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REVIEW ARTICLE

Biofertilizers: A sustainable strategy for enhancing physical, chemical, and biological properties of soil

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Abstract

A biofertilizer is a biologically derived substance that can enhance soil fertility. It is beneficial for enhancing soil fertility by introducing microorganisms that produce organic nutrients and perhaps decreasing plant illnesses. An extensive review was done to examine the efficacy of several biofertilizers in improving soil properties, including their physical, chemical, and biological characteristics. The secondary data and material for the article were gathered from a variety of sources, including government reports, published research papers, reports from various organizations, and pertinent websites that were examined and their conclusions presented. Although biofertilizers have proven to be a very sustainable method for improving soil quality and increasing crop output, there is a lack of extensive research on their effects on soil's physical, chemical, and biological aspects. This study aims to offer a comprehensive understanding of various biofertilizers and their effects. This investigation indicated that biofertilizers such as Nitrogen-fixing bacteria, phosphate solubilizers, and potassium solubilizers help to increase NPK content in the soil leading to an increase in the productivity of soil. Moreover, biofertilizers help to enhance soil physical properties (soil bulk density, soil moisture, soil temperature, and soil color), chemical properties (soil pH, soil nitrogen content, soil phosphorus content, soil potassium content, and soil organic carbon content), and chemical properties (population of bacteria, fungi, and actinomycetes). Overall, by overcoming the challenges with biofertilizers in agriculture, we can attain agricultural sustainability.

Keywords

Actinomycetes, Biofertilizer, Mycorrhiza, Phosphate Solubilizing Bacteria, Sustainability

Introduction

Bio-fertilizers are natural mixtures that include advantageous microorganisms such as mycorrhizal fungi, phosphorus-solubilizing bacteria, and nitrogen-fixing bacteria (Rao et al. 2014). These microorganisms improve nutrient availability and stimulate soil fertility by developing symbiotic relationships with plants. Biofertilizers, as opposed to chemical fertilizers, support long-term soil health, enhance the soil's physical, chemical, and biological properties, and lessen their negative environmental effects (Pahalvi et al. 2021). In addition, they increase plant tolerance and serve as an important tool in the fight against pests. To lower resistance and promote long-term advantages, biofertilizers employ techniques of controlling insect pests that are sustainable, affordable, and well-liked in the community (Ghimirey et al. 2024a). Most subsistence and commercial farmers are attracted to the adaptation of biofertilizers rather than solely depend upon synthetic fertilizers (Dhar et al. 2015). To meet the demand for food for the increasing population, it is necessary to enhance production technology. However, with the implementation of enhanced technologies and high-yielding cultivars, the crop becomes vulnerable to many biotic and abiotic pressures, particularly biotic stresses such as diseases (Parajuli et al. 2022; Ghimirey et al. 2024b). Biofertilizers are environmentally friendly which helps in promoting resilient, well-balanced agro-ecosystems.

Biofertilizers are essential for improving different physical characteristics of the soil. By developing symbiotic relationships with plant roots, mycorrhizal fungi improve soil structure, increase water infiltration, lessen erosion, and improve aeration (Thangavel et al. 2022). These fungi also improve soils' ability to retain water, increasing their drought resistance. Soil compaction is reduced by the actions of biofertilizers, such as earthworms induced by the decomposition of organic matter, which improves root penetration and nutrient absorption (Bashir et al. 2021; Marahatta et al. 2024). Moreover, biofertilizers aid in mineralizing organic matter, which releases vital nutrients and promotes soil nutrient cycling (Basu et al. 2021; Chaurasia et al. 2024b).

Similarly, biofertilizers also enhance soil chemical properties by promoting the nitrogen fixation process (Chaurasia et al. 2024a). Furthermore, by dissolving insoluble phosphates, phosphorus-solubilizing bacteria in biofertilizers increases phosphorus availability (Arif et al. 2017). With the breaking down of organic matter, microbial activity in biofertilizers releases vital nutrients and increases the soil's nutrient availability. In general, biofertilizers improve cation exchange capacity, which helps retain and exchange essential nutrients (Singh et al. 2016). However, some biofertilizers also affect soil pH by producing organic acids (Patra et al. 2021). Essentially, biofertilizers encourage a balanced, nutrient-rich soil environment, which promotes sustainable agricultural methods and lessens reliance on artificial fertilizers (Bhardwaj et al. 2014).

