

Review

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Review

Microbial Fertilizers: A Study on the Current Scenario of Brazilian Inoculants and Future Perspectives

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Abstract: The demand for a more sustainable agriculture, coupled with the need for optimized crop productivity, has driven the use of microorganisms for the biocontrol of diseases and pests, as well as for growth promotion. The use of plant growth-promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF) in Brazilian production systems has become increasingly common, with the number of microbial inoculant registrations in the country growing every year. PGPR and PGPF occupy various niches in the rhizosphere, playing a crucial role in soil nutrient cycling, as well as influencing various plant physiological processes. In this review, we address the main mechanisms used by these microbial agents in growth promotion and the use of strain co-inoculation as a strategy to enhance the efficacy of these products. Subsequently, we conduct an analysis of the available inoculants in Brazil, detailing the microorganisms available for the main Brazilian crops, and the prospects of this market regarding research and development of new products for the coming years based on the current challenges faced.

Keywords: beneficial microorganisms; co-inoculation; soil microbiome

1. Introduction

The need for more sustainable agriculture with less environmental impact has transformed the way we use chemical fertilizers, once seen as a solution for maintaining productivity. Today, we understand the impact of these inputs on soil, the environment, and human health. Additionally, these inputs are expensive and inefficient and a large portion of nutrients ends up getting retained in the soil in insoluble forms [1].

In this context, the use of growth-promoting microorganisms is increasing, which is a more sustainable practice that can help better utilize nutrients in the soil and reduce chemical fertilization. The interaction between plants and microorganisms is essential for plant development. Microorganisms contribute to the chemical composition of the rhizospheric environment, influencing growth, morphology, and root permeability through the release of metabolites [2].

Several processes are regulated by plant growth-promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF), such as nutrient mineralization and solubilization, production of growth-regulating phytohormones, induction of systemic resistance, increased resistance to abiotic stresses, inhibition of plant diseases through antibiotic production, reduction of ethylene in roots, production of siderophores, and iron chelation [3].

The use of growth-promoting microorganisms has become a trend in Brazilian agriculture. According to the National Association of Inoculant Producers and Importers, in 2022, 134.9 million doses were delivered by associated companies, which represents an increase of 30 million doses in comparison to 2021. In this panorama, there is growing interest in research and development of new inoculants with more effective, multifunctional strains and formulations that increase the shelf life of these products. Co-inoculation of microbial agents with different mechanisms of action and

synergistic interactions is one of the strategies used, with an increase in registrations of these products in recent years. This practice was used in 35% of the soybeans grown in the country in the 22/23 harvest [4].

Based on this, this article aims to provide a review of the main mechanisms used by PGPR and PGPF in promoting growth and thus discuss the state of the Brazilian inoculant market (Figure 1). Furthermore, it aims to describe the crops with the most registered microbial inoculants and their prevalent mechanisms of action. In conclusion, it will also discuss market trends based on challenges in Brazilian agriculture.

