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Biofertilizers: A Sustainable Solution for Enhanced Crop Yield and Soil Health in Modern Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The global demand for food production requires an enhancement in crop yield to meet the needs of the increasing population. However, soil degradation due to intensive agricultural practices, such as using pesticides and chemical fertilizers, poses a significant challenge to sustainable food production. Soil health and plant productivity are intricately linked to interactions among plants, soil, and microorganisms. Biofertilizers, containing living or dormant microorganisms, have emerged as a promising solution to enhance soil microbial status, stimulate natural soil microbiota, and improve nutrient accessibility and decomposition of organic matter. This review provide a comprehensive overview of the role of biofertilizers, including nitrogen-fixing, phosphorus-solubilizing, potassium-solubilizing, sulphur-solubilizing, and zinc-solubilizing biofertilizers, in promoting plant growth, improving soil fertility, and increasing crop yield. The efficacy of biofertilizers in various crops, such as wheat, cotton, soybeans, and peas, is discussed, highlighting their potential to reduce the

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reliance on chemical fertilizers, mitigate soil degradation, and contribute to sustainable agricultural development. Moreover, a case study on the impact of Rhizobium inoculation on crop yield and soil fertility provides valuable insights into the practical application and benefits of biofertilizers in agricultural systems. In conclusion, using biofertilizers presents a promising avenue for enhancing food security, promoting sustainable farming practices, and fostering economic development while ensuring environmental sustainability.

Keywords: Biofertilizer; legumes; crop yield enhancement; rhizobium; soil health; sustainable agriculture.

1. INTRODUCTION

With the world population growing rapidly, it's more important than ever to boost crop yields to meet future food needs. Healthy soil is essential for food production throughout a person's life. Unfortunately, over the past few decades, intensive farming practices like the widespread use of pesticides and chemical fertilizers have degraded soils around the globe. This has led to a loss of soil fertility, caused by reduced biodiversity, poorer water retention, and disruptions to vital nutrient cycles. Soil health and the productivity of our crops are strongly affected by the intricate relationships among plants, soil, and the microbes living there (Harman et al*.,* 2020). These soil microbes interact with each other and with plant roots in many ways, playing countless important roles that help maintain the natural balance of soil ecosystems (Kumar et al*.,* 2021c). When the partnership between plants and these soil microbes supports plant health, growth, and yield, it's a positive relationship but if it hinders plants, it can have negative effects instead. The fertility of soil is closely tied to the balance between its microorganisms and the plants it supports (Vishwakarma et al*.,* 2020). One promising way to restore and maintain soil health is by using biofertilizers. These naturally derived products can boost the microbial life in soil, helping vital soil communities thrive. They make nutrients more available and improve the breakdown of organic matter (Chaudhary et al*.,* 2021). For example, applying biofertilizers to apricot orchards has been shown to change the soil's microbial makeup and speed up decomposition, which makes nutrient cycling in the soil more efficient under different farming conditions (Agri et al*.,* 2021; Baldi et al*.,* 2021). Biofertilizers can form a high-level microbial diversity in soil may outcome better crop productivity for sustainable agriculture (Agri et al*.,* 2022). The positive impact of beneficial soil microbes on crop productivity has been reported in many recent studies, but the role of consortium in agriculture is not entirely unstated. Using a consortium a combination of different beneficial microbes can help plants take up nutrients more efficiently, defend themselves against harmful pathogens, and better cope with stressful conditions (Aguilar-Paredes et al*.,* 2020).

Every living creature needs nutrients to survive. For plants, there are 17 essential nutrients required for healthy growth and development (Kumar et al*.,* 2021a). While plants get oxygen, hydrogen, and carbon from the air and water around them, they have to absorb all the other nutrients in inorganic forms directly from the soil (Gong et al*.,* 2020). This is where biofertilizers come in. Biofertilizers are products containing living or dormant microorganisms that can settle around plant roots and help plants grow by improving the supply of nutrients (Malusa and Vassilev, 2014; Fasusi et al*.,* 2021). These helpful microbes in the soil are capable of mobilizing nutrients and turning them into forms that plants can absorb such as by fixing nitrogen, making phosphorus and zinc available, or producing substances that promote plant growth (Bhattacharjee and Dey, 2014; Mazid and Khan, 2015). Biofertilizers can be applied in several ways, including treating seeds, spraying soil or roots, or even as a foliar spray on leaves. These applications boost microbial activity by encouraging the microbes to multiply, which in turn helps move nutrients to where plants need them most. As a result, soil fertility improves, leading to healthier crops and better harvests (Pandey and Singh, 2012; Ismail et al*.,* 2013).

