. *Azospirillum* species mainly identified as rhizosphere bacteria and its colonization of the rhizosphere have been studied extensively [22–24]. *Azospirillum* with the plant having C₄-dicarboxylic pathway (Hatch and Slack pathway) of photosynthesis formed associative symbiosis because they fix nitrogen in salts of organic acids such as malic and aspartic acid [25]. So, it is mainly beneficial for C₄ plants like maize, sorghum, sugarcane, etc. Despite all these benefits that bear great promise as a growth-promoting N₂-fixing biofertilizer, the main problem that limits the use of *Azospirillum* is great uncertainty and unpredictability of the results [26].

2.1.4 Cyanobacteria

Blue green algae (BGA) are known as cyanobacteria. Cyano means blue, so that means it is blue bacteria. These belong to eight different families, phototrophic in nature, and produce auxins, indole acetic acid (IAA), and GA. N-fixing blue green algae have been shown to be the most important in maintaining and improving the productivity of rice fields [27]. Favorable condition for biological nitrogen fixation by BGA is considered to be one of the reasons for relatively stable yield of rice under flooded condition. BGA forms symbiotic association capable of fixing nitrogen with fungi, fern, and flowering plants, but the most common symbiotic association has been found between a free floating aquatic fern, the *Azolla* and the *Anabaena azollae* (BGA) [28]. This association produces 40–60 tons of organic matter per hectare per year. Despite the importance of N₂-fixing cyanobacteria in rice cultivation, the production and application are poorly developed. Biofertilizers should be seriously considered for supporting sustainable agriculture practice [29].

2.1.5 Azolla

Azolla is known as free floating water fern that fixes atmospheric N₂ in symbiotic association with BGA (*Anabaena azollae*) in rice field. They are free-living organism and use energy derived from photosynthesis to fix nitrogen. It is a fast-growing water fern and can double its weight within a week [30]. The most common species occurring in India is *A. pinnata*. *Azolla* is rich organic manure and mineralizes soil nitrogen rapidly which can be available to the crop in a very short period. *Azolla* can help rice or other crops through dual cropping or green manuring of soil [31].

2.2 Phosphate-solubilizing biofertilizer (PSB)

Several experiments have showed the ability of different bacterial species to solubilize insoluble inorganic phosphate minerals, such as tricalcium phosphate,

dicalcium phosphate, hydroxyapatite, and rock phosphate. Phosphate-solubilizing bacteria are common in the rhizosphere, and secretion of organic acids like citric, oxalic, tartaric, acetic, lactic, gluconic, glyoxylic, maleic, and fumaric helps to convert insoluble form of phosphorus to plant available form [32]. Some of the bacterial genera are *Achromobacter*, *Agrobacterium*, *Micrococcus*, *Enterobacter*, and *Erwinia*. Among the soil bacterial communities, ectorhizospheric *Pseudomonas* and *Bacillus* and endosymbiotic rhizobia are found most effective phosphate solubilizers [33]. A higher amount of organic substances is present in the rhizosphere attracting the phosphate-solubilizing bacteria, and population is more in rhizospheric soil compared to the non-rhizospheric soil [34, 35]. Application of rock phosphate with PSB (*Bacillus megaterium* var. *phosphaticum*) showed that without phosphorus application PSB amendment could increase sugarcane yield up to 12.6% and it also improved sugar yield and juice quality [36]. Results of a greenhouse pot experiments with onion (*Allium cepa* L.) showed that application of *G. fasciculatum* along with *A. chroococcum* and 50% recommended P rate resulted in greater root length, plant height, bulb fresh weight, root colonization, and P uptake. Also the rate of chemical phosphatic fertilizer can be brought down [37]. Phosphate-solubilizing bacteria may be of greatest value in allowing the use of cheaper P sources.

2.3 Phosphate-mobilizing biofertilizer (PMB)

The symbiotic association between plant roots and fungi is termed as “mycorrhizal association.” Arbuscular mycorrhizal fungi (AMF) form symbiotic relationship with about 90% of land plant species [38]. These are of two types, ectomycorrhiza found in trees and found beneficial for forest trees, and endomycorrhiza for crop plants [39]. The functional symbiosis in mycorrhizal fungus is obligatory and depends on host photosynthates and energy. The plant acquires carbon for various mycorrhizal benefits to the host plant. The fungi capture nutrients from soil solution with the help of mycelium that extends from the root surfaces into the soil matrix. So, it results more efficient nutrient uptake and improved plant growth when mycorrhizal fungi colonized the root systems [40].

In higher plants, phosphorus and other nutrients are often mediated with mycorrhizal association, in which symbiotic association is performed by higher plants and associative fungi (*Glomus*) [41]. Hyphae of AMF do not solubilize the insoluble unavailable phosphorus but assimilate them from soil for their own requirement. Mycorrhizal roots can take up several times more phosphorus per unit root length than non-mycorrhizal roots. Mycorrhizal symbiosis also increased the tolerance of heavy metal contamination or drought, as well as lesser susceptibility of root pathogens. AMF also helps to improve soil quality by having a direct influence on soil aggregation [42]. This association is generally found very effective in agroforestry. The other crops benefited from AMF are sorghum, barley, wheat, tobacco, cotton, soybean, apple, citrus, grape, etc.

2.4 Organic matter decomposer

Composting is a key technology to use different types of organic wastes (crop residues, rural and urban wastes), and it takes about 4–6 months for its maturity for use as a source of plant nutrients. To decompose these organic waste, some cellulolytic and lignolytic microorganisms are introduced which help to decompose that organic wastes at a faster rate and make it ready for use within 2–3 months. Many soilborne fungal species like *Aspergillus niger*, *Penicillium*, *Trichoderma viride*, *Trichurus spiralis*, *Phanerochaete chrysosporium*, etc. act as an activator in the decomposition process of plant bodies containing cellulose or lignin [43].

2.5 Potassium-solubilizing biofertilizer (KSB)

Some soil microorganisms are capable of solubilising potassium from K-bearing minerals such as muscovite, mica, orthoclase and illite. These minerals are the potential source of available K in soil. Microorganism produces organic substances which react with these K bearing minerals to solubilize K and enhances available K in the soil solution [44]. These organisms also produce various types of amino acids, growth-promoting compounds (IAA, GA, etc.), and vitamins, promoting the crop growth and yield [45]. *Frateruria aurantia*, a K-solubilizing bacteria, is capable of mobilizing mixture of potassium from mica into a usable form for the plants, which has fairly been applied to crops in association with other biofertilizers without any antagonistic effects [46, 47]. Application of high-K-bearing clay mineral with K-solubilizing bacteria can help to mitigate the K requirement in agricultural soils [48].

2.6 Sulfur-solubilizing biofertilizer (SSB)

Sulfur is one of the major elements in oil seed crops and some vegetables (onion, oat, cauliflower, etc.) and some species (ginger, garlic, etc.). It is essential for biochemical synthesis of some important glycosides, pungent compound, and disease resistance properties. Khandkar et al. [49] observed that the nodule in black gram was increased due to sulfur application. Deficiency of sulfur in agricultural soils could be corrected by application *Azotobacter pasturianam* as biofertilizer [50].

2.7 Zinc-solubilizing biofertilizer (ZSB)

Zinc is one of the micronutrients whose deficiency affects the crop growth and crop yield [5, 8]. Zinc fertilizers are very costly and its availability is also limited. So, zinc solubilizers can play a vital role for providing adequate supply of zinc to the crop and enhancing the crop growth and yield. The microorganisms which are well known for solubilization of zinc are *Bacillus subtilis*, *Thiobacillus thiooxidans*, and *Saccharomyces* sp. [51]. These strains are used as zinc biofertilizers and get positive response to the crop. Sometime application of zinc fertilizers combination with zinc biofertilizers (*Bacillus* sp.) gave better response and increased zinc concentration in the soil [46].

