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A Review of the Importance of Biofertilizers in Sustainable Farming

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Abstract
Considering the current high expense of chemical fertilization and the detrimental impact on human health and ecology, the exploitation of biofertilizers in agriculture acquires immense significance. Studies have illustrated that biofertilization supplies plants with necessary nutrients in adequate quantities, thereby increasing their yield. The employment of biofertilization in sustainable agriculture is becoming increasingly significant as the amount of nutrients in the soil also influences the quality of the harvest. Plant growth-promoting microbes stimulate the growth of plants via diverse methods to make nutrients accessible to the plant while also protecting against various abiotic and biotic stresses. The aim of this review is to discuss the different types of biofertilizers, their mode of action, and important roles in increasing crop productivity.

Keywords: Biofertilizer, Sustainable agriculture, Plant growth promoting microbes, Mechanism of action of biofertilizer, Limitations

1. Introduction

The advent of the Green Revolution resulted in the excessive application of synthetic fertilizers, which has antagonistically impacted soil well-being and water resources. They also resulted in a reduction in advantageous microflora and microfauna in the soil, which has also rendered crops more susceptible to disease. Chemical fertilization also leads to health and environmental concerns, including changes in the soil pH, soil and food contamination from heavy metals and radioactive substances, air pollution from NO, N_2O, NO_2, and other gases, and groundwater contamination from nitrates (Savci, 2012; Zhao, et al., 2024).

In 1895, the introduction of "Nitragin," a preparation comprising nitrogen-fixing rhizobium strains, marked the beginning of the commercial history of biofertilizers. In the 1950s, phosphorus-dissolving bacteria were first employed as biofertilizers to alter soil phosphorus into a usable form for plants. Reports suggested that several groups of microorganisms, including bacteria, fungi, and algae, through a variety of diverse mechanisms, promote growth in plants (Zhao, et al., 2024). Biofertilizers are renewable, non-bulky, inexpensive, and ecologically friendly sources of plant nutrients that complement chemical fertilizers and are crucial for enhancing nutrient supply and crop sustainability in future years. Biofertilizers in agriculture can increase crop yields by 10% - 40% and replace approximately 25% - 30% of chemical fertilizers (Pal et al., 2015). Biofertilizer formulations contain one or more species of microorganisms that can mobilize nutrients from non-usable to usable form through biological processes like nitrogen fixation, phosphate and potassium solubilization or mobilization, silicate solubilization, sulfur oxidation in the soil, secretion of substances that promote plant growth, production of antibiotics and various enzymes, and biodegradation of organic materials in soil and other environments. According to reports, biofertilization increases crop output by 10–40% by increasing the content of proteins, vitamins, amino acids, and nitrogen fixation processes (Bhardwaj, et al., 2014).

Plant Growth Promoting Microbes (PGPMs)

Biofertilizers, also known as plant-growth-promoting microbes (PGPMs), plant-growth-promoting bacteria (PGPB), or plant-growth-promoting rhizobacteria (PGPRs), colonize the plant's rhizosphere or interior, facilitating growth by increasing the supply or availability of essential nutrients to the host plant (Zhao, et al., 2024). PGPMs colonize the root (rhizosphere) or attach to its outer surface (rhizoplane). Some endophytic PGPMs live in the intracellular spaces of the root cortex gaps between root cells, while others develop symbiotic relationships with the host plants by nodule formation. The direct processes utilized by PGPMs for plant growth and development include mineralization and solubilization of minerals such as potassium, iron, nitrogen, and phosphorus; the phytohormone such as gibberellin, auxin, and cytokinin production; and plant ethylene regulation via ACC deaminase. They also use indirect processes such as hydrogen cyanide synthesis, antibiotics, iron sequestration, volatile organic chemicals, and induction of systemic resistance (Fadiji, 2024).