2. BIOFERTILIZERS

Biofertilizers have been shown to boost plant growth and increase yields by anywhere from 10% to 40% (Stewart and Roberts, 2012). When these beneficial microbes are added to the rhizosphere the zone of soil surrounding plant roots, they settle in and even enter the plant itself, encouraging stronger and healthier growth (Nosheen et al*.,* 2021). Not only do biofertilizers make more nutrients available to plants, enhancing soil fertility and crop output, but they also help protect crops from pests and diseases. Research has found they can improve the survival rate of seedlings, keep root systems healthy for longer, reduce the need for harmful chemical fertilizers, and even shorten the time it takes for plants to flower (Gupta et al., 2015a). Interestingly, once biofertilizers are established after being applied several times (usually 3-4 applications), the beneficial microbes they bring can reproduce and sustain themselves without needing further additions (Bumandalai et al., 2019). For optimal growth, plants need 17 essential nutrients, with nitrogen (N), phosphorus (P), and potassium (K) required in especially large amounts (Umesha et al., 2018; Bumandalai et al., 2019). Microorganisms used in biofertilizer production often produce growth-promoting substances like phytohormones such as indole acetic acid (IAA) as well as amino acids and vitamins. These help encourage healthy growth, improve soil fertility, and ultimately support bigger, better harvests (Parikh et al., 2012).

3. ROLE OF BIOFERTILIZER

Biofertilizers are organic products made up of carefully selected microorganisms, often sourced from the roots and surrounding soil of healthy plants. Research shows that using biofertilizers can increase plant growth and yields by 10 to 40 percent (Stewart & Roberts, 2012). When applied to the rhizosphere the soil area near roots or even inside the plant, these beneficial microbes establish themselves and create a supportive environment that helps plants thrive (Nosheen et al., 2021; Verma et al., 2025). Beyond simply boosting nutrient levels and improving soil fertility, biofertilizers also help defend plants against pests and diseases. Studies have found that they can improve seedling survival rates, allow roots to remain healthy for longer, reduce reliance on harmful chemicals, and even speed up the time it takes for plants to flower (Gupta et al., 2015b). Another advantage is that biofertilizers are no longer necessary after 3–4 years of continuous use since the parental inoculum is sufficient for growth and multiplication (Bumandalai et al., 2019). Several microorganisms, including nitrogen-fixing soil bacteria and cyanobacteria, phosphate-solubilizing bacteria, Molds, and mushrooms, are routinely utilized as biofertilizers (Umesha et al., 2018).

4. TYPES OF BIOFERTILIZERS

Based on their functions and mechanisms of action biofertilizers are divided into groups. Nitrogen-fixers (N-fixers), potassium solubilizers (K solubilizers), phosphorus solubilizers (P solubilizers), and plant growth-promoting rhizobacteria (PGPR) are the most used biofertilizers (Nosheen et al.,2021; Salimani et al., 2025). One gram of abundant soil can contain up to 10^{10} colony-forming units of bacteria of 2000 kg/ha live weight (Raynaud & Nunan, 2014). Cocci, bacilli, and spirals are types of soil bacteria.