2.8 Plant growth-promoting rhizobacteria (PGPR)

Plant growth promoting rhizobacteria (PGPR), when grown in association with host plant, result in stimulation of growth of their host. It represents a wide variety of soil bacteria. These bacteria vary in their mechanism of plant growth promotion but generally influence growth via P solubilization, nutrient uptake enhancement, and plant growth hormone production [33, 52, 53]. Bertrand et al. [54] showed that a rhizobacterium belonging to the genus *Achromobacter* could enhance root hair number and length in rapeseed. The PGPR inoculants promote growth by any of the following mechanism: (i) suppression of plant disease (bioprotectants), (ii) improved nutrient acquisition (biofertilizers), and (iii) phytohormone production (biostimulants).

3. Potential of biofertilizers

The competent strains of nitrogen-fixing, phosphate-solubilizing, or cellulolytic microorganisms are used for application in seed, soil, and roots of saplings or

composting areas with the intention to amplify the number of such microorganisms and speed up those microbial processes which supplement the availability of nutrients that can be easily assimilated by plants (**Table 1**).

3.1 *Rhizobium*

They can fix nitrogen 50–100 kg/ha with legumes only. The symbiotic relationship between leguminous crops and *Rhizobium* is very important for crop production system. It has been proven to be useful for pulse legumes like chickpea, red gram, pea, lentil, black gram, oil seed legumes like soybean and groundnut, and forage legumes like berseem and lucerne [77]. The suitable strain is capable to increase the crop yield up to 10–35% since N is fixed at 40–200 kg/ha which is able to meet up to 80–90% of N need of the crop [46].

3.2 *Azotobacter*

The presence of this organism has been reported from the rhizosphere of various crop plants such as rice (*Oryza sativa* L.), maize (*Zea mays* L.), sugarcane (*Saccharum officinarum* L.), bajra (*Pennisetum glaucum* L.), vegetables, and plantation crops [78]. It can fix N up to 25 kg/ha under optimal conditions and increase yield up to 40–50% [5]. It has been observed that *Azotobacter* improved the seed germination and crop growth owing to the affirmative response of B vitamins, NAA, GA, and other chemicals produced during the biochemical process that exhibited antagonistic relationship with root pathogens [17].

3.3 *Azospirillum*

Apart from their nitrogen-fixing ability of about 20–40 kg/ha, they are also known to produce various growth-regulating substances. The *Azospirillum* form associative symbiosis with plants having the C₄-dicarboxylic pathway of photosynthesis (Hatch and Slack pathway), as they grow and fix nitrogen on salts of organic acids such as malic and aspartic acid [25]. Thus, *Azospirillum* is mostly recommended for C₄ plants like maize, sugarcane, sorghum, pearl millet, etc. [5].

3.4 *Azolla*

Azolla can fix 100–150 kg N/ha/year in rice fields along with *Anabaena* [79]. It can also be incorporated as green manure by adding in the fields prior to rice planting. The most widespread species in India is *A. pinnata* and can be reproduced on commercial scale by vegetative means. India has recently introduced some species of *Azolla* (*A. caroliniana*, *A. microphylla*, *A. filiculoides*, and *A. mexicana*) for their large biomass production [80].

3.5 Blue green algae (BGA)

In India, rice is one of the main staple food crops grown by farmers by using of BGA and *Azolla* as a plant nutrient provider. Generally, BGA has been reported to be able to supply 50–100 kg/ha nitrogen through biological N fixation, and in addition, it is also known to supply plant growth-promoting substances to crop under puddled condition [81].

Keeping in view the importance of biofertilizer for sustainability in agriculture sector, the government of India has also ensured the quality and production of biofertilizers under Section 3 of essential commodities, Act 1955. The government

Biofertilizer	Recommended crop	Effect	Reference
Nitrogen-fixing biofertilizers			
<i>Rhizobium</i>	Bean	Increased straw and grain yield, harvest index, and agronomic fertilizer use efficiency	Yanni et al. [55]
		Increased nodule dry weight and seed yield	Koskey et al. [56]
	Cowpea, common bean, peas, fenugreek	Increased vegetative growth parameters, shoot minerals, and yield	Arafa et al. [57]
	Pea	Increased mean seed yield	Abera and Abeba [58]
	Faba bean	Improved enzymatic activity in inoculated soil	Beshir et al. [59]
<i>Bradyrhizobium</i>	Pigeon pea	Induced improvement in nodule dry weight, plant biomass, and shoot N uptake	Youseif et al. [60]
<i>Azotobacter</i>	Mulberry	Increased trends in silk filament length, cocoon weight, shell weight, and shell ratio	Moorthi et al. [61]
	Pearl millet	Improved plant height, dry matter accumulation, no. of effective tillers, grain per ear, and grain and stover yield	Yadav et al. [62]
	Cauliflower	Increased morphological character and yield	Subedi et al. [63]
	Wheat	Enhanced grain yield	Mahato and Kafle [64]
<i>Azospirillum brasilense</i>	Maize	Increased plant growth and improved biochemical traits	Zeffa et al. [65]
	Wheat	Enhanced plant growth and increased root depth, fresh weight of roots and shoots, and nutrient use efficiency	Sayed et al. [66]
<i>Azospirillum lipoferum</i>	Foxtail millet	Improved seed weight, panicle, dry weight of shoot and root, total N content of shoot, and root and grain yield	Rao and Charyulu [67]
<i>Cyanobacteria</i>	Rice	Improved yield	Bhoosan et al. [68]
<i>Azolla</i>	Rice	Increased grain and straw yield	Mishra et al. [69]
	Rice	Reduction in weed emergence	Biswas et al. [70]
Phosphate-solubilizing biofertilizers			
<i>Pseudomonas spp.</i>	Chickpea	High nodulation and stimulation of plant growth	Malik and Sandhu [71]
<i>Bacillus spp.</i>	Amaranth	Improved nutrient use efficiency	Pandey et al. [72]
<i>Aspergillus niger</i>	Wheat	Improved growth and P uptake	Xiao et al. [73]

Biofertilizer	Recommended crop	Effect	Reference
<i>Bacillus thuringiensis</i>	Rice	Increased shoot length	David et al. [74]
Phosphate-mobilizing biofertilizers			
VAM	Jatropha	Reduced salt stress	Kumar et al. [75]
	Maize	Enhanced concentration of P in plant	Sudova and Vosatka [76]

Table 1.
Effect of biofertilizers on crop improvement.

has issued a fertilizer (control) amendment order (FCO), 2006, with the gazette notification, S.O. 391 (E), dated on March 24, 2006, for biofertilizer production. After coming into enforcement of this order, four biofertilizers came under the FCO, i.e., *Rhizobium*, *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria [82]. Though the effect of biofertilizers on the crop production is slow, they possess vast potential for meeting plant nutrient requirements and sustaining soil quality while curtailing the use of chemical fertilizers. The development of biofertilizers has paced up in the last 20 years, and phosphate-solubilizing bacteria (PSB) have been reported to be used most widely among the farming community [83, 84].

4. Role of biofertilizers in alleviating abiotic stress in plants

4.1 Salinity

The condition of soil salinity generally inhibits the crop growth. High concentration of salts imparts pessimistic effects on plant metabolism and growth owing to the osmotic stress and accumulation of Na^+ and Cl^- ions [85]. Salt stress is responsible for obliteration of the microbial communities and carbon cycling in the soil [86]. Several researchers have recommended various chemical, physical, and biological methods for improving crop growth and performance under salt-affected soils [87–89]. Apart from this, various other advancements, counting traditional breeding and genetic engineering, have also been tried to improve the salinity tolerance in plants. However, such intercessions have little success rate, owing to the intricacy of salinity tolerance and slight genetic variability among germplasm accessions [90]. Among these methods, the biological means of improving crop growth has identified some promising outcomes so far.