The common PGPB, such as *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azospirillum*, *Nostoc*, *Anabaena*, *Acetobacter*, *Bacillus megaterium*, *Azolla*, *Bacillus polymyxa*, etc., significantly contribute to crop yield and overall plant growth and development (Mahanty, et al., 2017). When heavy metal ions are present in high concentrations in the environment, *Bacillus*, *Pseudomonas*, and mycorrhizal fungi can enhance plant growth, phytoremediation efficiency, and tolerance by oxidizing, reducing, or acidifying heavy metals through the secretion of chelating agents, siderophores, metabolites, extracellular polymers, and ACC-deaminase (Zainab, et al., 2021; Zhao, et al., 2024). The *Sesbania sesban* plant showed increased tolerance against metals in association with PGPR like *Bacillus gibsonii* and *Bacillus xiamenensis* (Zainab, et al., 2021). A few species of PGPR that have an important role in the heavy metal bioremediation include *Achromobacter xylosoxidans*, *A. chroococcum*, *B. subtilis*, *B. megaterium*, *Bradyrhizobium*, *Pseudomonas sp.*, *Brevibacillus sp.*, *Kluyvera ascorbata*, *Mesorhizobium*, *Pseudomonas putida*, *Pseudomonas aeruginosa*, *Ralstonia metallidurans*, *Rhizobium*, *Sinorhizobium sp.*, *Variovox paradoxus*, *Ochrobactrum sp.*, *Psycrobacter sp.*, *and Xanthomonas sp.* (Shinwari, et al., 2015). According to a study, the combination of three bacterial biofertilizers—*Pseudomonades*, *Bacillus lentus*, and *Azospirillum brasilens*—has increased the expression of antioxidant enzymes and the amount of chlorophyll in stressed leaves, thereby increasing photosynthetic activity and helping plants to stay healthy under stressful environments (Heidari, et al., 2012). Reports indicate that biofertilizers like *Trichoderma harzianum*, *P. fluorescens*, and *Bacillus subtilis* can prevent plant diseases caused by fungal pathogens like *Fusarium spp.*, *Pythium spp.*, *Rhizoctonia spp*., and *Sclerotium spp.* and improve plant growth. The antifungal metabolites, including HCN, phenazines, pyrrolnitrin, 2,4-diacetylphloroglucinol, pyoluteorin, viscosinamide, and tensin, have been reported to be produced by many rhizobacteria (Bhattacharyya, et al., 2012).

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2. Types of biofertilizer

Microbial inoculants have gained popularity as biofertilizers because they supply specific nutrients like nitrogen (fixation, mineralization) and phosphorus (mineralization, solubilization) along with other nutrients to the soil. Furthermore, they also offer improved resistance to both biotic and abiotic stress, defence against plant diseases and enhance phytohormone production (Fadiji, 2024). Depending on the characteristics and function biofertilizers, can be categorized as follows:

1. **Nitrogen fixing microbes (NFMs)**
2. **Phosphate solubilising microbes (PSMs)**
3. **Phosphate mobilising microbes (PMMs)**
4. **Potassium solubilising microbes (PSMs)**
5. **Silicate solubilising microbes (SSMs)**
6. **Zinc solubilising microbes (ZSMs)**

i. Nitrogen fixing microbes (NFMs)

Nitrogen (N) is a basic element required by plants for synthesizing amino acids, nucleic acids, vitamins, and other nitrogenous substances (Fasusi, et al., 2021). Plants cannot utilize 78% of the available atmospheric N_2 (Mahanty, et al., 2017). The enzyme nitrogenase has an important role in N fixation in all nitrogen-fixing organisms. Soil contains N in two forms, namely inorganic (~2% mineral N) and organic (~98%). Inorganic forms of N include ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2), and nitrate (NO_3). Organic N is converted to NH_4^+ or NO_2 through mineralization by plants (Soumare, et al., 2020). When N becomes accessible, plants and microbes compete strongly for it. The synthetic N fertilizers can be used to compensate for N inadequacy in agricultural soils, as excess N is continually lost in ionic or gaseous form through soil erosion, denitrification, leaching, and chemical volatilization, but its uncontrolled application results in environmental problems such as eutrophication, the greenhouse effect, contamination of groundwater, and acid rain (Liu, et al., 2014). Thus, biological nitrogen fixation (BNF) can be regarded as a sustainable supply of N for crop production, as fixed N is more resistant to denitrification, leaching, and volatilization and is utilized directly by plants. BNF is a natural mechanism where air nitrogen (N_2) is converted to a simple, soluble, nontoxic state (NH_4^+), which plant cells employ to synthesize numerous biomolecules (Soumare, et al., 2020).

