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Biofertilizers as a potential tool towards sustainable agriculture

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ABSTRACT

Chemical fertilizers are extensively used in agriculture to increase crop production; however, this practice can lead to environmental damage. Biofertilizers stand out as a more sustainable alternative to the process. To better understand how biofertilizers promote plant growth, we conducted a review using a bibliometric research approach, where various mechanisms of action of biofertilizers were identified, primarily those arising from the activity of live microorganisms in the soil. Microorganisms contribute to plant development by nitrogen fixation, phosphate solubilization, and exudate production. These mechanisms can directly impact plant growth or indirectly alleviate abiotic stress or promote disease biocontrol in crops. Furthermore, the literature highlights that the disposition of digested biomass in the soil can enhance nutrient availability to plants. Therefore, knowledge of these mechanisms is of great importance for promoting more productive and sustainable agriculture.
KEYWORDS: Plant growth promotion. Microorganisms. Nutrients.

INTRODUCTION

One of the biggest challenges in global agriculture is combining sustainability with maintaining or increasing crop productivity. Biofertilizers have been reported in the literature as a contributing technology that enhances agricultural production while promoting environmental quality. Biofertilizers are mainly characterized by the presence of living microorganisms that will be added to the soil and plant and will act, directly or indirectly, in plant development (DANIEL *et al*., 2022). Among the processes favored by the soil microbiota to promote plant growth are nitrogen fixation, phosphate solubilization, production of exudates, and biocontrol of pests. Furthermore, biofertilizers are also characterized by the addition of stabilized organic matter to the soil to serve as a source of organic nutrients for plants (VELU *et al.*, 2021). Certain biofertilizers are currently used in agriculture, contributing to reduce fossil/industrial fertilizer consumption (BAO, J. *et al.*, 2021) and the costs of crop production.

Knowledge of the biogeochemical processes and mechanisms that drive soil-plant-organism-atmosphere interactions is significant for agricultural improvement, leading to the discovery of new biofertilizer products and technologies for agricultural purposes (NURMAYULIS *et al.*, 2021). It is well-established that a plant's absorption capacity strongly depends on soil characteristics, especially in terms of the microbiota present (BENJELLOUN *et al.*, 2021). Since soil microorganisms contribute to the cycling of various essential macronutrients such as nitrogen and phosphorus, they can either limit or promote crop development (MENDOZA-ARROYO *et al.*, 2020), depending on the mechanism involved in the soil-plant-microorganism interactions. In this sense, we aimed to carry out a bibliometric review of the use of biofertilizers in soils and to evaluate the main mechanisms and microorganisms used in the processes of increasing agricultural productivity and sustainability.

STRATEGY OF THE STUDY

The research of this review focused on the mechanisms of action of biofertilizers for agricultural purposes. For that, a search was conducted in the Scopus database, which has comprehensive coverage of the content (Scopus.com). The search used the term “Biofertilizer” in the Scopus database. The survey considered the term present in title, keywords, and abstracts. The search resulted in 5,167 articles. To refine the documents, only articles published from the year 2017 were considered. Only ‘Articles’ were also considered in the search, totaling 2,417 journals. The found documents were exported to the Bibliometrix tool in RStudio version 4.1.0 for Desktop in BibTeX format. Figure 1 shows a thematic map of the most frequent words in the titles, keywords, and abstracts of the analyzed papers.

Figure 1. Thematic map of the most frequently cited keywords ("Biofertilizer" in the Scopus database)