Several researches of recent past have suggested the efficiency of cyanobacteria for remediation of salt-affected soil in laboratory studies and field trials [91–95]. There have been a variety of suggested mechanisms involved in reclaiming the salt-affected soils and promotion of plant growth by cyanobacteria. Li et al. [96] suggested the nitrogen fixation, extracellular polymeric substance production, the accumulation of compatible solutes, plant growth hormone production, active export of ions through K^+/Na^+ channels and Na^+/H^+ antiporters, and defense enzyme productions as possible mechanisms for salt-affected soil remediation using cyanobacteria. Khalilzadeh et al. [97] suggested that enhanced grain filling speed, photosynthesis, plant water accumulation, and flag leaf salt accumulation were some plausible mechanisms for cycocel and PGR-induced salt tolerance shown in wheat plants under pot experiment. After investigating the salt stress

and inoculation effect on nodulation and growth of forage cowpea (*Vigna unguiculata* cv. Baladi), Omara and Tamer [98] reported the alleviation of detrimental effects of salt stress by applying dual inoculation with tolerant *Bradyrhizobium* SARSRh3 + *Bradyrhizobium* SARS-Rh5 due to improvement in nodulation, growth dynamics, increase in K uptake, and reduced Na uptake in forage cowpea plants.

The use of bacterial inoculation, specifically, plant growth-promoting rhizobacteria (PGPR), has proved to be effective in improving plant stress tolerance. Several reports claimed that PGPR successfully improved growth of a wide range of agricultural crops under environmental stress conditions [99–104]. The PGPR are also known to use several mechanisms to sustain the plant growth under salt stress. Rhizobacteria trigger the plant antioxidant defense mechanism by modifying the key enzymes activity, viz., superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) that forage the overproducing reactive oxygen species (ROS) and ultimately defend the plants from salt toxicity [100, 105]. PGPR-inoculated plants have also been reported to have changes in their root architecture owing to the increased indole-3-acetic acid (IAA) level that facilitates the plants to take up more nutrients under salinity stress condition in soil [106, 107]. In a field trial, Kamaraj and Padmavathi [108] reported that the seeds treated with triple inoculation of bio-fertilizer such as *Rhizobium*, phosphate-solubilizing bacteria, and VAM at 600 gm/ha gave higher crop growth and seed yield parameters under saline stress condition.

The use of microorganisms as biofertilizers has also been reported to alleviate the effect of salinity on vegetables. The inoculation of seeds of various vegetables, such as tomato, pepper, bean, and lettuce, with PGPR has resulted in augmented root and shoot growth, dry weight, fruit, and seed yield and improved the resistance of plants to salt stress [109]. Mahmood et al. [110] revealed that PGPR and Si synergistically improved the salinity tolerance in mung bean. The use of arbuscular mycorrhiza (AM) has also been recorded to improve salt stress in tomato, onion, and lettuce [111–113].

4.2 Drought

Drought stress influences a range of growth parameters and stress-responsive genes in plants under the situation of stress. Inadequate quantity of water generally reduces the cell size and membrane integrity; create reactive oxygen species; and lowers down the crop productivity by promoting leaf senescence [114]. The plant-associated microbes possess a variety of mechanisms to deal with harmful impact of drought on plants and soil. Apart from the water content, these microbes also supply nutrients and provide favorable environmental conditions for the sustainable growth of plants. These microbes are known to encourage plant growth and development by various potential mechanisms which include:

- a. Synthesis of various phytohormones such as IAA, cytokinins, and abscisic acid
- b. Production of bacterial exopolysaccharides
- c. Production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase
- d. Promoting systemic tolerance

The PGPR have the ability to produce plant hormones like IAA that encourage plant growth under stress condition. IAA is the most vigorous auxin that regulates the vascular tissue differentiation, adventitious and lateral root differentiation, cell division, and shoot development under drought stress [115]. The exopolysaccharides

synthesized by microbes also enable certain plants to tolerate drought. Three drought-tolerant bacterial strains, viz., *Proteus penneri* (Pp1), *Pseudomonas aeruginosa* (Pa2), and *Alcaligenes faecalis* (AF3), inoculated in maize crop resulted in increased relative water content, protein, and sugar [116]. Sandhya et al. [117] have also reported the improved plant resistance against drought stress by the use of exopolysaccharide-producing bacteria. Under the stress environment, ACC is an immediate precursor of ethylene. The ACC deaminase produced by bacteria hydrolyzes ACC into ammonia and alpha-ketobutyrate [118]. Vardharajula et al. [119] have reported the decrease in antioxidant activity and enhanced production of proline, free amino acid, and sugar in plants with microbial inoculants under drought stress. The mycorrhizal inoculation in consortium with specific bacteria has also been recorded to improve plant growth, nutrient uptake, and relative water content to decrease the effect of drought. Ortiz et al. [120] revealed that the association of *Pseudomonas putida* and *Bacillus thuringiensis* reduced the stomatal conductance and electrolyte leakage owing to the accumulation of proline in shoot and root.

Tomato (*Lycopersicon esculentum* Mill) cv. Anakha treated with phosphate-solubilizing bacteria (*Bacillus polymyxa*) was reported to secrete excess proline to resist the drought condition [121]. Giri et al. [122] studied the physiological response of peas (*Pisum sativum* L.) when inoculated with ACC deaminase bacteria *Variovorax paradoxus* 5C-2 under moisture stress and watering conditions. It was reported that the bacterial effects were more apparent and consistent in moisture stress condition. The AM fungal inoculation reduced the concentration of malondialdehyde and soluble protein in plant leaf and enhanced the activities of SOD, POD, and CAT, which ultimately led to the improved osmotic adjustment and drought tolerance of mycorrhizae citrus-grafting seedlings [123]. Inoculation of *Glomus versiforme* in citrus plants has also been reported to improve the osmotic status of the plant in drought condition owing to the enhanced levels of nonstructural carbohydrates, K^+ , Ca^{+2} , and Mg^{+2} , which helped the plants to resist the drought condition [124]. Ruiz-Sanchez et al. [125] revealed the increase in photosynthetic efficiency and the antioxidative response of rice plant in drought stress after inoculation of arbuscular mycorrhiza.

Phosphate-solubilizing microorganisms have positively increased the plant growth and phosphorus absorption in maize resulting in increasing the efficiency of plant tolerance to drought stress conditions [126]. Inoculation of *Pseudomonas* spp. to basal plants under water stress improved their antioxidant and photosynthetic pigment content. *Pseudomonas* spp. were also found to have affirmative influence on the seedling growth and seed germination under water stress [127]. Chavoshi et al. [128] reported that phosphorus- and potassium-solubilizing bacterial consortium was able to increase biomass and important physiological traits in red bean under limited irrigation conditions. Li et al. [129] investigated the response of synergistic application of superabsorbent polymer (SAP) and biofertilizers (*Paenibacillus beijingsis* BJ-18 and *Bacillus* sp. L-56) on plant growth, including wheat and cucumber in drought stress. Both the biofertilizers amended with SAP were recorded to promote germination rate of seeds, plant growth, and soil fertility (urease, sucrose, and dehydrogenase activities). Moreover, the quantitative real-time PCR analysis revealed that biofertilizer + SAP significantly regulated the expression levels of genes involved in ethylene biosynthesis, stress response, salicylic acid, and transcription activation in plants in the drought stress condition.

5. Application and doses of biofertilizers

Biofertilizers are usually applied along with carrier material in order to enhance their efficacy. Khosro and Yousef [130] elucidated that the use of these

microorganisms along with carrier material makes it possible for the users to handle them easily, facilitate their long-term storage, and augment their effectiveness. The biofertilizers are usually used as seed treatment in which the inoculant is mixed with water to make form of slurry and then mixed with seeds (**Table 2**). In this case, the carrier material is generally used as fine powder to get the tight coating of inoculant on the seed surface. For this purpose the use of adhesive, such as gum arabic, methyl ethyl cellulose, sucrose solutions, and vegetable oils, is recommended.