In 1888, the *N*-fixing bacteria strain *Bacillus radicicicola* was isolated for the first time by Beijerinck, which was later named *Rhizobium leguminosarum* by Frank in 1889. During BNF, nitrogen-fixing bacteria utilize the nitrogenase enzyme for converting atmospheric N_2 gas to NH_3. The nitrogen-fixing microbes (NFMs) can be symbiotic, free-living, and associative microbes. These NFMs include symbiotic bacteria like *Rhizobium* associated with legumes; free-living bacteria belonging to genera viz. *Azotobacter, Azospirillum, Bacillus*, or *Clostridium*; *Frankia* associated with actinorhizal plants; and cyanobacteria associated with cycad (Soumare, et al., 2020). The members of the Rhizobiaceae family, like *Rhizobium, Bradyrhizobium, Sinorhizobium, Azorhizobium*, and *Mesorhizobium,* are all referred to as Rhizobia and develop symbiosis in leguminous plants, while free-living and endophytic microbes like cyanobacteria, *Azospirillum, Azotobacter*, etc., develop non-symbiotic associations with host plants (Mahanty, et al., 2017). *Rhizobium,* which develops symbiosis with legumes, forming nodules, is resistant to temperature fluctuations and significantly improves crop production by transforming N_2 gas into usable forms. Reports indicate that *Rhizobium* inoculants enhanced the production of Bengal gram, lentil, pea, alfalfa, berseem, groundnut, and soybean in multiple locations and soil types (Bhardwaj, et al., 2014). *Azospirillum* species belonging to the Rhodospirillaceae family, including *A. zeae, A. thiophilum, A. rugosum, A. picis, A. oryzae, A. canadense, A. mazonense,* and *A. melinis*, are reported to fix N_2 in grass rhizospheres. Plants inoculated with *Azospirillum* strains increase growth and yield by altering cell wall flexibility, root structure, and auxin secretion (Fasusi, et al., 2021). *Azotobacter* fixes N_2 in the soil and produces vitamins like thiamine and riboflavin and plant hormones, namely indole acetic acid (IAA), gibberellins (GA), and cytokinins (CK). *A. chroococcum* encourages plant growth by increasing seed germination and developing root architecture and by suppressing pathogenic bacteria around crop root systems. This genus contains several species, including *A. chroococcum, A. vinelandii, A. beijerinckii, A. nigricans, A. armeniacus, and A. paspali,* used as a bioinoculant for different crops, including wheat, oats, barley, mustard, rice, linseeds, sunflower, castor, maize, sorghum, cotton, jute, sugar beets, tobacco, tea, coffee, rubber, and coconut (Bhardwaj, et al., 2014).

ii. Phosphate solubilising microbes (PSMs)

Phosphorus (P) accounts for around 0.2% of the dry weight of plants and is necessary for their growth and development. Plants absorb P from the soil as phosphate anions that are immobilized by precipitation with cations including Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+}, depending on soil conditions. P is extremely insoluble in these forms; therefore, a significant amount of soluble inorganic phosphate is added to the soil as chemical fertilizer, which quickly immobilizes it, and plants typically have limited access to this overall application (Brahmaprakash, et al., 2012). Biofertilizers convert insoluble forms of phosphates such as tricalcium, iron, and aluminum phosphates into usable forms, scavenge phosphate from soil, and produce hormones and anti-metabolites that stimulate root growth. The synthesis of organic acids like gluconic acid, ketogluconic acid, and acid phosphatases are the main processes for mineral phosphate solubilization. (Bhattacharjee, et al., 2014; Pal, et al., 2015). Various soil bacteria solubilize inorganic P by using hydroxyl and carboxyl groups of low molecular weight acids, including citric and gluconic acids, to chelate cations bound to phosphate. Organic phosphorus mineralization involves the synthesis of phosphatases that hydrolyze phosphoric ester. It has been found that phosphate solubilization and mineralization can occur simultaneously in the same bacterial strain. Different bacteria species, including *Pseudomonas, Bacillus, Rhizobium, Burkholderia, Achromobacter, Agrobacterium, Micrococcus, Acetobacter, Flavobacterium,* and *Erwinia,* can dissolve insoluble inorganic phosphorus into usable forms (Mahanty, et al., 2017). It has been found that Bacillus strains produced lactic, isovaleric, isobutyric, and acetic acid combinations, which help in phosphate solubilization. Other organic acids that aid phosphate solubilizers include succinic, malonic, oxalic, and glycolic acids. Other processes for phosphate solubilization include chelating agents and inorganic acids, including carbonic, nitric, and sulfuric acid (Pal et al., 2015).

iii. Phosphate mobilising microbes (PMMs)

P mobilizers increase the availability of P to plants by facilitating the mobilization of inaccessible soluble P from distant places in soil to plant roots. Mycorrhizae are prominent P mobilizers forming a mutually beneficial connection occurring in some fungus and plant roots. The fungi derive their carbon requirement from the host’s photosynthates, and the host plant gets important minerals, especially P, calcium (Ca), copper (Cu), and zinc (Zn), whose mobilization is facilitated by fine-absorbing fungal hyphae. (Brahmaprakash, et al., 2012; Pal et al., 2015). The hyphae enter the host root cortical cells and spread thereby, forming sac-like structures known as vesicles for storing P as phospholipids. The fungal hyphae also form arbuscules, which facilitate the nutrient transportation from distant locations to the roots and vesicles (Pal et al., 2015).