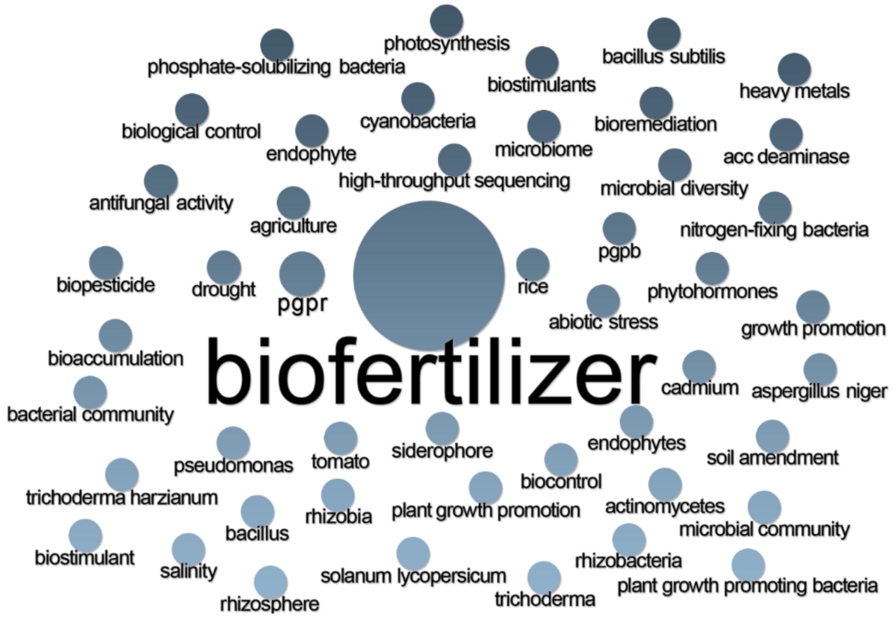

Figure 1 enabled an overview of the most significant words related to the term "biofertilizer". Different mechanisms are used for plant growth promotion by the soil microbiota, such as obtaining nutrients ("nitrogen-fixing bacteria" and "phosphate-solubilizing bacteria"), exudates production ("siderophore", "ACC deaminase" and ("phytohormones"), control of diseases ("biological control", "biocontrol", "antifungal activity" and "biopesticide"), and abiotic stress relief ("abiotic stress", "salinity", "drought", "cadmium" and "heavy metals"). In addition, the intense presence of terms related to microorganisms, responsible for the maintenance of soil health and crop growth, was verified ("plant growth promotion", "plant growth promotion bacteria", "PGPR" - plant growth promotion rhizobacteria, "PGPB" - plant growth promotion bacteria, "microbial community"). Analyzing the articles showed the importance of another two mechanisms that weren't in the thematic map: the importance of the production of exopolysaccharides by microorganisms and the disposition of nutrients present in biomass. The authors considered these mechanisms of great importance to complement the research.

SOLID BIOMASSES AS BIOFERTILIZERS

The use of biomass in soils acts as releasing nutrients, furnishing organic carbon for the system, and promoting microorganism activity. However, sometimes, certain biomass type does not suitable to being disposed of in soils, because it requires chemical and physical stabilization (VELU *et al.*, 2021). In aerobic or anaerobic digestion, the biomass is treated and becomes stable for disposal as a plant biofertilizer. The process is carried out by the action of different microorganisms that are inoculated together with substrates. After the digestion process, the biomass will be suitable for use in the soil. Thus, the action of microorganisms takes place mainly in the production of material that will be used in the soil (YONG, Z. J.; BASHIR; HASSAN, 2021).

The waste digestion process is composed of two essential materials, the substrate and the inoculant. The inoculum contains the microorganisms necessary for the digestion process and the substrate will be used and degraded by these organisms. The sludge from some processes is often used as an inoculant, such as the digestion of animal manure or urban effluent treatment processes. The substrates can come from different materials, such as food and agricultural residues (TSACHIDOU *et al.*, 2021) and algal biomass (VELU *et al.*, 2021).

Biomass digestion can also be solid, called compost. Substrate and inoculant, which may come from manure, are also added to the compost. The result of this process is CO_2 and pathogen-free humus. Substrate materials must be added to achieve an ideal C:N ratio and can come from agricultural residues, branches, grass, sawdust and biochar. Factors such as humidity, aeration, temperature, and pH must also be observed and are essential for the proper functioning of composting (ASADU *et al.*, 2018). Another type of composting is vermicomposting, which consists of adding worms to the process. This process can help remove heavy metals from the process, resulting in a compound suitable for use as a biofertilizer (NING *et al.*, 2021).