5.1 Seed treatment

The seed treatment of biofertilizer is done by suspending 200 g of biofertilizer in 300–400 mL of water and mixed tenderly with 10 kg of seeds using an adhesive-like acacia gum, jiggery solution, etc. Thereafter, the seeds are spread on a clean sheet/cloth under the shade to dry. The shade dried seeds should be sown within 24 hours.

Name of organism	Mode of action	Host crops for which used	Method of application	Rate of inoculant	Remarks
<i>Rhizobium</i>	Symbiotic N ₂ fixation	Legumes like pulses, soybean, groundnut	Seed treatment	200 g per 10 kg seed	Leaves residual N in soil for the next crop
<i>Azotobacter</i>	Nonsymbiotic N ₂ fixation	Cereals, millets, cotton, vegetable	Seed treatment	200 g per 10 kg seed	Also controls certain diseases
<i>Azospirillum</i>	Associative N ₂ fixation	Nonlegumes like maize, barley, oat, sorghum, millet, sugarcane, rice, etc.	Seed treatment	200 g per 10 kg seed	Produces growth-promoting substances, can be applied to legumes as co-inoculant
Phosphate solubilizers	Phosphorus solubilization	Soil application for all crops	Seed treatment	200 g per 10 kg seed	Can be mixed with rock phosphate
Blue green algae (BGA)	Nonsymbiotic N ₂ fixation	Rice	Soil application	10 kg/ha	Reduces soil alkalinity, has growth-promoting effects
<i>Azolla</i>	Symbiotic N ₂ fixation	Rice	Soil application	1 ton dried material/ha	—
Mycorrhiza (VAM)	Symbiotic association	Many tree species, wheat, sorghum, ornamentals	Soil application	—	Usually seedlings are inoculated

Table 2.
Application and doses of biofertilizers for various crops [43].

5.2 Seedling root dip

This method is generally applied for transplanted crops. For rice crop, a bed filled with water is prepared in the field, and recommended biofertilizers are mixed in this water. The roots of seedlings are dipped for 5–10 min and then transplanted.

5.3 Soil treatment

Four kilograms of the recommended biofertilizer is mixed in 200 kg of compost and kept overnight. This mixture is then incorporated in the soil at the time of sowing or planting.

5.4 Liquid biofertilizers

Bhattacharyya and Kumar [131] stated that biofertilizers manufactured in India are mostly carrier based and the microorganisms have the shelf life of only 6 months. The advantage of liquid biofertilizer over powder based is that microorganisms have longer shelf life up to 2 years and they are tolerant to UV radiations and high temperature (55°C). The count is as high as 10⁹ c.f.u/ml, which is maintained constant up to 2 years. Since they are liquid formulation, the application in the field is very easy and simple. They are applied using hand sprayer, power sprayer, and fertigation tanks and as basal manure mixed along with farm yard manure (FYM) [132, 133].

For all leguminous crops, *Rhizobium* is generally applied as seed inoculant. *Azospirillum*/*Azotobacter* is inoculated through seed, seedling root dip, and soil application methods in transplanted crops. For direct sown crops, *Azospirillum* is usually incorporated through seed treatment or soil application.

6. Constraints in biofertilizer use

Despite little investment, eco-friendly character, and advantages of biofertilizers, adoption of this organic input by farmers has remained far from satisfactory. There are several constraints at production, marketing, and field level which limit the adoption of biofertilizers among the wide community of farmers.

6.1 Production constraints

- **Raw material:** Biofertilizers are generally prepared as carrier-based inoculants with effective microorganisms. Granular form of carrier material like peat, perlite, charcoal, etc. is commonly recommended for soil inoculation of the biofertilizer [46]. These carrier materials for seed and soil treatment are not easily available and accessible to the small and marginal farmers. In India, these carriers are neither available in adequate quantities nor in desirable quality, which is one of the reasons for the lack of popularity of biofertilizers among the Indian farmers [134].
- **Specificity of strains for different agroclimatic regions:** The majority of the strains of biofertilizers is not only crop specific but is also soil and agroclimate specific. The lack of region-specific strains is one of the major constraints associated with biofertilizer use. This confines their extensive and optimum use with expected performance [46, 135].

- **Biological constraints:** There is likelihood of presence of ineffective or antagonistic strains in the bio-inoculants, and removal of these strains from the bio-inoculant is generally a complicated task. The selected strains should also have the ability to compete with other strains, N-fixing or nutrient-solubilizing/nutrient-mobilizing ability over a range of environmental conditions, and ability to survive in broth and in inoculants carrier [134, 136]. This largely affects the efficiency of desired microorganism as biofertilizer.
- **Technical constraints:** Biofertilizers possess the tendency to mutate during fermentation which increases the cost of production and quality control. A broad range of research is needed to reduce such undesired changes [5].
- **Economic constraints:** For the production of quality product, the use of high-tech instruments and equipment is required. In the absence of these facilities, production of contamination free product is uncertain. Moreover, the lack of trained human resources in the production units and lack of suitable training on the production techniques also serve as a limitation of the widespread use of biofertilizers [137].

6.2 Marketing constraints

- **Limited transportation and storage facilities:** The serviceable life of biofertilizers prepared with common carriers like peat or lignite is usually less than 6 months. It has been recommended that best results of biofertilizers are possible only if the material is used within 3–4 months of production. But often the biofertilizers are subjected to very high temperature during transportation and storage which reduces their efficiency and leads to lack of interest among the dealers due to nominal profit margin [138, 139].
- **Low demand:** Owing to the lack of adequate promotion and awareness about the advantages of biofertilizers, farmers refrain themselves from adopting this sustainable practice due to different methods of inoculation and no visual variation in the crop growth immediately as in the case of inorganic fertilizers [46].

6.3 Field-level constraints

- Soil conditions like acidity, presence of salts and toxic elements, application of pesticides, water logging and drought [140]
- Poor organic matter content of many soils around the world
- Extreme annual and diurnal variation in soil temperature
- Poor competition and adaptability as compared to native soil microflora [46]

7. Conclusion

Enhancing agricultural crop production needs to be ushered through new horizons without causing any harm to the natural resources and environmental quality. So, low-cost and eco-friendly biofertilizers could play a critical role in increasing crop yield by cutting the use of chemical fertilizers and increased nutrient use efficiency vis-à-vis maintaining long-term soil fertility and quality. However, lack

of consistent responses in different soils and environmental conditions, difficulties in application, limited shelf life, and slow action are reasons restraining the wide-spread commercialization of biofertilizers. We need to apprehend that biofertilizers are extremely specific to crops, soils, and edaphic factors and their sustainability in soils largely depends on pH, soil organic matter, native microbiota, and soil moisture and temperature regime. Our understanding on particular strain effectiveness with specific to crop, soil, and climate needs to be strengthened through extensive research and development. Research should also focus on standardizing biofertilizer dose in a particular soil and crop. Efforts from the government should be emphasized on frequent monitoring of the biofertilizer manufacturing units to assure proper method of production and top quality of the produce and storage. Wide publicity and large-scale utilization of this new era technology through research institutions, nongovernment organizations (NGOs), scientific training, farmer fairs or exhibitions, extension workers, and media are urged.