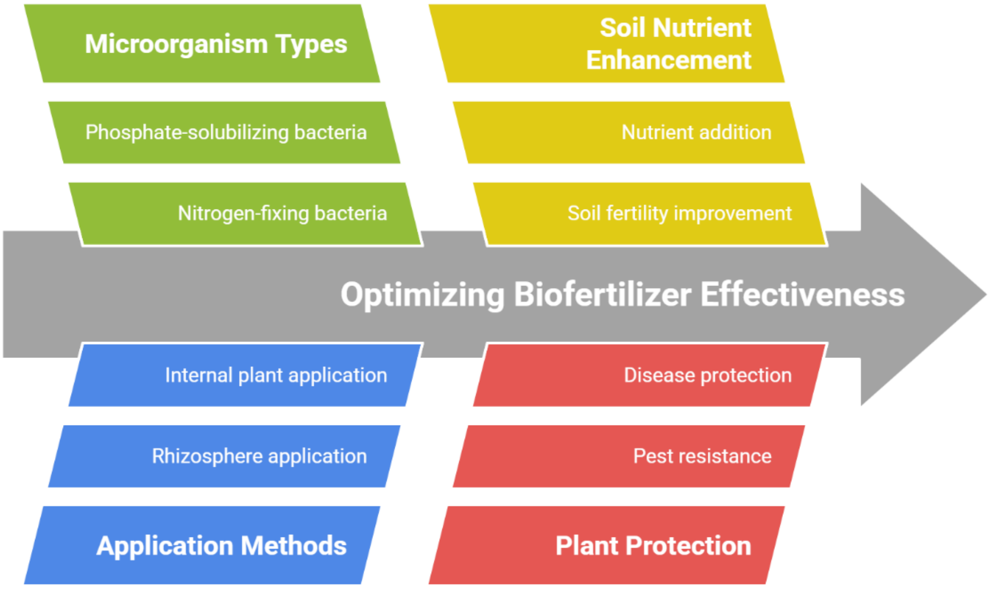

Fig. 1. Enhancing plant growth with biofertilizers

4.1 Nitrogen-Fixing Biofertilizers

Nitrogen is a vital macro-nutrient essential by plants because it improves the growth of the shoot system, helps in reproduction, is a constituent of chlorophyll responsible for the deep green colour, and also increases the size of the grains (Sandhu et al*.,* 2021). Even though about 78% of the air around us is made up of nitrogen, most of it exists as dinitrogen (N_2), which has very strong triple bonds. This makes it unavailable to plants in its natural state. For plants to use nitrogen, it first needs to be converted into a plant-friendly form through a process called biological nitrogen fixation. Special microorganisms known as diazotrophs can do this job, turning dinitrogen gas into non-toxic, soluble ammonia (Abbey et al*.,* 2019). Once ammonia is produced, other types of bacteria get involved: ammonia-oxidizing bacteria convert it into nitrite, and then nitrifying bacteria transform that nitrite into nitrate (Roy et al*.,* 2020). However, if plants don’t use all the available nitrate, another group of bacteria will convert the leftover nitrate back into nitrogen gas through a process called denitrification. This returns nitrogen to the atmosphere, completing the cycle (Mahanty et al*.,* 2017). Some beneficial bacteria, like Azotobacter and Bacillus species, play important roles in fixing nitrogen and promoting the growth of crops like maize and even forest plants (Etesami et al*.,* 2014; Azeem et al*.,* 2022). In soybean plants, inoculation of *Bradyrhizobium japonicum* showed improvement in its biomass, nodule formation, and Nitrogen fixing rate (Htwe et al*.,* 2019). Plant height and chlorophyll content in maize plants were improved by *Azotobacter chroococcum* (Jain et al*.,* 2021). Nitrogen fixation, IAA, and siderophores production improved the yield of mung bean as shown by *Bradyrhizobium* sp. (Alkurtany et al*.,* 2018). Nitrogen-fixing microbes are considered free-living, symbiotic, and associative nitrogen-fixing bacteria (Aasfar et al*.,* 2021). In nitrogen-deficient conditions, plant growth was promoted by the application of *Pseudomonas protegens* which was reported by Jing et al*.,* (2020).

4.2 Symbiotic Nitrogen-Fixing Microbes

One of the most studied mutualistic relationships between plant root nodules and nitrogen-fixing microorganisms is *Rhizobium* and legume symbiosis. Mutualistic relationships begins when legume roots release special compounds called flavonoids and isoflavonoids into the soil around them. These compounds attract Rhizobium bacteria, signaling that the plant is ready to form a partnership (Hawkins & Oresnik, 2022). Once they receive this signal, the Rhizobium bacteria start to infect the plant by causing changes in the root hairs. They form what's known as an infection thread, a kind of tunnel that lets the bacteria travel into the root hair cells. Once inside, the bacteria are released into the plant cell’s cytoplasm, where they transform into a specialized form called bacteroids. As these bacteroids develop, they become enclosed within plant-made structures known as symbiosomes. Symbiosomes are where nitrogen fixation actually happens (Cissoko et al*.,* 2018; Jimenez-Jimenez et al*.,* 2019; Suzaki et al*.,* 2019). Through this process, the Rhizobium bacteria convert atmospheric nitrogen into a form that plants can use, helping to naturally enrich the soil and boost crop yields (Brahmaprakash and Sahu, 2012). For example, one study found that Rhizobium meliloti, a nitrogen-fixing bacterium, also produces chitinase - an enzyme that enhances peanut yields (Mondal et al*.,* 2020). Likewise, the partnership between alfalfa and Rhizobium doesn't just improve nitrogen fixation; it also leads to the production of more plant hormones and promotes overall plant growth (Fang et al*.,* 2020).