In the composting process, the addition of specific microorganisms in raw material degradation can bring specific biomass, which can act as disease prevention in crops or result in compost with higher nutrient fractions. The addition of *Bacillus* sp. and *Paenibacillus* sp. present in pig manure in a composting trial was able to inhibit the fungus *Rhizoctonia cerealis* that causes wheat sharp eyespot (XU, Y *et al.*, 2020). It has been reported that the addition of the bacteria isolates *Streptomyces* spp. can increase the NPK contents of the resulting compost due to its ability to fix nitrogen and solubilize potassium (ASADU *et al.*, 2018). However, the addition of certain microorganisms in the process can change the composting time, as with the addition of *Trichoderma*. This microorganism used in composting resulted in compost rich in nutrients and capable of biological disease control (ORGANO *et al*., 2022)

It is also worth highlighting the use of biomass from pyrolysis processes, called biochar. The use of biochar as a biofertilizer can also increase the availability of nutrients in the soil, such as potassium, nitrogen, phosphorus, and sodium (LUO, K. *et al.*, 2023). The use of this compound together with organic fertilization can reduce the loss of P from the soil and increase its available stock in the soil to be used by plants (LI, F. *et al.*, 2021). Thus, different biomass can be used in the production of biofertilizers (from digestion, composting, and pyrolysis processes), resulting in a material rich in organic matter to be degraded by the soil microbiota and release essential nutrients for the plant (VELU *et al.*, 2021).

NITROGEN FIXATION

Nitrogen is an essential nutrient for the synthesis of amino acids, proteins, and other compounds (BENJELLOUN *et al.*, 2021). In crops, nitrogen is supplemented through the application application of inorganic nitrogen (chemical fertilizers). However, the application of chemical fertilizers has drawbacks such as the leaching of this compound into water bodies, causing environmental damage such as eutrophication (BAO, Y. Q. *et al.*, 2023). Thus, N-fixing microorganisms in the soil reduce the use of inorganic nitrogen by chemical fertilizers and contribute to the maintenance of the environment (HETT *et al.*, 2023).

The action of nitrogen-fixing microorganisms is directly linked to the action of the nitrogenase enzyme (SINGH, P. *et al.*, 2021), responsible for fixing N to the plant. Furthermore, the strains used as biofertilizers must have the genes that allow this process (*nif*) (JUNG, B. K. *et al.*, 2018). Bacteria that can fix nitrogen are called diazotrophic, and these can be rhizospheric or endophytic. In addition, they can be free-living bacteria in the soil or be in symbiosis with plants (MATSE *et al.*, 2020), forming nodules where the fixation mechanism occurs endophytically (BENJELLOUN *et al.*, 2021). Nitrogen fixation occurs mainly through the action of bacteria and cyanobacteria (SUEBRASRI *et al.*, 2020).

The plant fixation of nitrogen by microorganisms directly influences the increase in agricultural growth and productivity, as well as reduces the agriculture dependency of fossil fuels. Uptake of N by the plant enables the formation of proteins and amino acids that have a direct action on the plant's photosynthesis, increasing its biomass (BENJELLOUN *et al.*, 2021). The analyzed works presented that there was an increase of N inside the plant (MATSE *et al.*, 2020).

Besides, the use of nitrogen-fixing cyanobacteria can also be observed. The *Anabaena* cyanobacteria strain has this characteristic and is used in rice cultivation, a crop commonly associated with flooded production systems. This feature presents favorable conditions for the growth of cyanobacteria (BAO, J. *et al.*, 2021; ZHANG, J. *et al.*, 2021).

PHOSPHATE SOLUBILIZATION

Phosphorus is essential for being part of the composition of molecules and is directly responsible for the development and growth of cultures. P can be present in the soil in inorganic forms, such as orthophosphates, metaphosphates, and polyphosphates, as well as in organic forms. However, although the soil has high levels of P in its composition, only the soluble orthophosphate form can be absorbed by living organisms. Thus, P is a limiting factor for plant growth, and the abiotic and biotic chemical processes that control the transformation and absorption of this element are important factors in its cycle and agricultural productivity (WANG *et al*., 2023).