Moreover, introducing microorganisms like *Trichoderma* and *Bacillus* stops the growth of soil-borne pathogens which helps to suppress disease (Guo et al. 2021). Additionally, they aid in the breakdown of organic matter because the microorganisms actively decompose organic residues, releasing vital nutrients and enhancing soil structure. Furthermore, by introducing a range of advantageous microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria, biofertilizers increase microbial diversity and foster a more resilient and dynamic soil microbiome (Odoh et al. 2020). By promoting disease resistance in plants, improved nutrient cycling, and healthy soil, this all-encompassing strategy supports sustainable agricultural methods (Ghimirey et al. 2024c). This study aims to investigate the effects of biofertilizers on the physical, chemical, and biological properties of soil. There is a considerable knowledge vacuum about biofertilizers, despite the obvious advantages of these fertilizers on soil qualities. Through sustainable means of enhancing soil quality, the present review clarifies the numerous mechanisms that biofertilizers have employed to support plant development, soil health, and protection against various plant infections. This review's objective is to go over the significant functions and uses of biofertilizers in a variety of fields, such as ecology, soil science, and agriculture.

Methodology

The article is compiled using secondary data and information sourced from government publications, published research papers, reports from various organizations, and relevant websites. The information for this research was collected using a methodical methodology. Electronic sources such as Google Scholar, PubMed, Scopus (Elsevier), Web of Science, Semantic Scholar, Academia, and other relevant websites were utilized to conduct a comprehensive search for existing literature. These sources were thoroughly examined, and the conclusions were succinctly presented.

Results and discussion

Concepts of biofertilizers and their relation to agricultural sustainability

A biofertilizer is a product that contains living microorganisms that have positive effects on the growth and development of plants (Mushtaq et al. 2021). Microbial strains employ diverse mechanisms to optimize nutrient absorption, enhance soil fertility, and boost crop yields. These mechanisms include nitrogen fixation, potassium and phosphorus solubilization, secretion of phytohormones, synthesis of compounds that inhibit phytopathogens, protection against abiotic and biotic stresses, and detoxification of subterranean pollutants (Bhardwaj et al. 2014).

At present, the world population is continuing to grow, and it is projected that by 2050, there will be roughly 9.7 billion individuals inhabiting the planet (Ehrlich and Harte 2015). The rapid expansion is closely linked to the extensive development of industry, cities, and agriculture. Given the increasing global population, traditional agriculture is crucial to fulfilling the nutritional needs of humanity (Chaurasia et al. 2020). It is projected that by 2020, the demand for food grain will reach 321 million tons, and traditional agriculture is necessary to ensure countries can produce enough food to sustain themselves (Gizaki et al. 2015). Conventional agricultural methods primarily rely on the extensive use of synthetic fertilizers and pesticides to provide plant nourishment and combat diseases (Van Bruggen et al. 2016). Applying these chemical inputs carefully and thoughtfully has undeniable benefits, not only for enhancing plant growth, crop yield, and quality but also for increasing farmers' income (Emmanuel et al. 2016). Regrettably, the escalated utilization of synthetic resources may present a significant risk to the ecological system by polluting water, air, and soil (Wassie 2020).

Biofertilizers are a crucial element of organic farming that help maintain a nutrient-rich soil environment (Sinha et al. 2010). When biofertilizers are used as seed or soil inoculants, they undergo multiplication and actively contribute to the nutrient cycle, ultimately enhancing crop productivity (Kumar et al. 2022). Biofertilizers enhance soil fertility through nitrogen fixation from the atmosphere and the solubilization of insoluble phosphates. Additionally, they generate chemicals that promote plant growth inside the soil (Mazid and Khan 2015). Biofertilizers are beneficial in enhancing the growth of several agricultural plants, including rice, pulses, millets, cotton, sugarcane, and vegetable crops (Rashid et al. 2016; Singh et al. 2014).