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References

- [1] Vessey VK. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*. 2003;**255**:571-586
- [2] Trimurtulu N, Rao DLN. Liquid Microbial Inoculants and their Efficacy on Field Crops. Amaravathi: ANGRAU, Agricultural Research Station; 2014. p. 54
- [3] Pal S, Singh HB, Farooqui A, Rakshit A. Fungal biofertilizers in Indian agriculture: Perception, demand and promotion. *Journal of Eco-friendly Agriculture*. 2015;**10**:101-113
- [4] Barman M, Paul S, Choudhury AG, Roy P, Sen J. Biofertilizers as prospective input for sustainable agriculture in India. *International Journal of Current Microbiology and Applied Sciences*. 2017;**6**:1177-1186
- [5] Singh M, Dotaniya ML, Mishra A, Dotaniya CK, Regar KL, Lata M. Role of biofertilizers in conservation agriculture. In: Bisht JK et al., editors. *Conservation Agriculture*. Singapore: Springer; 2016. pp. 113-134
- [6] Sharma A, Kumar S, Ahmed N, Sharma OC, Debnath S. Protection of fruit growing soils from the threats on the mark. In: Sharma A et al., editors. *Soil Management Strategies-Thriving to Optimise Fruits Production*. New Delhi: Kalyani Publishers; 2015. pp. 158-170
- [7] Shelat HN, Vyas RV, Jhala YK. Biofertilizers and PGPR for evergreen agriculture. In: Verma DK, Srivastav PP, editors. *Microorganisms in Sustainable Agriculture, Food and the Environment*. Boca Raton: CRC Press; 2017
- [8] Debnath S, Pachauri SP, Srivastava PC. Improving use efficiency of applied phosphorus fertilizer by zinc fertilization in basmati rice-wheat cropping system. *Indian Journal of Agricultural Research*. 2015;**49**:414-420
- [9] Gupta N, Debnath S, Sharma S, Sharma P, Purohit J. Role of nutrients in controlling the plant diseases in sustainable agriculture. In: Meena VS et al., editors. *Agriculturally Important Microbes for Sustainable Agriculture*. Singapore: Springer Nature; 2017. pp. 217-262
- [10] Wani SP. Inoculation with associative nitrogen fixing bacteria: Role in cereal grain production improvement. *Indian Journal of Microbiology*. 1990;**30**:363-393
- [11] Sheraz MS, Hassan GI, Samoon SA, Rather H, Showkat A, Dar A, et al. Biofertilizers in organic agriculture. *Journal of Phytology*. 2010;**2**:42-54
- [12] Cooper J. Multiple responses of rhizobia to flavonoids during legume root infection. In: Callow JA, editor. *Advances in Botanical Research: Incorporating Advances in Plant Pathology*. Cambridge: Academic Press; 2004. pp. 1-62
- [13] Schwencke J, Caru M. Advances in actinorhizal symbiosis: Host plant-*Frankia* interaction, biology, and applications in arid land reclamation: A review. *Arid Land Research and Management*. 2001;**15**:285-327
- [14] Stephens JHG, Rask HM. Inoculant production and formulation. *Field Crops Research*. 2000;**65**:249-258
- [15] Gomare KS, Mese M, Shetkar Y. Isolation of *Azotobacter* and cost effective production of biofertilizer. *Indian Journal of Applied Research*. 2013;**3**:54-56
- [16] Becking J. The family Azotobacteraceae. *PRO*. 2006;**6**:759-783
- [17] Mazid M, Zeba HK, Quddusi S, Khan TA, Mohammad F. Significance of Sulphur nutrition against metal induced

oxidative stress in plants. Journal of Stress Physiology & Biochemistry. 2011;7:165-184

[18] Triplett E. Diazotrophic endophytes: Progress and prospects for nitrogen fixation in monocots. Plant and Soil. 1996;186:29-38

[19] James EK, Olivares FL, Baldani JI, Dobereiner J. *Herbaspirillum*, an endophytic diazotroph colonizing vascular tissue in leaves of *Sorghum bicolor* L. Moench. Journal of Experimental Botany. 1997;48:785-797

[20] Boddey RM, Da Silva LG, Reis V, Alves BJR, Urquiaga S. Assesment of bacterial nitrogen fixation in grass species. In: Triplett EW, editor. Prokaryotic Nitrogen Fixation: A Model System for Analysis of a Biological Process. Wymondham, UK: Horizon Scientific Press; 2000. pp. 705-726

[21] James EK. Nitrogen fixation in endophytic and associative symbiosis. Field Crops Research. 2000;65:197-209

[22] Burdman S, Kigel J, Okon Y. Effect of *Azospirillum brasilense* on nodulation and growth of common bean (*Phaseolus vulgaris* L.). Soil Biology and Biochemistry. 1997;29:923-929

[23] Pereg-Gerk L, Gilchrist K, Kennedy IR. Mutants with enhanced nitrogenase activity in hydroponic *Azospirillum brasilense* wheat association. Applied and Environmental Microbiology. 2000;66:2175-2184

[24] Steenhoudt O, Vanderlayden J. *Azospirillum*, a free living-nitrogen fixing bacteria closely associated with grasses: Genetic, biochemical and ecological aspects. FEMS Microbiology Reviews. 2000;24:487-506

[25] Arun KS. Bio-Fertilizers for Sustainable Agriculture. Mechanism of P-Solubilization. Sixth ed. Jodhpur,

India: Agribios Publishers; 2007. pp. 196-197

[26] Van de Broek A, Dobbelaere S, Vanderleyden J, Vandommelen A. *Azospirillum*-plant root interactions: Signaling and metabolic interactions. In: Triplett EW, editor. *Prokaryotic Nitrogen Fixation: A Model System for Analysis of a Biological Process*. Wymondham, UK: Horizon Scientific Press; 2000. pp. 761-777

[27] Watanabe I, Roger PA. Nitrogen fixation in wetland rice fields. In: Subba Rao NS, editor. Current Developments in Biological Nitrogen Fixation. Oxford: IBH, New Delhi; 1984. pp. 237-276

[28] Rahman MM, Amano T, Shiraiwa T. Nitrogen use efficiency and recovery from N fertilizer under rice-based cropping systems. Australian Journal of Crop Science. 2009;3:336-351

[29] Hashem MA. Problem and prospects of cyanobacterial biofertilizers for rice cultivation. Australian Journal of Plant Physiology. 2001;28:881-888

[30] Kannaiyan S. Blue green algae biofertilizers. In: Kannaiyan S, editor. The Biotechnology of Biofertilizers for Rice Crops. Coimbatore, India: Tamil Nadu Agric. University publications; 1990. p. 225

[31] Ghosh N. Promoting biofertilisers in Indian agriculture. Economic and Political Weekly. 2004;5:5617-5625

[32] Kim KY, Jordan D, McDonald GA. Effect of phosphate solubilizing bacteria and vesicular-arbuscular mycorrhizae on tomato growth and soil microbial activity. Biology and Fertility of Soils. 1998;26:79-87

[33] Richardson AE. Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Australian Journal of Plant Physiology. 2001;28:897-906

- [34] Ahmad M, Nadeem SM, Naveed M, Zahir ZA. Potassium-solubilizing bacteria and their application in agriculture. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi: Springer; 2016. pp. 293-313
- [35] Bahadur I, Maurya BR, Kumar A, Meena VS, Raghuwanshi R. Towards the soil sustainability and potassium-solubilizing microorganisms. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi: Springer; 2016. pp. 225-266
- [36] Sundara B, Natarajan V, Hari K. Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugar cane and sugar yields. Field Crops Research. 2002;77:43-49
- [37] Carter OG. The effect of chemical fertilizers on seedling establishment. Animal Production Science. 1967;7:174-180
- [38] Gadkar V, David-Schwartz R, Kunik T, Kapulnik Y. Arbuscular mycorrhizal fungal colonization factors involved in host reorganization. Plant Physiology. 2001;127:1493-1499
- [39] Karandashov V, Bucher M. Symbiotic phosphate transport in arbuscular mycorrhizas. Trends in Plant Science. 2005;10:22-29
- [40] Adholeya A, Tiwari P, Singh R. Largescale inoculums production of arbuscular mycorrhizal fungi on root organs and inoculation strategies. In: Declerck S, Strullu DG, Fortin A, editors. Soil Biology, Volume 4, *In vitro* Culture of Mycorrhizae. Berlin Heidelberg: Springer-Verlag; 2005. pp. 315-338
- [41] Rillig MC, Wright SF, Eviner VT. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of the five plant species. Plant and Soil. 2002;238:325-333
- [42] Kumar A, Patel JS, Bahadur I, Meena VS. The molecular mechanisms of KSMs for enhancement of crop production under organic farming. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi: Springer; 2016. pp. 61-75
- [43] Narayanasamy G, Arora BR, Biswas DR, Khanna SS. Fertilizers, manures and biofertilizers. In: Goswami NN et al., editors. Fundamentals of Soil Science. New Delhi: Indian Society of Soil Science; 2012. pp. 579-621
- [44] Dotaniya ML, Meena VD, Basak BB, Meena RS. Potassium uptake by crops as well as microorganisms. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi: Springer; 2016. pp. 267-280
- [45] Sharma A, Shankhdhar D, Shankhdhar SC. Potassium-solubilizing microorganisms: Mechanism and their role in potassium solubilization and uptake. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for Sustainable Agriculture. New Delhi: Springer; 2016. pp. 203-219
- [46] Mazid M, Khan TA. Future of bio-fertilizers in Indian agriculture: An overview. International Journal of Agricultural and Food Research. 2014;3:10-23
- [47] Raghavendra MP, Nayaka SC, Nuthan BR. Role of rhizosphere microflora in potassium solubilization. In: Meena VS, Maurya BR, Verma JP, Meena RS, editors. Potassium Solubilizing Microorganisms for