Several microorganisms in the rhizosphere are capable, through different mechanisms, of extracting or solubilizing P from insoluble fractions and poorly soluble natural inorganic phosphates. The P mineralization process can occur in different ways, such as the release of the phosphatase enzyme that acts in the breakdown of organic P. Another way is the soil acidification by the release of organic acids or producing of inorganic acids. This process is also important in the solubilization of inorganic phosphates, especially primary phosphate compounds in the soil (PATEL *et al.*, 2020).

The solubilization of P by the soil microbiota depends on several factors such as the strain of the microorganism, the type of phosphate to be solubilized, the excretion of P hydrolytic enzymes (SUEBRASRI *et al.*, 2020) and nature of the organic materials produced (MENDOZA-ARROYO *et al.*, 2020). Chemical fertilizers provide only a small amount of phosphorus needed by the plant due to the immobilization of P. Thus, the use of efficient phosphate solubilizing microorganisms can help plant development by increasing the levels of phosphorus in the rhizosphere (ASTRIANI *et al.*, 2020).

Microorganisms such as *Penicillium oxalicum* showed the ability to excrete oxalic acid, malic acid, and citric acid. This release depends on the source of phosphorus available for solubilization and these acids are responsible for solubilization, they also make the soil pH more acidic. Unlike nitrogen fixation, which had a predominance of bacteria involved in the process, in the solubilization of phosphates there is a high incidence of fungal action in the process. The effects of phosphate solubilizing microorganisms in the plant are the higher productivity and growth of the specimens, thus increasing their productivity (RAMÍREZ-CARIÑO *et al.*, 2023).

PRODUCTION OF PHYTOHORMONES

The promotion of plant growth by the action of microorganisms also stands out for their ability to produce growth-stimulating phytohormones (DHAWI, 2023). These compounds can act directly on the plant's development or increasing its capacity to absorb water and nutrients, relieving abiotic stresses such as salinity, thermal stress, water stress, and soil contamination by heavy metals (KANG *et al.*, 2020).

These composts can act as both substrate and signaling molecules. Signaling can be translated as a communication pathway between plants and the microbiota through which hormones can change the microbial structure or activity. The metabolism of microorganisms could synthetized phytohormones that contribute to plant growth (WAADT, 2020). The release of phytohormones in the soil can occur through active transport, diffusion, or root exudates, particularly from plants experiencing water scarcity, which have higher phytohormone concentrations to maintain (DHAWI, 2023).

In the literature, several studies associate plant growth and development with the production and metabolization of phytohormones. The mechanisms of action of phytohormones can occur directly or indirectly. Phytohormones such as auxin/IAA, gibberellins, and cytokinins, directly promote plant growth by increasing root surface area, chlorophyll content, and plant weight, thereby facilitating the uptake of water and nutrients (NURMAYULIS *et al.*, 2021). Among these, indole-3-acetic acid (IAA) is the most used in plant growth due to the action of phytohormones (HORSTMANN *et al.*, 2020). IAA increases root length and surface area and, in the process, increases the level of root exudates available for uptake by plants (OLANREWAJU; GLICK; BABALOLA, 2017).

Abscisic acid (ABA), jasmonic acid (JA), and salicylic acid (SA) are considered signaling phytohormones. They assist in monitoring plant conditions in abiotic stress environments such as water or thermal stress (KUBI *et al.*, 2021). High levels of ABA and JA indicate signs of abiotic stress in the plant that can harm its development. SA is the phytohormone related to plant resistance, where higher levels are beneficial to plants under stress. All these plant hormones have their values favored by the inoculation of microorganisms in the soil, indicating that specific rhizobacteria inoculated in soil under abiotic stress can relieve adverse effects favoring plant growth (KANG *et al.*, 2020).