Nitrogen-fixing bacteria

Nitrogen is the primary limiting nutrient for plant growth. Plants are unable to decrease atmospheric N_2, hence they need externally obtained nitrogen for their growth and development (Gupta et al. 2012). The capacity of nitrogen-fixing (NF) bacteria to establish a mutually beneficial connection with leguminous plants and convert atmospheric nitrogen into a usable form has been utilized in agriculture to fulfill the nitrogen needs of these plants as illustrated in Fig. 1 (Sharma et al. 2023). Nitrogen-fixing microorganisms employ an enzyme complex called Nitrogenase to transform atmospheric nitrogen into ammonia (Barney 2020). Nitrogen fixers can be categorized into two groups: symbiotic and non-symbiotic. The Rhizobiaceae family members that form symbiotic associations with leguminous plants are classified as symbiotic organisms (Díez-Méndez and Menéndez 2021). Conversely, non-symbiotic microbes, such as *Cyanobacteria*, *Azospirillum*, *Azotobacter*, etc., exist in both free-living and endophytic forms (Chatterjee et al. 2019). The process of N_2 fixation is carried out by the nitrogenase enzyme complex. Dinitrogenase reductase provides the electrons, which dinitrogenase utilizes to convert N_2 into NH_3 by reduction. Enzymes form a bond with oxygen, which causes them to lose their activity (Mahanty et al. 2017).

Phosphorus solubilizers

Phosphorus is recognized as a crucial resource for the economy, and its reserves are diminishing (Cordell and White 2013). Annually, a total of 16 million metric tons of phosphorus is extracted, primarily from North Africa. This extraction process has challenges associated with transporting the resource across vast distances and dealing with its volatile pricing (Jupp et al. 2021). According to Darwish et al. (2017), it is projected that phosphate rock will be exhausted within 100 years. Simultaneously, the extensive utilization of phosphate fertilizers causes the dissemination of this element in the surroundings, potentially leading to the eutrophication of water reservoirs. Efficient phosphorus management should incorporate recycling, aligning with the principles of a circular economy.

Phosphorus solubilizing biofertilizer (PSB) is applied to enhance the availability and accessibility of phosphorus, hence stimulating the growth and development of