4.3 Free-Living Nitrogen-Fixing Bacteria

Azotobacter is a well-known example of a free-living, non-symbiotic, and photo-trophic bacterium. One species in particular, *Azotobacter chroococcum*, is especially valuable as a biofertilizer since it can fix up to 10 mg of nitrogen for every gram of carbon source it uses (Mukherjee et al*.,* 2022). Azotobacter not only helps fix nitrogen but also produces important plant hormones such as indole acetic acid (IAA), gibberellic acid, naphthalene acetic acid, and vitamin B complex. These substances encourage root growth, improve plants’ ability to take up minerals, and enrich soil fertility while also protecting plant roots from harmful pathogens (Sumbul et al*.,* 2020). Other notable examples of beneficial free-living bacteria include *Bacillus*, *Clostridium*, and *Azospirillum*. For instance, using Bacillus species has been shown to significantly boost the growth of peanut plants (*Arachis hypogaea*), protect them from stress, and promote the production of helpful compounds like ammonia and IAA (Gohil et al*.,* 2022). Similarly, *Azospirillum brasilense* can reduce the need for nitrogen fertilizers, improve nutrient uptake, and increase both plant biomass and grain yield in wheat crops (Galindo et al*.,* 2022).

4.4 Associative Nitrogen-Fixing Bacteria

The Spirillum lipoferum was originally discovered by M.W. Beijerinck in 1925 (Soumare et al*.,* 2020). This bacterium was first found living among the roots of cereal plants known for their natural ability to fix nitrogen in the soil (Soumare et al*.,* 2020). Another closely related bacterium, *Azospirillum*, is a gram-negative, non-nodulating, nitrogen-fixing species that forms beneficial relationships with the roots of plants that utilize the C_4 dicarboxylic pathway for photosynthesis. These plants include important crops like sugarcane, maize, sorghum, pearl millet, as well as major cereals such as wheat, rice, and barley (Yasuda et al*.,* 2022; Kumar & Pareek, 2022). In addition to their role in fixing nitrogen, *Azospirillum* bacteria are known to produce several growth-promoting hormones e.g. cytokinins, gibberellins, and indole acetic acid, which help plants take up essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), and encourage robust root growth (Yasuda et al*.,* 2022; Kumar & Pareek, 2022).

4.5 Phosphorus-Solubilizing Biofertilizers

Phosphorus is the second macro-nutrient that is responsible for plant growth limitation (Bechtaoui et al*.,* 2021). It is an important constituent of organic and nucleic acids which is responsible for the synthesis of ATP and several amino acids. In the nodulation process, amino acid synthesis, and proteins in leguminous plants Phosphorous helps (Wang et al*.,* 2020). A soluble form of phosphorus is phosphate anion (orthophosphate), and their uptake is facilitated by rhizosphere microbes which help in plant nutrition. Different microbes can solubilize the remaining unavailable form of P into available form *via* organic acid production by bacteria which lowers the pH of the soil, making them available for the plant's nutrition (Mahanty et al*.,* 2017). *Bacillus, Rhizobium, Aerobacter, Burkholderia, Aspergillus*, and *Penicillium are* examples of phosphate-solubilizing bacteria and fungi (PSB and PSF). Plant growth parameters *via* P solubilization and IAA production were improved by inoculation of *Alcaligenes* sp (Abdallah et al*.,* 2016). The yield and growth of wheat plants were enhanced by *Rhizobium leguminosarum and Pseudomonas moraviensis* which showed IAA and solubilization (Igiehon et al*.,* 2019; Fahsi et al*.,* 2021). Application of Arbuscular fungi can make greater availability of P in plants and protect them from stress conditions as reported by Nacoon et al. (2020). Safflower growth is improved by *Bacillus subtilis* which protects plants from salinity stress and is also known as PSB as reported by (Zhang et al*.,* 2019). *By* increasing the soil enzymes and bacteria population under field conditions, nano Phos containing phosphate-solubilizing bacteria enhanced maize production (Chaudhary et al*.,* 2021).