The arbuscular mycorrhizal fungi (AMF), which are prevalent in agricultural soils, contribute about 5-50% of soil microbe biomass (Brahmaprakash, et al., 2012). AMF can occur in natural environments ranging from the arctic to the tropical ecosystems. The nine genera of fungi developing symbioses include *Glomus, Gigaspora, Scutellospora, Acaulospora, Entrophospora, Archaeospora, Gerdemannia, Geosiphon*, and *Paraglomus.* Other fungi like *Penicillium, Aspergillus, Chaetomium,* and *Trichoderma spp*. have improved yield by facilitating P absorption in plants and can be applied as fungal biofertilizers (Pal, et al., 2015). Nevertheless, tillage along with the use of synthetic fertilizers or pesticides, mainly fungicides, might decrease the advantages of AMF for plants. The most significant function of AMFs in boosting plant growth and soil fertility has increasingly been recognized as a sustainable agricultural solution (Fasusi, et al., 2021).

iv. Potassium solubilizing microbes (KSMs)

Potassium (K), an important macronutrient, regulates enzyme activity like amylases and helps in starch decomposition and coordination of root shoot ratios. Insufficient K causes poor root development, increased susceptibility to diseases, and decreased plant growth and output (Fasusi, et al., 2021). Microbes can solubilize K by lowering the pH, increasing cation chelation, and acidolysis of the surrounding region. The rhizospheric microorganisms produce organic acids that can dissolve mineral K slowly or chelate Si and Al ions associated with K minerals. Thus, the synthesis of organic acids by microorganisms acidifies the microbial cells and their surrounding environment, which eventually leads to the release of K ions from the mineral through protonation and acidification. The mineral K solubilization appears to be most commonly mediated by glycolic acid and succinic acid (Verma, et al., 2017).

There are reports that show soil contains several KSMs, including *Bacillus edaphicus*, *Bacillus mucilaginous (*Zhao, et al., 2008)*; Azotobacter chroococcum*, and *Rhizobium spp*., which aid in potassium solubilization, leading to higher yields of corn, chili, cotton, pepper, sorghum, and wheat (Zhao, et al.,2019). KSMs have been shown to improve growth in cotton and rape, pepper and cucumber, sorghum, wheat, tomato, chili, Sudan grass, and tobacco (Verma, et al., 2017).

v. Silicate solubilising microbes (SSMs)

Silicon (Si) is one of the most common elements, accounting for around 27.7% of the earth's crust, yet the majority of it is insoluble. The plant roots absorb Si from the soil, usually as monosilicic acid [Si $(OH)_4$], and it is accumulated in the form of amorphous silica, primarily in plant cell walls. The important silicate solubilizing microbes (SSMs) that dissolve Si from natural silicates, primarily aluminum silicates (Al_2SiO_5), include *Proteus mirabilis*, *Bacillus caldolyticus*, *Pseudomonas*, and *Bacillus mucilaginosus var. siliceous* (Kumawat, et al., 2019).

The microbes hydrolyze Al_2SiO_5, by producing organic acids, like citric acid, oxalic acid, keto acid, and hydroxy carbolic acid, and form complexes with cations, thereby facilitating the removal and retention of cations in a dissolved state (Santi, et al., 2018). Silicate solubilizing bacteria (SSB) solubilize insoluble silicates, potassium, and phosphates, increasing soil fertility and plant production. Si benefits plants by fastening growth, increasing leaf surface area for photosynthesis, creating a mechanical barrier against insect pests by its deposition on plant tissues, and protecting plants against abiotic stresses such as drought, salt, metal toxicity, nutrient deficiency, high temperature, freezing, etc. (Ma, et al., 2006). The application of SSB on oil palm seedlings has improved chlorophyll content and resistance to drought and promoted root growth (Santi, et al., 2018). In rice tissue, Si promotes plant growth and productivity by improving stem strength, leaf erectness, and the rate of photosynthesis and reducing the negative effects of stress. Si is absorbed by rice roots from the soil as silicic acid via Si influx (Lsi1) and efflux transporters (Lsi2), which is then transported to shoots by xylem and discharged by the Lsi6 transporter. The Si deposits under the cuticle and intracellular spaces undergo precipitation in plant cells as phytoliths (Chaganti, et al., 2023).