Sustainable Agriculture. New Delhi: Springer; 2016. pp. 43-59

[48] Samoon HA, Dar SA, Zehra B, Mahdi SS, Hassan SA. Bio-fertilizers in organic agriculture. Journal of Phytology. 2010;2:9-14

[49] Khandkar MR, Shinde DA, Kanekar VS, Jambley NR, Jain NK. Growth, nodulation and yield of rainfed black gram as influenced by phosphate and sulphate fertilization in vertisol. Indian Journal of Plant Physiology. 1985;28:318-322

[50] Saraf CS. Sulphur fertilization to pulses in yield and quality. In: Proc. TSIFAI Symp. Sulphur in Indian Agriculture. New Delhi; 1988. p. S II/2-1

[51] Raj SA. Bio-fertilizers for micronutrients. Biofertilizer Newsletters. 2007;15:8-10

[52] Bashan Y, Harrison SK, Whitmoyer RE. Enhanced growth of wheat and soybean plant inoculated with *Azopirillum brasilense* is not necessary due to general enhancement of mineral uptake. Applied and Environmental Microbiology. 1990;56:769-775

[53] Goldstein AH, Braverman K, Osorio N. Evidence for mutualism between a plant growing in a phosphate-limited desert environment and a mineral phosphate solubilizing (MPS) rhizobacterium. FEMS Microbiology Ecology. 1999;30:295-300

[54] Bertrand H, Plassard C, Pinochet X, Touraine B, Normand P, Cleyet Marel JC. Stimulation of the ionic transport system in *Brassica napus* by a plant growth-promoting rhizobacterium (*Achromobacter* sp.). Canadian Journal of Microbiology. 2000;46:229-236

[55] Yanni Y, Zidanb M, Dazzoc F, Rizka R, Mehesena A, Abdelfattaha F, et al. Enhanced symbiotic performance

and productivity of drought stressed common bean after inoculation with tolerant native rhizobia in extensive fields. Agriculture, Ecosystems and Environment. 2016;232:119-128

[56] Koskey G, Mburu SW, Njeru EM, Kimiti MJ, Ombori O, Maingi. Potential of native rhizobia in enhancing nitrogen fixation and yields of climbing beans (*Phaseolus vulgaris* L.) in contrasting environments of eastern Kenya. Frontiers in Plant Science. 2017;8:443. DOI: 10.3389/fpls.2017.00443

[57] Arafa MM, El-Batanony NH, Nofal AM. Inoculation effect of rhizobial strains on growth, yield and chemical composition of some legume crops in new reclaimed soil. Middle East Journal of Agriculture Research. 2018;7:352-363

[58] Abera T, Abebe Z. Effects of fertilizer, rhizobium inoculation and lime rate on growth and yields field pea in horro and gedo highlands. Advances in Crop Science and Technology. 2018;6:397. DOI: 10.4172/2329-8863.1000397

[59] Beshir HM, Walley FL, Bueckert R, Taran B. Response of snap bean cultivars to rhizobium inoculation under dryland agriculture in Ethiopia. Agronomy. 2015;5:291-308

[60] Youseif SH, Abd El-Megeed FH, Saleh A. Improvement of faba bean yield using *Rhizobium/Agrobacterium* inoculant in low-fertility sandy soil. Agronomy. 2017;7:2. DOI: 10.3390/agronomy7010002

[61] Moorthi M, Senthilkumar A, Thangaraj A. The effect of biofertilizer *Azotobacter chroococcum* on the growth of mulberry crop *Morus indica* L. and the yield of *Bombyx mori* L. International Journal of Environment, Agriculture and Biotechnology. 2016;1:4-7

[62] Yadav PK, Verma R, Bamboriya JK, Yadav S, Jeeterwal RC. Response of

pearl millet *Pennisetum glaucum* L. to integrated nitrogen management. International Journal of Current Microbiology and Applied Sciences. 2019;8:429-437

[63] Subedi R, Khanal A, Aryal K, Chhetri LB, Kandel BP. Response of *Azotobacter* in cauliflower (*Brassica oleracea* L. Var. *Botrytis*) production at Lamjung, Nepal. Acta Scientifica Malaysia. 2019;3:17-20

[64] Mahato S, Kafle A. Comparative study of *Azotobacter* with or without other fertilizers on growth and yield of wheat in Western hills of Nepal. Annals of Agrarian Science. 2018;16:250-256

[65] Zeffa DM, Perini LJ, Silva MB, de Sousa NV, Scapim CA, Oliveira ALM, et al. *Azospirillum brasilense* promotes increases in growth and nitrogen use efficiency of maize genotypes. PLoS One. 2019;14:e0215332

[66] Sayed E, Hamed EA, Althubiani AS. Enhancement of plant growth by soil inoculation with *Azospirillum brasilense* HM1 isolated from soil of Saudi Arabia. International Journal of Current Microbiology and Applied Sciences. 2015;4:238-248

[67] Rao KVB, Charyulu PBBN. Evaluation of effect of inoculation of *Azospirillum* on the yield of *Setaria italica* (L.). African J. Biotech. 2005;4:989-995

[68] Bhooshan N, Pabbi S, Singh A, Sharma A, Chetan, Jaiswal A, et al. Impact of blue green algae (BGA) technology: An empirical evidence from northwestern indo-Gangetic Plains. Biotech. 2018;8:324. DOI: 10.1007/s13205-018-1345-5

[69] Mishra N, Patra AK, Garnayak LM, Mohanty AK, Swain SK. Long-term effects of integrated nutrient management on productivity and soil properties of rice (*Oryza sativa*)–rice

cropping system in coastal Odisha. Indian Journal of Agronomy. 2017;62:239-246

[70] Biswas M, Parveen S, Shimozawa H, Nakagoshiw N. Effects of *Azolla* species on weed emergence in a rice paddy ecosystem. Weed Biology and Management. 2005;5:176-183

[71] Malik DK, Sindhu SS. Production of indole acetic acid by *Pseudomonas* sp.: Effect of coinoculation with *Mesorhizobium* sp. *Cicer* on nodulation and plant growth of chickpea (*Cicer arietinum*). Physiology and Molecular Biology of Plants. 2011;17:25-32

[72] Pandey C, Negi YK, Maheshwari DK, Rawat D, Prabha D. Potential of native cold tolerant plant growth promoting bacilli to enhance nutrient use efficiency and yield of *Amarathus hypochondriacus*. Plant and Soil. 2018;428:307-320. DOI: 10.1007/s11104-018-3681-y

[73] Xiao C, Zhang H, Fang Y, Chi R. Evaluation for rock phosphate solubilization in fermentation and soil–plant system using a stress-tolerant phosphate-solubilizing *Aspergillus niger* WHAK1. Applied Microbiology and Biotechnology. 2013;169:123-133