4.6 Phosphorus-Mobilizing Biofertilizers

They are beneficial bacteria that effectively mobilize the soluble phosphorus and mineralization of the organic phosphorus compound, both are unavailable forms of phosphorus. These phosphorus-mobilizing microorganisms (PMBs), which include well-known groups like Bacillus, Pseudomonas, and Rhizobium (Kirui et al*.,* 2022; Verma et al., 2025), contribute through several processes. Firstly, PMBs release phosphatase enzymes that help transform organic phosphorus compounds into forms that plants can absorb. Secondly, they produce organic acids, which help dissolve mineral-bound phosphorus in the soil. Thirdly, some of these bacteria establish mutually beneficial partnerships with mycorrhizal fungi. These fungi act like extensions of plant roots, drawing up soluble phosphorus from parts of the soil that plant roots alone can’t reach, thanks to their fine hyphal networks (Nassal et al*.,* 2018; Etesami et al*.,* 2021). Arbuscular mycorrhizal fungi (VAM) are especially valuable, as they can transport both mineral and organic forms of phosphorus into plants-a major advantage. Common AMF include species from the Acaulospora, Glomus, Entrophospora, and Paraglomus genera. There are also ectomycorrhizal fungi, such as Amanita, Laccaria, and Boletus species, that contribute to this process. Additionally, certain fungal endophytes like Serendipita have been shown to boost potassium levels in crops such as maize and help protect plants from salt stress (Haro & Benito, 2019).

4.7 Potassium-Solubilizing Biofertilizers

Potassium (K) is recognized as the third essential macronutrient that plants need for healthy growth. It plays an important role in many plant processes, such as controlling the opening and closing of stomata (which affects water regulation), aiding in nutrient absorption, supporting protein synthesis, enhancing crop quality, and helping plants withstand stressful conditions (Santosh et al*.,* 2022). In the soil, potassium can be found in several forms, which depend on the soil’s composition. These include water-soluble potassium, forms that are available to plants, and forms that are locked away and not immediately accessible (Basak et al*.,* 2022). Much of the soil's potassium is actually trapped within silicate minerals like illite, orthoclase, biotite, and feldspar, making it largely unavailable to plants in its natural state. Bacteria and fungi contribute to the release (solubilization) of this inaccessible potassium. The main way they do this is by acidifying the soil essentially, they secrete organic acids that help break down these minerals and release potassium in a form that plants can utilize (Varga et al*.,* 2020). There are also mechanisms for solubilization of the K, namely, siderophores production, exchange reaction, and complexation (Sattar et al*.,* 2019). Examples of some potassium-solubilizing bacteria include *Bacillus mucilaginous, B. edaphicus.* Potassium-solubilizing fungi are *Aspergillus spp*. and some arbuscular mycorrhiza fungi. Potato plant health parameters and yield were improved by *Bacillus cereus* which also showed K solubilization (Ali et al*.,* 2021). Dal et al. (2020) reported that via P and K solubilization the combination of *Rhizophagus irregularis* and in wheat crop *A. vinelandii* improved the soil enzyme activities and its growth.

4.8 Potassium-Mobilizing Biofertilizers

Through the solubilization process, potassium-mobilizing microorganisms (PMMs) effectively release the unavailable potassium (Patel et al*.,* 2021). Potassium-mobilizing microorganisms (PMM), also known as potassium-dissolving or potassium-solubilizing bacteria, play a vital role in making potassium available to crops. For example, research by Ghaffari et al*.* (2018) showed that Frateuria and *Bacillus megaterium* are particularly effective at mobilizing potassium for crop growth. Other beneficial microbes, like Azotobacter, have been shown to enhance both potassium uptake and solubilization in wheat, resulting in improved plant growth and more active soil microbial communities (Game et al*.,* 2020). Additionally, bacteria such as Enterococcus and Pseudomonas aeruginosa have demonstrated the ability to solubilize not only potassium but also phosphorus. Their presence has been linked to taller maize plants, higher yields, and better overall nutrient uptake (Kumar et al*.,* 2021b). Moreover, *Bacillus aryabhattai* has been found to trigger the expression of genes involved in potassium solubilization, helping plants better cope with stress and promoting their growth (Chen et al*.,* 2022).