Another phytohormone important for plant growth is ethylene. Ethylene is an essential phytohormone for plant development where it acts as a growth regulator. However, abiotic stress levels can increase plant ethylene levels causing adverse effects such as root growth inhibition. One of the ways to regulate this growth is through the action of the enzyme ACC deaminase, responsible for the degradation of ACC, the main precursor of ethylene in plants (KUMAWAT *et al.*, 2021). It has been reported that *Pseudomonas* sp. can produce the enzyme ACC deaminase under conditions of water, thermal and alkaline stress (KARNWAL, 2021). Other microorganisms that also showed ACC deaminase activity were *Streptomyces* sp. (HORSTMANN *et al.*, 2020), *Enterobacter* sp. and *Pseudomonas* sp., (ANDY; MASIH; GOUR, 2020), *Bacillus subtilis* and *B. pumilus* (PANDEY, S.; GUPTA, S.; RAMAWAT, 2019).

PRODUCTION OF SIDEROPHORES

Siderophores are low molecular weight molecules that have a great affinity with iron molecules (Fe), which can bind. Thus, they are carriers of this micronutrient and can transport it to plants and other microorganisms promoting their development. Some growth-promoting bacteria (PGPB) have the characteristic of producing siderophores. So, they are used as a nutrient in plant cells or by reducing their availability to pathogens (ANDY; MASIH; GOUR, 2020). Iron is important in the biosynthesis and maintenance of chlorophyll and chloroplast biogenesis, being part of the light-absorbing composition of chlorophyll. Normally, Fe presents insolubility characteristics and is unavailable in the soil. Thus, siderophores can be secreted by fungi, plants, and plant growth-promoting bacteria (NING *et al*., 2023).

The soluble Fe-siderophore complex can be incorporated by plants and bacteria and after its entry into the cell, it becomes available again to carry out the process again. In the literature, numerous microorganisms are reported as siderophore producers. The PGPB reported are from *Bacillus subtilis*, *Pseudomonas* (PANDEY, S.; GUPTA, S.; RAMAWAT, 2019), *Streptomyces* (HORSTMANN *et al.*, 2020), *Enterobacter* (MENDOZA-ARROYO *et al.*, 2020), among others.

PRODUCTION OF EXOPOLYSACCHARIDE

Exopolysaccharides (EPS) are high molecular weight compounds that can be excreted by microorganisms. They are mainly composed of complex organic macromolecules and may be part of the composition of microbial biofilms that have the function of protecting these organisms (OJUEDERIE; OLANREWAJU; BABALOLA, 2019). In the soil, EPS acts as a bonding agent for the aggregation of soil particles, accumulation of organic matter, and increasing the water retention capacity of the upper layer of the soil (CHITTORA *et al.*, 2020).

These characteristics of water retention and soil cementation contribute to the regulation of nutrients and water flow that reach the plant roots, thus, it contributes to the maintenance of plant growth in soils that suffer from adverse abiotic factors, especially those that suffer from stress due to lack of water and saline stress (NIU *et al.*, 2018). Also, the production of EPS by microorganisms tolerant to heavy metal toxicity enables plants to grow in contaminated soils, reducing the accumulation of these elements in roots and leaves. Thus, EPS production can be used as a parameter to identify stress-tolerant microorganisms. In the literature, several microorganisms are reported as capable of excreting EPS into the medium, such as *Klebsiella* sp. (GOHIL *et al.*, 2023), *Enterobacter* sp. (MENDOZA-ARROYO *et al.*, 2020), *Pseudomonas fluorescens*, *Enterobacter hormaechei*, *Pseudomonas migulae* (NIU *et al.*, 2018), among others.

BIOLOGICAL CONTROL OF PLANT DISEASES

Microorganism Controlling Fungal and Bacterial Diseases

Among the diseases that harm plant health is *Fusarium* wilt disease. The disease is caused by fungi of the *Fusarium* genus (HADDOUDI *et al.*, 2021). This disease is transmitted through the soil and can infest populations and cause the death of crops. Hot and humid climates are conducive to the development of this disease. Several studies report the presence of these pathogens in different parts of the world causing damage to different crops. In addition to wilt, microorganisms of the *Fusarium* genus can cause other diseases such as rust, rot, and canker diseases (ZHAO, X. *et al.*, 2021).