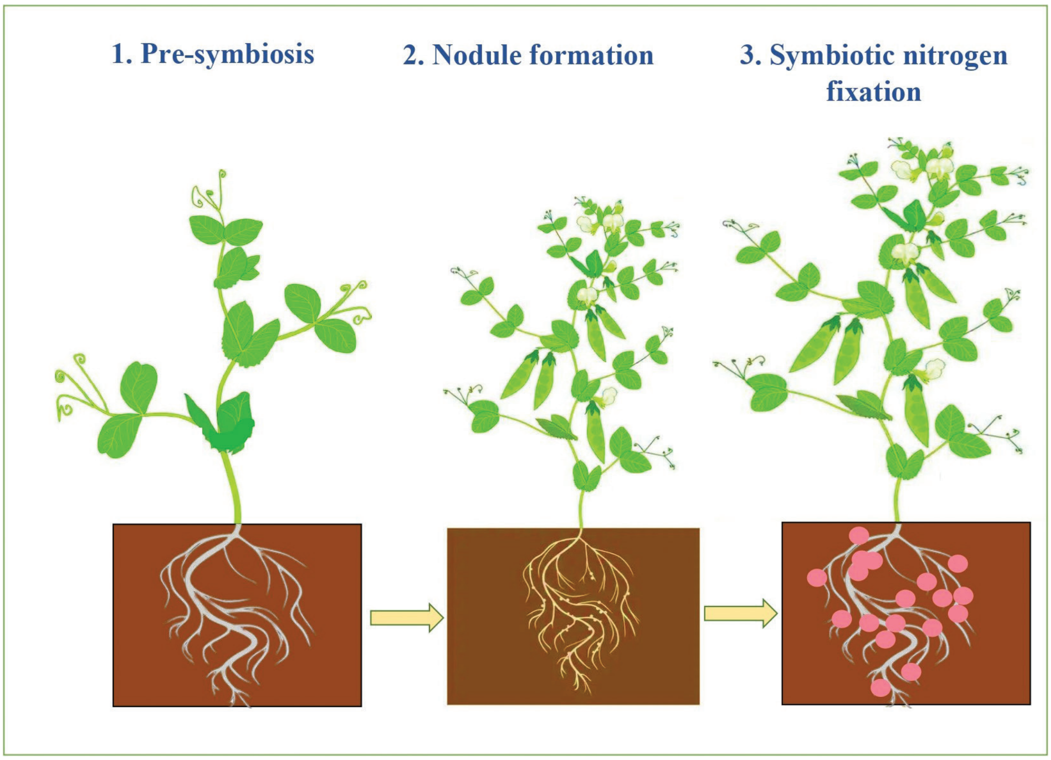

Figure 1. Schematic diagram representing the process of symbiotic nitrogen fixation. Source: Masson-Boivin and Sachs 2018.

plants. PSB, or phospho-bacterin, is a substance that aids in the solubilization of insoluble phosphates such as di- and tri-calcium phosphates, hydroxyapatites, and rock phosphates (Abbey et al. 2019). This process makes these phosphates more easily accessible to plants (Mahdi et al. 2010). The solubilization effect is accomplished through the creation of organic acids by phospho-bacterin, which results in a reduction in soil pH. This, in turn, causes the disintegration of phosphate compounds and the subsequent liberation of abundant phosphorus that may be utilized by plants (Sharma 2002; Glick 2012; Mahanty et al. 2017). The bacteria capable of solubilizing and mobilizing phosphorus (P) include *Pseudomonas*, *Bacillus*, *Rhizobium*, *Burkholderia*, *Achromobacter*, *Agrobacterium*, *Micrococcus*, *Aerobacter*, *Flavobacterium*, *Aspergillus*, *Erwinia* as shown in Fig. 2 (Mahdi et al. 2010; Mahanty et al. 2017).

Potassium solubilisers

Potassium is one of the three fundamental elements that plants require. Potassium (K) plays a crucial role in various biochemical and physiological processes in plants, such as the regulation of stomata (Wang et al. 2013; Hasanuzzaman et al. 2018). Stomata are responsible for controlling the opening and closing of pores in plants. The optimal operation of stomata is crucial for the process of photosynthesis (Falquetto-Gomes et al. 2023).

In the soil system, there are three simultaneous forms of Potassium: unavailable, slowly available, and quickly available forms (Yadav and Sidhu 2016). Applying biofertilizers can aid in remedying this condition by converting the insoluble potassium into soluble forms, making it accessible for plants to absorb as shown in Fig. 3 (Bahadur et al. 2014). For instance, bacteria such as *Frateuria aurantia* can mobilize and solubilize potassium (K) that is otherwise inaccessible, hence promoting plant growth as reported by Meena et al. (2016).

The Potassium-Solubilizing Microorganisms (KSM) are shown in Table 1. The simultaneous introduction of *Azospirillum brasilense* and *Rhizobium meliloti* has a positive impact on grain production and the concentration of nitrogen (N), phosphorus (P), and potassium (K) in *Triticum aestivum* (Mohammadi and Sohrabi 2012).

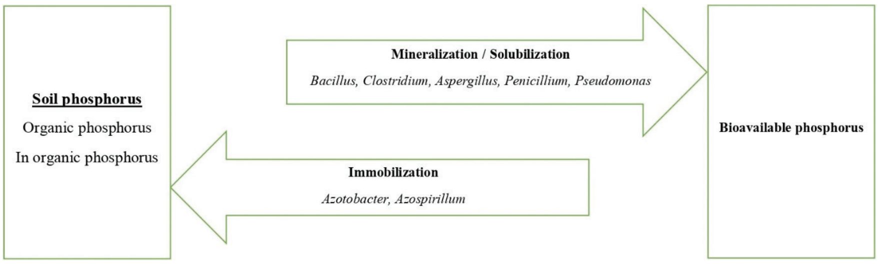

Figure 2. Schematic diagram of soil phosphorous mobilization and immobilization by bacteria. Adapted and modified from: Khan et al. 2009.