vi. Zinc Solubilising Microbes (ZSMs)

Zinc (Zn) is a key micronutrient for plant growth, development, disease resistance, and stress tolerance. It plays a crucial role in various biomolecules, such as lipids, proteins, and auxins. Zn is vital for carbohydrate metabolism, protein and chlorophyll production, membrane lipid protection from reactive oxygen species, and plant growth hormone biosynthesis, including auxin (Srithaworn, et al.,2023). Zn deficiency in plants causes reduced leaf growth, chlorosis, increased vulnerability to heat, light stress, and pathogenic damage (Fasusi, et al., 2021). Plants can absorb Zn as a divalent cation, though only a small amount of total Zn is soluble in the soil. The remaining Zn is present in the form of insoluble complexes and minerals. Zn deficiency in soil can be compensated for using zinc fertilizers in the form of Zn sulfate or Zn-EDTA; however, their use causes an economic and environmental burden, so a better approach to

this problem is the use of Zn solubilizing microbes (Kamran, et al., 2017).
The most important mechanism for the solubilization of Zn is the formation of organic acid. The pH of the surrounding soil is lowered by bacterial strains that release organic acids by sequestering Zn cations (Kamran, et al., 2017; Kumar, et al., 2019). It is widely acknowledged that gluconic acid and its derivatives, e.g., 2-keto-gluconic acid, 5-keto-gluconic acid (Kumar, et al., 2019) convert insoluble forms of Zn, including oxide, carbonate, and phosphate, into soluble and accessible forms. Numerous microbial strains, such as *Gluconacetobacter, Pseudomonas*, and *Acinetobacter,* have been shown to produce large amounts of gluconic acid, which is believed to be responsible for the solubilization of Zn. Instead of gluconic acid, *Burkholderia cepacian* solubilized Zn using various organic acids like oxalic, formic, tartaric and acetic acids (Upadhayay, et al.,2022). Other mechanisms that possibly contribute to Zn solubilization are the formation of siderophores, amino acids, chelated ligands, vitamins, protons, and oxido-reductive systems on cell membranes (Kamran, et al., 2017; Upadhayay, et al.,2022). The inoculation of plants with different PGPRs like *Pseudomonas, Rhizobium* strains, *Bacillus aryabhattai,* and *Azospirillum* has shown increased growth and Zn content (Fasusi et al., 2021).

3. Limitations in the application of biofertilizers

The beneficial microorganism's usage in biofertilizer production is becoming popular in recent years; however, owing to the difficulty of replicating its useful effect on crop productivity in fluctuating natural surroundings, they are still not widely utilized on a large scale. The main challenges to applying microbial biofertilizer are the lack of knowledge and insufficient encouragement and promotion about the environmentally beneficial value of microbial biofertilizer, insufficient availability of appropriate carriers for biofertilizer formulation, a lack of storage facilities to prevent its contamination, and extreme weather conditions. It must be stored in a low-density plastic bag that is between 50 and 75 microns thick at room temperature or in a cold storage far away from direct sunlight or heat. Furthermore, they are selective in action, and their credibility can be damaged by lack of labelling, including the name of microorganisms used and the expiration date. (Bhattacharjee, et al., 2014; Fausi, et al., 2021; Saini, et al., 2021). Researchers are also exploring innovative methods to improve formulation techniques and application methods to enhance the stability and efficacy of the biofertilizers in varying environmental conditions.

4. Conclusion

The biofertilizers are vital for sustainable agriculture as they aid in the uptake of nutrients from soil or atmosphere, stimulate plant growth through the synthesis of growth-promoting chemicals, help in the bioremediation of toxic metals present in the soil, and protect plants from both abiotic and biotic stresses. They help to maintain soil structure and its properties without any negative impact on the environment. The overdependence on chemical fertilizers for increased production is not sustainable due to the high expenses required for setting up and maintaining fertilizer factories, along with harmful environmental impact. There are various studies carried out that showed different types of biofertilizers may aid farmers in increasing their crop yield per unit area at low cost, serving as an alternative to chemical fertilization. Biofertilization has become even more crucial in rain-fed farming due to its low cost, as the majority are small and marginal agricultural workers. Thus, biofertilization is the ideal method of practicing organic farming and lowering growing costs.

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