To control the pathogen, different microorganisms can be used, which normally do not act directly on pathogen suppression, but act on stimulating the growth of microbial consortia that will act against the disease (DANIEL et al., 2022). This microbial community will create a more competitive environment for the pathogen by inhibiting its growth (FU, L. *et al.*, 2017).

Several microorganisms have been reported to be efficient in suppressing *Fusarium* in plantations, such as the *Bacillus* genus (HADDOUDI *et al.*, 2021), *Streptomyces* genus, can disrupt the cytoplasmic membrane of the fungus *Fusarium* resulting in the elimination of the disease in soils. *Penicillium* genus, also have antifungal properties, excreting metabolites such as proteases, cellulases, and β-1,3-glucanase that inhibit the growth of the *Fusarium* genus (ZHANG, G. *et al.*, 2020). Generally, the greatest antifungal activity is related to the presence of biosynthetic genes of the strains and the production of secondary metabolites that inhibit the growth of pathogens (HADDOUDI *et al.*, 2021).

Another disease reported causing agricultural damage is rot disease or white mold. One of the pathogenic microorganisms that can cause this disease in crops is *Sclerotinia sclerotiorum* which is transmitted through the soil and causes disease and death in different crops around the world. The fungus can produce sclerotia, structures formed by its mycelium that contain reserve substances, enabling the fungus to survive in the soil for many years. These sclerotia can germinate under favorable environmental conditions giving rise to infectious hyphae thus causing an epidemiological outbreak in susceptible plants (SUN *et al.*, 2017). The control of this pathogen can be performed by microorganisms such as *Trichoderma*, that can act in different ways in the control of diseases such as rot and wilt of roots and fruits, through direct attack to the pathogen and nematodes or in the induction of resistance by the plants that are being attacked (ZIN; BADALUDDIN, 2020).

Among the diseases caused by bacteria in plants is bacterial canker caused by actinobacteria of the *Clavibacter* genus. *Clavibacter michiganensis* subsp. *michiganensis* is the most studied causative microorganism and they are plant pathogens, occupying mainly the xylem vessels (KIM, D. *et al.*, 2021). The presence of the pathogen in soil leads to plant infection. The disease enters through the root and is then carried to all parts of the plant by the xylem. The pathogen can generate water stress in the plant causing wilt. In addition, the pathogen produces exopolysaccharides that protect them from the plant's defense system, allowing them to spread inside the plant (GARTEMANN *et al.*, 2003).

Microorganism Controlling Plant Diseases Caused by Nematode

Among several nematode species, three of them represent the most important plant disease in crop production worldwide (*Meloidogyne* sp.; *Heterodera* sp., and *Pratylenchus* sp.), causing important crop yield reduction (WU, H. Y. *et al.*, 2014). Microorganisms were tested as agents aiding nematode control in crops. Two mechanisms were highlighted in the microorganism-plant interaction, (i.e., direct and indirect ones). The direct mechanism consists of a competition organism-organism, while the indirect one consists in give better conditions to plant resisting infections or injuries (BENEDETTI *et al.*, 2021). The microorganism can also produce chemical compounds, which are toxic with the potential to affect the life nematode cycle (MOAZEZIKHO *et al.*, 2020).

The occurrence of a certain microorganism ¨per si¨ can affect the nematode population, including antagonistic, predatory, and parasitic organisms. In tropical and subtropical climate regimes, the control of nematodes is mandatory mainly when the genus *Meloidogyne* sp. occurs (CANNAYANE; RAJENDRAN, 2001). The genus *Trichoderma* sp. affects nematodes reproduction (viable eggs) which became an alternative to biocontrol of nematodes (SANDOVAL *et al.*, 2020). The genus *Bacillus* and *Pseudomonas* were also reported as producing good control, inhibiting nematodes (HUANG, K. *et al.*, 2020). *Citrobacter freundii* and *Pseudomonas putida*, inoculation in tomato, indicating a high control potential of this pathogen (MOAZEZIKHO *et al.*, 2020).