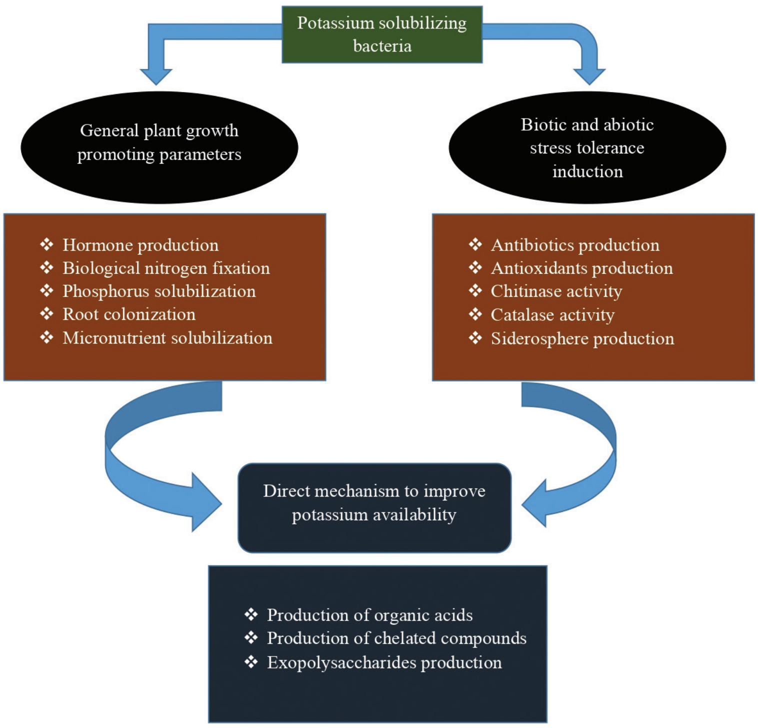

Figure 3. Direct and indirect mechanisms used by potassium-solubilizing bacteria. Source: Ahmad et al. 2016.

Table 1. Mechanism used by bacteria for potassium solubilization.

Bacterial strain	Mechanism used	Source of microorganism	References
Sphingomona, *Burkholderia*	Acidification, complexation	Oak – mycorrhizosphere	Uroz et al. (2007)
B. circulans GY92	Lipo-chitooligosaccharides production	Soybean	Lian et al. (2001)
B. mucilaginosus	Mica through organic acids	Sudan grass	Basak and Biswas (2009)
B. edaphicus	Tartaric acid, oxalic acid	Wheat	Sheng and He (2006)
B. edaphicus	Production of organic acids	Cotton and rapeseed	Sheng (2005)
B. mucilaginosus	Organic acids	Pepper and cucumber	Supanjani et al. (2006)
B. glathei	Siderophores, organic ligands	Mycorrhizosphere, bulk soil	Calvaruso et al. (2007)
P. glucanolyticus	Organic acids	Black pepper	Sangeeth et al. (2012)
P. mucilaginosus	Tartaric, citric, oxalic acids	Silicate minerals	Liu et al. (2012)
E. hormaechei	Organic acids	Okra	Prajapati et al. (2013)

Effects of biofertilizers on the physical properties of soil

Biofertilizers are essential for improving the physical characteristics of soil and creating a more favorable and fruitful growing environment for plants (Fig. 4). Biofertilizers improve soil structure by encouraging the production of stable soil aggregates, which increase porosity, improve aeration, and increase water infiltration (Kumar et al. 2015). Moreover, the application of biofertilizers improved soil bulk density, soil temperature, and soil moisture (Sharma et al. 2012). Beneficial microbes are added to the soil to aid in the effective cycling of nutrients, increasing the availability of vital nutrients for plants and improving soil fertility in general (Altomare et al. 2011).