4.9 Sulphur-Solubilizing Biofertilizers

Sulphur is a crucial nutrient for all plants, as it's involved in several key biological functions. It plays an important role in the formation of chlorophyll, activates certain enzymes, and is essential for the synthesis of amino acids and vitamins. Sulphur also promotes nodulation, which is especially important for plant growth and development (Wang et al*.,* 2019). To make sulphur available to plants, sulphur-solubilizing or sulphur-oxidizing bacteria are needed. These helpful microorganisms convert the highly insoluble form of sulphur, hydrogen sulphide (H_2S), into sulphate (SO_4^{2-}), which plants can readily absorb. The opposite process, called assimilatory sulphate reduction, is carried out by sulphate-reducing bacteria (Wang et al*.,* 2019). Most sulphur transformations in soil-such as mineralization, immobilization, oxidation, and reduction-are driven by microbial activity (Malik et al*.,* 2021). Among aerobic sulphur-oxidizing bacteria, common genera include *Bacillus*, *Beggiatoa, Aquifer, Paracoccus, Sulfolobus, Thiobacillus, Thermithiobacillus,* and *Xanthobacter*. There are also phototrophic (light-loving) anaerobic sulphur-oxidizers like *Allochromatium, Chlorobium, Rhodobacter,* and *Rhodopseudomonas,* along with certain non-phototrophic, strictly anaerobic bacteria such as *Wolinella succinogenes* (Kusale et al*.,* 2021). Specific microbes, such as *Thiobacillus thiooxidans* and *Bradyrhizobium japonicum*, have been used as biofertilizers to improve sulphur uptake in cereal crops, medicinal plants, and forage crops, leading to better plant health and yields (Zhang et al*.,* 2018).

4.10 Zinc-Solubilizing Biofertilizers

Zinc is needed during protein synthesis, DNA–protein interaction, growth hormone production, seed development, and production of chlorophyll and protects plants from stress conditions (Umair Hassan et al*.,* 2020). Insoluble forms of zinc are generally ZnO, $Zn_3(PO_4)_2$, $ZnCO_3$, and metallic Zn. Divalent cations is the usable form of zinc by the plant (Ayoub et al*.,* 2022). Zinc-solubilizing fertilizers contain the zinc-solubilization bacteria which produce the organic acids to solubilize the insoluble zinc to Zn^{+2}, thereby enhancing zinc uptake in plants (Nitu et al*.,* 2020). Some examples of zinc-solubilizing bacteria and fungi which improved the soil enzyme activities and availability of Zn in crop plants are *Bacillus subtilis, Pseudomonas striata, Serratia, Burkholderia cenocepacia, Aspergillus niger,* *A. nomius*, and *A. oryza* (Batool et al*.,* 2021). In the roots of cucumber plants *Leclercia adecarboxylata* solubilizes Zn and produces siderophores which enhances the Zn (Kang et al*.,* 2021). Studies have shown that certain beneficial microbes can significantly enhance plant growth and health. For instance, the application of Bacillus species and Pseudomonas taiwanensis in maize has been linked to improved plant growth and higher chlorophyll levels (Chaudhary & Sharma, 2019; Hussain et al*.,* 2020). In addition, pot experiments with soybean revealed that inoculating the plants with Trichoderma longibrachiatum and Bacillus megaterium resulted in better seed germination (Bakhshandeh et al*.,* 2020). Similarly, incorporating phosphate-solubilizing bacteria (PSB) alongside fertilizers into sandy soils has been found to boost the growth of fava beans (Ding et al*.,* 2021).

Table 1. Summarizing the major types of biofertilizers, the key associated microbes, and their main functions

Type of biofertilizer	Key associated microbes	Main functions
Nitrogen-fixing (Free-living)	Azotobacter, Bacillus, Clostridium, Azospirillum, Cyanobacteria (Anabaena, Nostoc), Rhodospirillum	Convert atmospheric nitrogen into ammonia, improve soil fertility, promote plant growth
Nitrogen-fixing (Symbiotic)	Rhizobium (legumes), Frankia (actinorhizal plants), Anabaena (Azolla), Cyanobacteria	Form nodules or associations with plants' roots for direct nitrogen fixation
Associative Nitrogen-fixers	Azospirillum, Acetobacter	Live in loose association with plant roots to fix nitrogen and boost nutrient uptake
Phosphate-solubilizing (Bacterial)	Bacillus, Pseudomonas, Rhizobium, Burkholderia, Alcaligenes, Enterobacter, Agrobacterium	Solubilize insoluble phosphorus compounds, release organic acids to increase P availability
Phosphate-solubilizing (Fungal)	Aspergillus, Penicillium, Trichoderma, Arbuscular mycorrhizae (Glomus, Acaulospora, etc.)	Solubilize/mineralize inorganic and organic phosphorus, symbiotic enhancement of P uptake
Potassium-solubilizing/mobilizing	Bacillus mucilaginous, Bacillus edaphicus, Frateuria, Pseudomonas, Enterococcus, Aspergillus, Arbuscular mycorrhizae	Release potassium from silicate minerals by acidification, enhance K uptake, promote tolerance to stress
Sulphur-solubilizing/oxidizing	Bacillus, Thiobacillus thiooxidans, Paracoccus, Beggiatoa, Sulfolobus, Xanthobacter, Bradyrhizobium	Convert elemental S or sulphides to plant-available sulphate, enhance nodulation and growth
Zinc-solubilizing	Bacillus subtilis, Pseudomonas striata, Serratia, Burkholderia cenocepacia, Aspergillus niger	Produce organic acids to solubilize unavailable Zn compounds, increase Zn uptake in plants
Plant Growth-Promoting Rhizobacteria (PGPR)	Pseudomonas, Bacillus, Bradyrhizobium	Produce phytohormones (IAA, gibberellins, cytokinins), siderophores for iron uptake, antibiotic substances, and disease suppression
Mycorrhizal Fungi	Glomus, Acaulospora, Entrophospora, Paraglomus, Amanita, Laccaria, Boletus	Form symbiotic association with roots, enhance uptake of P, K, Zn; protect from stress and pathogens
Cyanobacteria (Blue-Green Algae)	Anabaena, Nostoc, Cylindrospermum, Aulosira	Nitrogen fixation, improvement of organic content, widely used in paddy fields