CHALLENGES AND FUTURE PERSPECTIVES

The production of biofertilizers from microorganisms holds great potential for promoting sustainable agriculture, aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger and Sustainable Agriculture), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). However, significant challenges must be overcome for this technology to achieve widespread adoption, spanning science, technology, and society (GAUTAM *et al*., 2021).

In the scientific field, selecting effective microorganisms for different soil types and crops is a major challenge, as environmental and climatic conditions directly influence the performance of microbial strains. Another critical concern is the ecological impact of introducing exogenous microorganisms into the soil, which may disrupt local ecological balance and affect native microbial biodiversity. To address these challenges, a multidisciplinary approach is required, integrating knowledge from microbiology, genetics, ecology, and agronomy, along with long-term studies to understand the ecological impacts and sustainability of biofertilizer use. Genetic engineering tools, such as CRISPR, can also be used to modify microorganisms, enhancing their efficiency in nutrient fixation and resistance to adverse conditions (MITTER *et al*., 2021).

From a technological perspective, large-scale biofertilizer production remains a challenge, particularly regarding cost and logistics. Maintaining microorganism viability during storage and transportation is a significant technical hurdle. Additionally, the lack of clear standards for biofertilizer production and application can lead to variable product quality, affecting their effectiveness. Integrating biofertilizers with traditional farming practices may also pose difficulties, especially in regions with limited access to technology. To overcome these obstacles, advancements in fermentation technology, such as bioreactors, can help reduce production costs and increase biofertilizer viability. Nanotechnology applications may improve microorganism delivery to the soil, enhancing effectiveness and reducing the amount required. Furthermore, integrating biofertilizers with precision agriculture technologies, such as soil sensors and drones, can optimize their application, minimizing waste and increasing efficiency (KAUR *et al*., 2024).

On the social front, the acceptance of biofertilizers faces significant barriers, particularly in less developed regions, where resistance may stem from a lack of knowledge, reliance on chemical fertilizers, or concerns about potential risks. Initial costs can also be a deterrent, as although biofertilizers can lower long-term expenses, the upfront investment may be prohibitive for small-scale farmers. The lack of education and training on the proper use of biofertilizers further limits their adoption and effectiveness. To overcome these challenges, public policies and government incentives, such as subsidies and farmer education programs, can promote biofertilizer adoption (SRIVASTAV *et al*., 2024). Social projects such as the installation of biodigesters in family farming areas offer social, economic, and environmental benefits. They allow the use of organic waste to generate biogas in addition to producing digestate with biofertilizer potential. This contributes to sustainability, reduces costs and promotes renewable energy. These projects also strengthen the local economy, reduce environmental impacts, and increase the autonomy of farmers, generating more efficient and conscious agriculture (CALGARO NETO; OLIVEIRA, 2021; MACHADO *et al*., 2019). In addition, awareness campaigns highlighting the environmental and economic benefits of biofertilizers can enhance acceptance, while international cooperation between developed and developing countries can accelerate technology and knowledge transfer, fostering global adoption of biofertilizers (SRIVASTAV *et al*., 2024).

FINAL CONSIDERATIONS

Biofertilizers promote the release of essential nutrients in the soil, particularly in the rhizosphere, benefiting plant growth and agricultural productivity. Microorganisms present in these bio-inputs help mitigate abiotic stresses, control pathogens, and stabilize biomass, improving soil health. However, scientific, technological, and social challenges still limit their large-scale adoption. There are gaps in understanding microbial interactions and their ecological impacts, as well as difficulties in production, storage, and product standardization. Economic and cultural barriers also hinder their acceptance by farmers, requiring investments in research, innovation, and public policies. Despite these challenges, biofertilizers offer environmental and economic advantages, contributing to agricultural sustainability and aligning with Sustainable Development Goals, such as food security, responsible consumption, and climate action.

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