Soil bulk density

Stable soil aggregate development is aided by beneficial microorganisms found in biofertilizers, such as nitrogen-fixing bacteria and mycorrhizal fungus. By generating pore spaces in the soil, these aggregates increase porosity and decrease bulk density, this leads to a decrease in soil compaction, improving the flow of water and air through the soil profile (Singh et al. 2020). Additionally, the decomposition of organic matter is aided by the activities of these microbes, which raises the soil's overall organic content (Bhattacharyya et al. 2022). By acting as a binding agent, this organic matter enhances soil structure and lowers bulk density. A progressive increase in soil bulk density is supported by the cumulative effect of using biofertilizers, even though these changes might not be apparent right away.

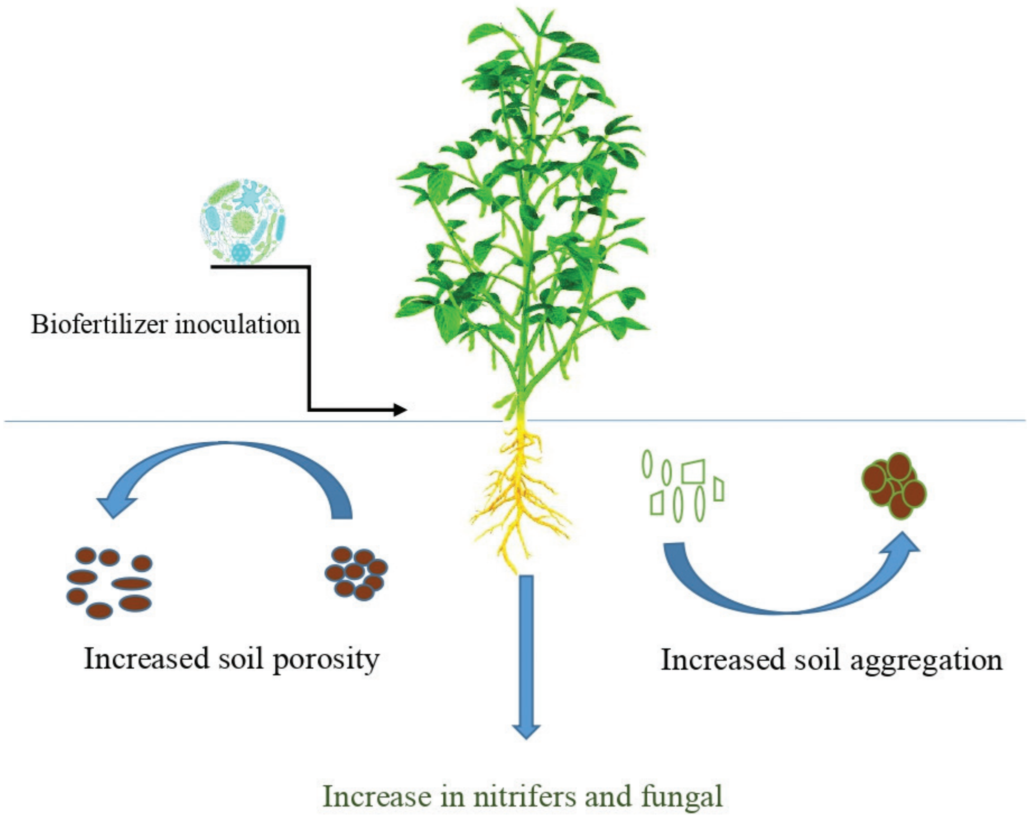

Figure 4. Schematic diagram representing the effect of biofertilizer on pore space of soil. Source: Chatterjee et al. 2017.

Soil moisture

By forming stable aggregates and increasing the amount of organic matter in the soil, the use of biofertilizers improves soil structure and increases soil moisture retention. Mycorrhizal fungi, one of the beneficial microorganisms found in biofertilizers, form symbiotic associations with plant roots, encouraging widespread root development that facilitates effective water absorption (Hosseinzadeh et al. 2021). Furthermore, using biofertilizers promotes healthy plant growth by increasing nutrient availability, which helps plants better control water intake (Tahiri et al. 2022). A more favorable environment for long-term plant growth is produced overall by decreased water evaporation, higher water-holding capacity, and enhanced resilience to changes in moisture levels.