5. SOME CASE STUDIES

With varying doses of nitrogen under field conditions, high nitrogen fixing and phytohormone-producing diazotrophs such as *Azotobacter* were isolated, identified, and used as bioinoculants on wheat. The impact of bio-inoculants was determined based on their effect on yield, dry weight, and survival rate of bacteria at different days of plant growth under field conditions in two consecutive seasons (2000–01 and 2001–02). Pronounced effects were seen using bio-inoculants in wheat crops. A net saving of 25–30 kg of nitrogen was observed using chosen bio-inoculants for wheat crops (Narula et al., 2005).

Kachroo and Razdan (2006) observed that nitrogen utilization efficiency was enhanced when Azotobacter and Azospirillum were co-inoculated in a 1:1 ratio in wheat. Additionally, the nitrogen content in wheat grains increased with higher nitrogen application rates. Similarly, Kader et al. (2002) found that the highest nitrogen uptake (23.2 mg plant-1) occurred with the treatment involving 168 kg N ha-1, cow dung, and Azotobacter, while the lowest uptake (11.03 mg plant-1) was observed in the control treatment in wheat.

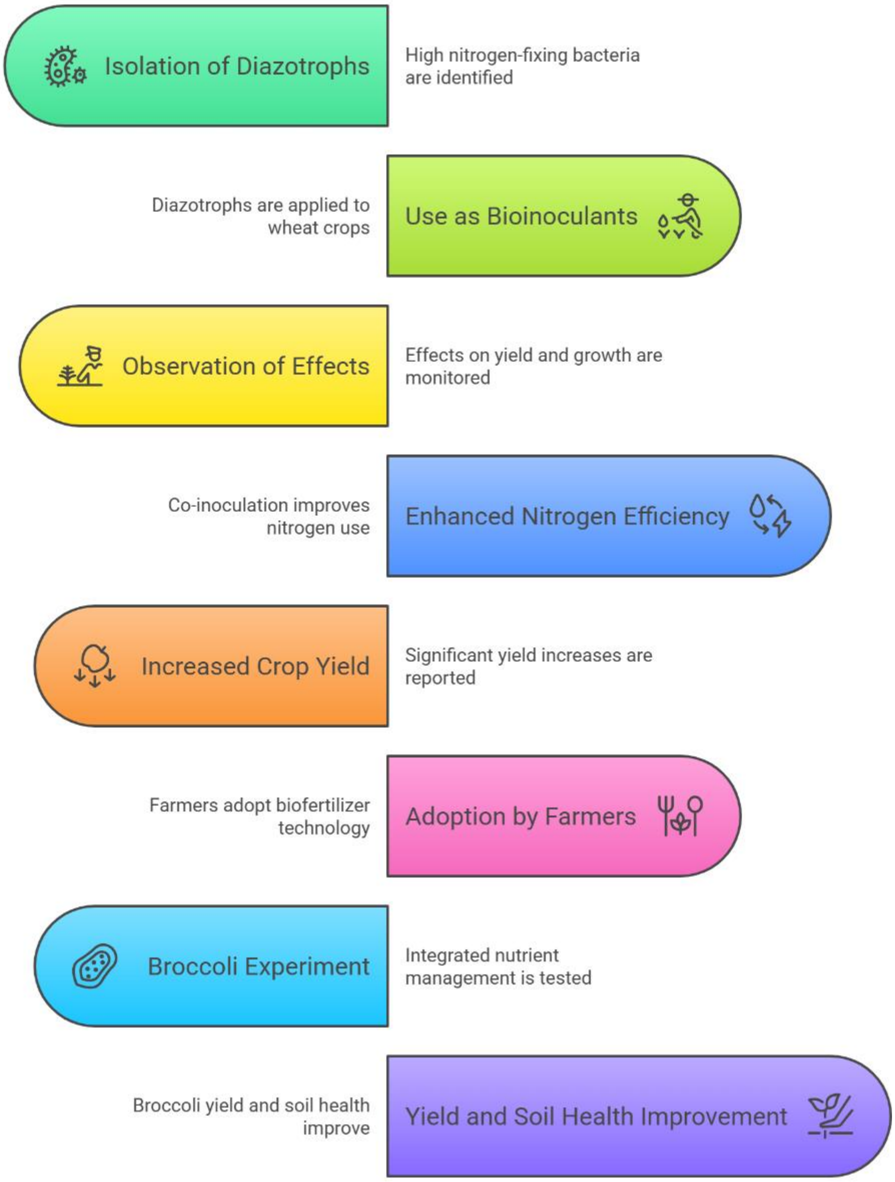

Fig. 2. Impact of bioinoculants on crop yield

Patil et al. (2015) found that plants inoculated with arbuscular mycorrhizal (AM) fungi and phosphate-solubilizing bacteria (PSB) in sterilized soil exhibited significantly enhanced growth and dry matter compared to those in unsterilized soil. Moreover, there was an increase in the percentage of root chlorophyll content in leaves. A synergistic effect was observed, leading to increased plant dry matter and root colonization percentage in Sorghum vulgare Pers. plants when both inoculants were used in sterilized soil compared to unsterilized soil.

Alemayehu, (2020) investigates the adoption of biofertilizer technology by smallholder farmers in the Lemu Bilbilo and Digelu Tijo districts of the Arsi Zone, Oromia Regional State, southeastern Ethiopia, since 2010. Specifically focusing on faba bean and field pea cultivation, the study assesses the impact of rhizobium-inoculated seeds on crop yields and farming sustainability. Through qualitative and quantitative methods involving 150 participants, including farmers and experts, the research reveals significant yield increases-79% for faba bean, 66% for wheat, and 42% for barley-compared to traditional methods. Farmers also report additional benefits such as improved soil fertility, reduced need for nitrogen fertilizers, and enhanced disease resistance. This study underscores the transformative potential of biofertilizer technology in bolstering agricultural productivity and sustainability in the region.