[74] David P, Raj RS, Linda R, Rhema SB. Molecular characterization of phosphate solubilizing bacteria (PSB) and plant growth promoting rhizobacteria (PGPR) from pristine soils. International Journal of Innovative Science, Engineering and Technology. 2014;1:317-324

[75] Kumar A, Sharma S, Mishra S. Influence of arbuscular mycorrhizal (AM) fungi and salinity on seedling growth, solute accumulation, and mycorrhizal dependency of *Jatropha curcas* L. Journal of Plant Growth Regulation. 2010;29:297-306

[76] Sudova R, Vosatka M. Differences in the effects of three arbuscular

- mycorrhizal fungal strains on P and Pb accumulation by maize plants. *Plant and Soil*. 2007;**296**:77-83
- [77] Saikia SP, Jain V. Biological nitrogen fixation with non-legumes: An achievable target or a dogma. *Current Science*. 2007;**92**:317-322
- [78] Mazid M, Khan TA, Zeba HK, Quddusi S, Mohammad F. Occurrence, biosynthesis and potentialities of ascorbic acid in plants. *International Journal of Plant, Animal and Environmental Sciences*. 2011;**1**:167-184
- [79] Mahajan A, Bhagat RM, Trikha A. Fertilizing bio-fertilizers. *Agriculture Today*. 2003a;**6**:36-37
- [80] Yadav RK, Abraham G, Singh YV, Singh PK. Advancements in the utilization of *Azolla-anabaena* system in relation to sustainable agricultural practices. *Proceedings of the Indian National Science Academy*. 2014;**80**:301-316
- [81] Mahajan A, Choudhary AK, Jaggi RC, Dogra RK. Importance of bio-fertilizers in sustainable agriculture. *Farm Forum*. 2003b;**3**:17-19
- [82] Yadav AK. Glimpses of biofertilizers covered in fertilizer (control) order, 1985 (amendment, march 2006). *Biofertilizer Newsletters*. 2006;**14**:3-7
- [83] Rao DLN. Microbial diversity, soil health and sustainability. *Journal of the Indian Society of Soil Science*. 2007;**55**:392-403
- [84] Rao DLN. Recent advances in biological nitrogen fixation in agricultural systems. *Proceedings of the Indian National Science Academy*. 2014;**80**:359-378
- [85] Deinlein U, Stephan AB, Horie T, Luo W, Xu G, Schroeder JI. Plant salt tolerance mechanisms. *Trends in Plant Science*. 2014;**19**:371-379
- [86] Rath KM, Rousk J. Salt effects on the soil microbial decomposer community and their role in organic carbon cycling: A review. *Soil Biology and Biochemistry*. 2015;**81**:108-123
- [87] Luo S, Tian L, Chang C, Wang S, Zhang J, Zhou X, et al. Grass and maize vegetation systems restore saline-sodic soils in the Songnen plain of Northeast China. *Land Degradation and Development*. 2018;**29**:1107-1119
- [88] Saifullah, Dahlawi S, Naeem A, Rengel Z, Naidu R. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Science of the Total Environment*. 2018;**625**:320-335
- [89] Zhao Y, Wang S, Li Y, Liu J, Zhuo Y, Chen H, et al. Extensive reclamation of saline-sodic soils with flue gas desulfurization gypsum on the Songnen plain, Northeast China. *Geoderma*. 2018;**321**:52-60
- [90] Krishna G, Singh BK, Kim EK, Morya VK, Ramteke PW. Progress in genetic engineering of peanut (*Arachis hypogaea* L.)— A review. *Plant Biotechnology Journal*. 2015;**13**:147-162
- [91] Jaiswal P, Kashyap AK, Prasanna R, Singh PK. Evaluating the potential of *N. calcicola* and its bicarbonate resistant mutant as bioameleorating agents for 'usar' soil. *Indian Journal of Microbiology*. 2010;**50**:12-18
- [92] Rady MM, Taha SS, Kusvuran S. Integrative application of cyanobacteria and antioxidants improves common bean performance under saline conditions. *Scientia Horticulturae*. 2018;**233**:61-69
- [93] Roman JR, Roncero-Ramos B, Chamizo S, Rodriguez-Caballero E, Canton Y. Restoring soil functions by means of cyanobacteria inoculation: Importance of soil conditions and species selection. *Land Degradation and Development*. 2018;**29**:3184-3193

- [94] Singh JS, Pandey VC, Singh DP. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agriculture, Ecosystems and Environment*. 2011;**140**:339-353
- [95] Singh V, Singh DV. Cyanobacteria modulated changes and its impact on bioremediation of saline-alkaline soils. *Bangladesh Journal of Botany*. 2015;**44**:653-658
- [96] Li H, Zhao Q, Huang H. Current states and challenges of salt-affected soil remediation by cyanobacteria. *Science of the Total Environment*. 2019;**669**:258-272
- [97] Khalilzadeh R, Sharifia RS, Jalilianb J. Growth, physiological status, and yield of salt-stressed wheat (*Triticum aestivum* L.) plants affected by biofertilizer and cycocel applications. *Arid Land Research and Management*. 2017;**32**:71-90. DOI: 10.1080/15324982.2017.1378282
- [98] Omara AD, Tamer G. Alleviation of salinity stress effects in forage cowpea (*Vigna unguiculata* L.) by *Bradyrhizobium* sp. inoculation. *Microbiology Research Journal International*. 2017;**23**:1-16
- [99] Ji SH, Gururani MA, Chun SC. Isolation and characterization of plant growth promoting endophytic diazotrophic bacteria from Korean rice cultivars. *Microbiological Research*. 2014;**169**:83-98
- [100] Islam F, Yasmeen T, Arif MS, Ali S, Ali B, Hameed S, et al. Plant growth promoting bacteria confer salt tolerance in *Vigna radiata* by up-regulating antioxidant defense and biological soil fertility. *Plant Growth Regulation*. 2015;**80**:23-36
- [101] Majeed A, Abbasi MK, Hameed S, Imran A, Rahim N. Isolation and characterization of plant growth-promoting rhizobacteria from wheat rhizosphere and their effect on plant growth promotion. *Frontiers in Microbiology*. 2015;**6**:198. DOI: 10.3389/fmicb.2015.00198
- [102] Rolli E, Marasco R, Vigani G, Ettoumi B, Mapelli F, Deangelis ML, et al. Improved plant resistance to drought is promoted by the root-associated microbiomes water stress-dependent trait. *Environmental Microbiology*. 2015;**17**:316-331
- [103] Timmusk S, Kim SB, Nevo E, Abd ElDaim I, Ek B, Bergquist J, et al. Sfp-type PPTase inactivation promotes bacterial biofilm formation and ability to enhance wheat drought tolerance. *Frontiers in Microbiology*. 2015;**6**:387. DOI: 10.3389/fmicb.2015.00387
- [104] Zahid M, Abbasi MK, Hameed S, Rahim N. Isolation and identification of indigenous plant growth promoting rhizobacteria from Himalayan region of Kashmir and their effect on improving growth and nutrient contents of maize (*Zea mays* L.). *Frontiers in Microbiology*. 2015;**6**:207. DOI: 10.3389/fmicb.2015.00207
- [105] Jha Y, Subramanian R. PGPR regulate caspase-like activity, programmed cell death, and antioxidant enzyme activity in paddy under salinity. *Physiology and Molecular Biology of Plants*. 2014;**20**:201-207
- [106] Vacheron J, Desbrosses G, Bouffaud ML, Touraine B, Moënne-Loccoz Y, Muller D, et al. Plant growth-promoting rhizobacteria and root system functioning. *Frontiers in Plant Science*. 2013;**4**:356. DOI: 10.3389/fpls.2013.00356
- [107] Goswami D, Dhandhukia P, Patel P, Thakker JN. Screening of PGPR from saline desert of Kutch: Growth promotion in *Arachis hypogaea* by *Bacillus licheniformis* A2. *Microbiological Research*. 2014;**169**:66-75