Soil temperature

By encouraging stable soil aggregates, increasing aeration, and boosting heat transmission, biofertilizers have an indirect impact on soil temperature. Humus is created as a result of the breakdown of organic matter which is aided by biofertilizers (Wong et al. 2020). Biofertilizers help in the formation of humus which acts as an insulating layer to mitigate extremes in soil temperatures (Khalid et al. 2021)**.** Better root systems, especially those containing mycorrhizal fungi, are encouraged by biofertilizers, which also improve water uptake and help control temperature (Ghorchiani et al. 2018). A more stable and favorable environment for plant growth is produced by the combined influence on soil structure and root development, even when the direct impact on soil temperature is minimal.

Soil color

Since most elements that affect soil color are related to organic matter, drainage, and mineral content, using biofertilizers usually has little direct effect on soil color. However, through their impacts on microbial activity and organic matter content, biofertilizers indirectly contribute to improved soil color. Biofertilizers accelerate the breakdown of organic matter in the soil, which helps humus to develop. A higher humus concentration can give the soil a deep, dark color (Sumathi et al. 2012).

Effects of biofertilizers on the chemical properties of soil

Effect on soil pH

The study found that the application of biofertilizers caused a little decrease in alkalinity and a slight increase in organic carbon content in the soil, compared to soil that was not treated with biofertilizers (Ramalakshmi et al. 2008). Houmani et al. (2015) further suggested that the acidification of the rhizosphere may occur by the release of organic acids via a mechanism involving the extrusion of protons.

Effect on soil nitrogen content

The soil's nitrogen content was greater in the presence of *Azospirillum*, *Rhizobia*, and so on. In their study, Karimi et al. (2018) found that the introduction of *Azospirillum* bacteria to wheat crops resulted in an increase in soil nitrogen availability due to the fixation of atmospheric nitrogen. *Azospirillum* is extensively researched as a plant growth-promoting bacteria (PGPB) and is often used as a model for studying plant-bacterial interactions (Orozco-Mosqueda et al. 2021). In the past four decades, research on *Azospirillum*-plant interactions has shown various pathways that illustrate the positive effects of this bacteria on plant growth (Cassán et al. 2020).

Effect on soil phosphorus content

The uptake of phosphorus (P) by plants from the soil is influenced by their roots' structure and the release of root exudates. Beneficial microorganisms can regulate this process present in the soil (Shen et al. 2011). These microorganisms can dissolve phosphorus, influence the growth and development of roots, and increase phosphorus absorption and other essential nutrients, (Saia et al. 2020). The mycorrhiza and phosphobacteria enhanced the soil's phosphorus availability. Phosphate-solubilizing bacteria can dissolve around 50–60% of bound phosphorus in the soil by releasing organic acids briefly (Goswami et al. 2019). Barra et al. (2019) noticed the enhanced accessibility of soil phosphorus resulting from the introduction of phosphobacteria inoculation.

Effect on soil potassium content

Potassium (K) is a highly prevalent constituent of soil composition, although its limited accessibility significantly constrains both plant development and ecosystem output (Garcia and Zimmermann 2014). The presence of potassium in various components of the arbuscular mycorrhizal (AM) fungus and mycorrhizal root section indicates that the AM fungi can absorb and transport potassium from the soil to the plant root (Zhang et al. 2017). The soil's potassium content was observed to be elevated in the co-inoculation of *Azophos* and *mycorrhiza* (Ramalakshmi et al. 2008).

Effect on soil organic carbon content

Soil carbon is an essential element of operational ecosystems and vital for ensuring the security of food, soil, water, and energy (Stockmann et al. 2015). The presence of beneficial microbes had a notable impact on the amount of organic carbon in the soil. Specifically, applying *Trichoderma* to the soil resulted in a greater increase in organic carbon content compared to inoculating the seeds with phosphate-solubilizing bacteria in soybean and maize (Imran et al. 2021). Bio-fertilizers have shown significant effects on chemical properties of soil (Heydari et al. 2020).