In Lahaul and Sapidi, India, a field experiment investigated broccoli's response to integrated nutrient management during the 2003 and 2004 summer seasons. Twelve treatments combining NPK synthetic fertilizer, cow manure (CM), and Azotobacter inoculation were evaluated. Marketable head yield increased linearly with CM application and Azotobacter inoculation. Integration of Azotobacter with the recommended practice (100% NPK + 20 Mt CM/ha) yielded the highest marketable head yield and net returns. Azotobacter integration with 75% NPK and 20 Mt CM/ha produced yields comparable to 100% NPK, saving 25% NPK fertilizers. Nutrient uptake in plant tissues and soil nutrient build-up followed similar trends. Application of 100% NPK + Azotobacter inoculation + 20 Mt CM/ha significantly increased soil organic C, available N, P, and K contents. Integration of CM and Azotobacter with synthetic fertilizers offers a sustainable approach to enhance broccoli yield and soil health in nutrient-depleted soils.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

The rise in the global population has increased the demand for food production. Biofertilizers have emerged as an effective and eco-friendly way to boost crop yields and ensure safer food products for consumers. Unlike traditional chemical fertilizers, biofertilizers help close the nutrient gap in agriculture, the difference between what crops need and what chemical fertilizers alone can supply, a gap that has recently exceeded 10 million tons worldwide. Heavy reliance on chemical fertilizers is increasingly unsustainable, not just because of escalating costs and the need for expensive manufacturing plants, but also due to their negative environmental impacts. Issues like soil degradation, water pollution, and the depletion of natural resources make chemical fertilizers a risky long-term solution. In contrast, biofertilizers harness beneficial microorganisms to naturally improve soil fertility, lower input costs, and reduce our dependence on imported agricultural chemicals. With more information and training, farmers and producers can easily adopt biofertilizer technologies, which are commercially promising and becoming more widely available globally. Their widespread use is expected to play a crucial role in fostering sustainable economic growth, promoting a healthier environment, and advancing food security. Overall, biofertilizers are not just a practical replacement for chemicals but a key component of a more resilient and sustainable agricultural future.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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