- [108] Kamaraj A, Padmavathi S. Alleviation of saline salt stress through pre-sowing biofertilizer seed treatment on crop growth and seed yield in green gram CV ADT3. *Journal of Pharmacognosy and Phytochemistry*. 2018;7(1):2205-2209
- [109] Egamberdieva D, Lugtenberg B. Use of plant growth-promoting rhizobacteria to alleviate salinity stress in plants. In: Miransari M, editor. *Use of Microbes for the Alleviation of Soil Stresses*. New York, NY, USA: Springer; 2014. pp. 73-96
- [110] Mahmood S, Daur I, Al-Solaimani SG, Ahmad S, Madkour MH, Yasir M, et al. Plant growth promoting rhizobacteria and silicon synergistically enhance salinity tolerance of mung bean. *Frontiers in Plant Science*. 2016;7:876
- [111] Latef AAHA, Chaoxing H. Effect of arbuscular mycorrhizal fungi on growth, mineral nutrition, antioxidant enzymes activity and fruit yield of tomato grown under salinity stress. *Scientia Horticulturae*. 2011;127:228-233
- [112] Cantrell IC, Linderman RG. Preinoculation of lettuce and onion with VA mycorrhizal fungi reduces deleterious effects of soil salinity. *Plant and Soil*. 2001;233:269-281
- [113] Aroca R, Ruiz-Lozano JM, Zamarreño ÁM, Paz JA, García-Mina JM, Pozo MJ, et al. Arbuscular mycorrhizal symbiosis influences strigolactone production under salinity and alleviates salt stress in lettuce plants. *Journal of Plant Physiology*. 2013;170:47-55
- [114] Tiwari S et al. *Pseudomonas putida* attunes morphophysiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery. *Plant Physiology and Biochemistry*. 2015;99:108-117
- [115] Goswami D, Thakker JN, Dhandhukia PC. Simultaneous detection and quantification of indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA) produced by rhizobacteria from l-tryptophan (Trp) using HPTLC. *Journal of Microbiological Methods*. 2015;110:7-14
- [116] Naseem H, Bano A. Role of plant growth-promoting rhizobacteria and their exopolysaccharide in drought tolerance of maize. *Journal of Plant Interactions*. 2014;9:689-701
- [117] Sandhya VZAS et al. Alleviation of drought stress effects in sunflower seedlings by the exopolysaccharides producing *Pseudomonas putida* strain GAP-P45. *Biology and Fertility of Soils*. 2009;46:17-26
- [118] Bal HB et al. Isolation of ACC deaminase producing PGPR from rice rhizosphere and evaluating their plant growth promoting activity under salt stress. *Plant and Soil*. 2013;366:93-105
- [119] Vardharajula S et al. Drought-tolerant plant growth promoting *Bacillus* spp.: Effect on growth osmolytes, and antioxidant status of maize under drought stress. *Journal of Plant Interactions*. 2011;6:1-14
- [120] Ortiz N et al. The contribution of arbuscular mycorrhizal fungi and/or bacteria to enhancing plant drought tolerance under natural soil conditions: Effectiveness of autochthonous or allochthonous strains. *Journal of Plant Physiology*. 2015;174:87-96
- [121] Shintu PV, Jayaram KM. Phosphate solubilising bacteria (*Bacillus polymyxa*)—An effective approach to mitigate drought in tomato (*Lycopersicon esculentum* mill). *Tropical Plant Research*. 2015;2:17-22
- [122] Giri B, Kapoor R, Agarwal L, Mukerji KG. Pre-inoculation with arbuscular mycorrhizae helps *Acacia auriculiformis* grow in degraded Indian wasteland soil. *Communications*

in Soil Science and Plant Analysis. 2004;**35**:193-204

[123] Gaspar T, Penel C, Hadege D, Greppin H. Biochemical, molecular and physiological aspects of plant peroxidases. In: Lobarzewski J, Greppin H, Penel C, Gaspar T, editors. Plant Peroxidases. Geneva: Imprimerie Nationale, University of Geneva; 1991. pp. 249-280

[124] Jasper DA, Abbot LK, Robson AD. The effect of soil disturbance on vesicular-arbuscular mycorrhizal fungi in soils from different vegetation type. The New Phytologist. 1991;**118**:471-476

[125] Ruiz-Sanchez M, Aroca R, Monoz Y, et al. The arbuscular mycorrhiza symbiosis enhances the photosynthetic efficiency and the antioxidative response of rice plants subjected to drought stress. Journal of Plant Physiology. 2010;**167**:862-869

[126] Zarabi M, Alahdadi I, Akbari GA, Akbari GA. A study on the effects of different biofertilizer combinations on yield, its components and growth indices of corn (*Zea mays* L.) under drought stress condition. African Journal of Agricultural Research. 2011;**6**:681-685

[127] Lewis JA, Papavizas GC. Biocontrol of plant diseases: The approach for tomorrow. Crop Protection. 1991;**10**:95-105

[128] Chavoshi S, Nourmohamadi G, Madani H, Heidari H, Abad S, Alavi Fazel M. The effect of biofertilizers on physiological traits and biomass accumulation of red beans (*Phaseolus vulgaris* cv. Goli) under water stress. Iranian Journal of Plant Physiology. 2018;**8**:2555-2562

[129] Li Y, Shi H, Zhang H, Chen S. Amelioration of drought effects in wheat and cucumber by the combined application of super absorbent polymer

and potential biofertilizer. PeerJ. 2018;**7**:e6073. DOI: 10.7717/peerj.6073

[130] Khosro M, Yousef S. Bacterial bio-fertilizers for sustainable crop production: A review. Journal of Agricultural and Biological Science. 2012;**7**:237-308

[131] Bhattacharyya P, Kumar R. Liquid biofertilizer-current knowledge and future prospect. In: National Seminar on Development and Use of Biofertilizers, Biopesticides and Organic Manures. West Bengal: Bidhan Krishi Viswavidyalaya Kalyani; 2000, November 10-12

[132] Verma M, Sharma S, Prasad R. Liquid biofertilizers: Advantages over carrier based biofertilizers for sustainable crop production. EnviroNews. 2011. Available from: <https://isebindia.com/09-12/11-04-4>

[133] Borkar SG. Microbes as Biofertilizers and their Production Technology. New Delhi, India: Wood Head Publishing India Pvt. Ltd.; 2015. pp. 7-153

[134] Mahdi SS, Hassan GI, Samoon SA, Rather HA, Dar SA, Zehra B. Bio-fertilizers in organic agriculture. Journal of Phytology. 2010;**2**:42-54

[135] Motghare H, Gauraha, R. Biofertilizers- types and their application. Krishi Sewa. 2012. Available from: <http://www.krishisewa.com/articles/organicagriculture/115-biofertilizers.html>

[136] Panda H. Handbook on Organic Farming and Processing. New Delhi: Asia Pacific Business Press Inc.; 2013. pp. 149-152

[137] Pathak AK, Christopher K. Study of socio-economic condition and constraints faced by the farmers in adoption of biofertilizer in Bhadohi district (Uttar Pradesh). Journal of

Pharmacognosy and Phytochemistry.
2019;**8**:1916-1917

[138] Mathur N, Singh J, Bohra S, Bohra A, Vyas A. Microbes as biofertilizers. In: Tripathi G, editor. Cellular and Biochemical Science. New Delhi: I. K. International Pvt. Ltd.; 2010. pp. 1089-1113

[139] Das D, Dwivedi BS, Meena MC, Singh VK, Tiwari KN. Integrated nutrient management for improving soil health and crop productivity. Indian Journal of Fertilisers. 2015;**11**:64-83

[140] Fierer N, Jackson RB. The diversity and biogeography of soil bacterial communities. Proceedings of the National Academy of Sciences. 2006;**103**:626-631