Effects of biofertilizers on the biological properties of soil

Biofertilizers are essential for improving the biological qualities of soil because they introduce beneficial microbes that aid in nitrogen fixation, phosphorus solubilization, and nutrient cycling. These microbes boost microbial diversity, promote disease suppression, and improve soil structure (Xiong et al. 2017). Biofertilizers lessen their influence on the environment, increase soil fertility over the long term, and encourage sustainable agriculture practices (Rashid et al. 2016). Overall, they support higher crop yields, a more sustainable farming method, and a better soil environment.

Bacteria

The impact of biofertilizers on soil microbes is complex (Sharma et al. 2012). Beneficial microorganisms like phosphate-solubilizing and nitrogen-fixing bacteria can be found in biofertilizers, which can directly increase their population and activity and increase the availability of nutrients for plants (Timofeeva et al. 2022). Furthermore, biofertilizers reduce harmful bacteria and promote a better soil ecology by increasing the diversity of soil microorganisms.

Fungi

Using biofertilizers has various effects on soil fungi, depending on the particular micro-organisms included in the fertilizer. Biofertilizers can enhance nutrient intake by fostering favorable symbiotic connections with plant roots, particularly those that contain mycorrhizal fungus (Filho et al. 2017). Certain biofertilizers have the potential to impact soil fungal communities by augmenting the number of microbial populations and modifying the dynamics of resource competition (Trabelsi and Mhamdi 2013). Specific formulations containing antagonistic microorganisms aid in suppressing soil-borne diseases, whereas formulations high in organic matter might hasten decomposition and include several fungi in the cycling of nutrients (Pathma et al. 2019).

Actinomycetes

Because biofertilizers frequently contain strains or nutrients that favor the development of these filamentous bacteria, their use can greatly benefit soil actinomycetes through direct growth promotion (Li et al. 2022). Increased antagonistic activities may result from this, especially in biofertilizers containing antagonistic bacteria like Streptomyces species, which reduce soil-borne diseases by producing antibiotics (Roopa and Gadag 2019). Furthermore, organic matter-rich biofertilizers promote actinomycetes' ability to break down complex organic compounds, which aids in the cycling of nutrients.

Challenges with biofertilizers

Despite the increasing popularity of using beneficial soil microorganisms in biofertilizers to improve plant productivity, widespread adoption on a large scale has been limited due to the challenge of replicating their positive impact on plants in natural environments with varying conditions (Ibáñez et al. 2023). The primary obstacles to the implementation of microbial biofertilizer include a limited understanding of the ecological significance of microbial biofertilizer among farming communities, insufficient efforts by agricultural extension workers to promote and motivate farmers to use biofertilizer products, a scarcity of appropriate carriers for biofertilizer formulation, inadequate storage facilities to prevent contamination of biofertilizer products, and the adverse effects of extreme climatic conditions, which result in inconsistent effectiveness of biofertilizers on plant productivity in natural environments (Gautam et al. 2021). Moreover, the application of biofertilizer products can lose credibility due to insufficient labeling, such as the absence of an expiry date and the omission of the names of the microorganisms utilized in the creation of the biofertilizer (Narayanasamy 2013). Additionally, it is important to note that most biofertilizers exhibit selectivity in their effects (Malusà et al. 2016).

Conclusion

Biofertilizers offer a sustainable solution for enhancing soil quality and promoting long-term soil sustainability by improving its physical, chemical, and biological properties. They reduce the necessity for artificial fertilizers by improving the variety of microorganisms, the accessibility of nutrients, and the structure of the soil. To achieve widespread application, it is necessary to address challenges such as crop-specific characteristics, limited shelf life, compatibility with existing procedures, and sensitivity to the environment. To be able to surmount these challenges and fully exploit the capabilities of biofertilizers in promoting robust and sustainable agricultural ecosystems, it is imperative to persist with research and teaching.

Conflict of interest

The authors hereby declare that they possess no conflict of interest in this paper.

Data availability statement

The data will be available on request to the corresponding author.

Ethics statement

The author confirm that they have adhered to the ethical policy of the journal.

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