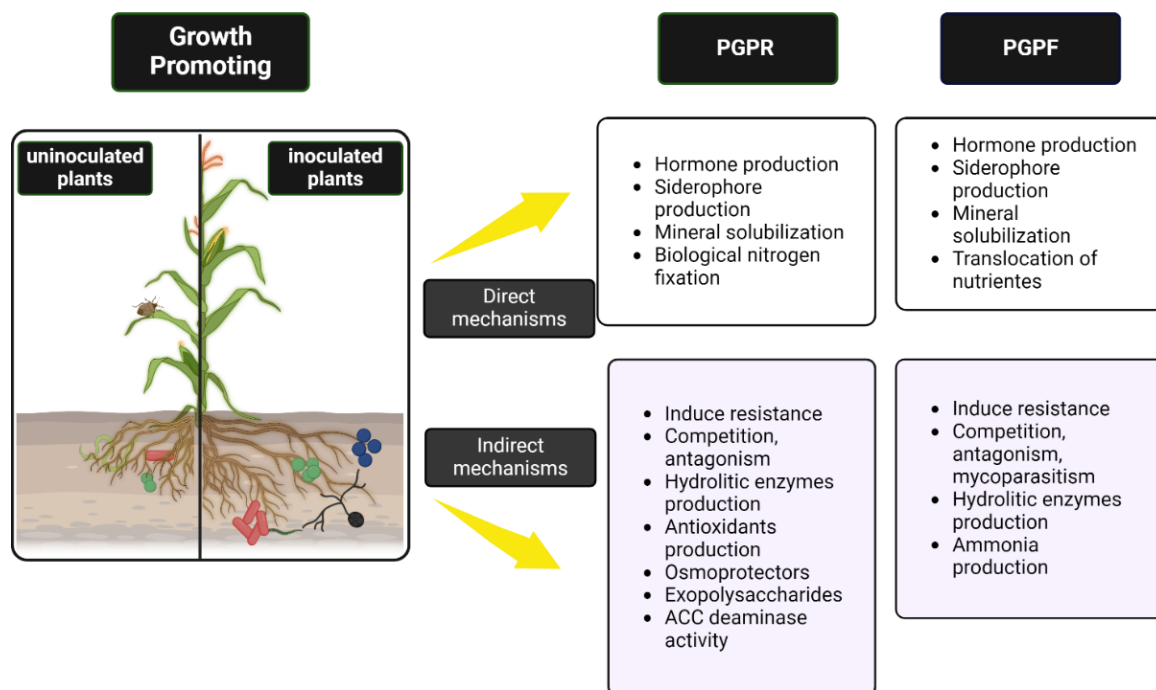


Figure 1. Direct and indirect mechanisms of PGPR and PGPF for plant growth promotion in the soil.

2. Plant Growth-Promoting Rhizobacteria (PGPR)

The beneficial interactions between plants and PGPR have emerged as a promising research area for the development of sustainable agriculture and the pursuit of more efficient cultivation methods. These bacteria can positively influence plant development through several mechanisms (Table 1), which will be discussed further on.

Table 1. Some examples of PGPR growth promotion mechanisms.

Specie	Mechanism of growth promotion	Culture	Reference
<i>Azospirillum brasilense</i>	Nitrogen fixation	Maize (<i>Zea mays</i>)	[5]
<i>Bradyrhizobium</i> sp.	Nitrogen fixation	Soybean (<i>Glycine max</i>)	Zilli et al., 2021[6]
<i>Pseudomonas</i> sp.	Phosphate solubilization	Pea (<i>Pisum sativum</i>)	Oteino et al. 2015[7]
<i>Pseudomonas</i> sp.	Phosphate solubilization	Maize (<i>Zea mays</i>)	Sarikhani et al., 2020[8]

<i>Pseudomonas brassicae</i>	Siderophore production	Mung bean (<i>Vigna radiata</i>)	Sun et al. 2022[9]
<i>Pseudomonas aeruginosa</i>	Phytohormone production	Mung bean (<i>Vigna radiata</i>)	Uzma et al., 2022[10]
<i>Pseudomonas putida</i>	Antioxidant activity	Maize (<i>Zea mays</i> L.)	Sandhya et al., 2010[11]
<i>Bacillus velezensis</i>	Phosphate solubilization and phytohormone production	Wheat (<i>Triticum aestivum</i>)	Afzal et al.2023[12]
<i>Bacillus velezensis</i>	Phosphate solubilization	Soybean (<i>Glycine max</i>) and Maize (<i>Zea mays</i>)	Mosela et al. 2022[13]
<i>Bacillus mojavensis</i>	VOCs production	<i>Arabidopsis thaliana</i>	Rath et al., 2018[14]
<i>Bacillus subtilis</i>	ACC deaminase activity	Tomato (<i>Solanum lycopersicum</i>)	Gowtham et al., 2020[15]
<i>Serratia sp.</i>	ACC deaminase activity and phytohormone production	Sunflower (<i>Helianthus annuus</i>)	Carlos et al., 2026[16]

2.1. Biofertilization: A Sustainable Approach to Enhance Soil Fertility

Nitrogen stands as a critical limiting factor for plant growth; its availability in the soil directly influences agricultural production. Biological nitrogen fixation (BNF) has proven to be an effective strategy to reduce reliance on nitrogen-based fertilizers. BNF is a complex biological phenomenon in which certain bacteria convert atmospheric gaseous nitrogen into plant-assimilable nitrogenous compounds. This process not only provides nitrogen to plants but also enriches the soil with essential nutrients, boosting its fertility and structure [17]. Several genera of rhizobacteria are capable of fixing nitrogen, e.g., *Rhizobium*, *Bradyrhizobium*, *Azospirillum*, and *Azotobacter*, which are the most commonly used as biofertilizers [18].

Rhizobium and *Bradyrhizobium* establish nodules on the roots of leguminous plants, where biological nitrogen fixation takes place. These bacteria possess an enzyme called nitrogenase, which breaks the triple bond of gaseous nitrogen (N_2) and transforms it into ammonia (NH_3), a compound assimilable by plants. The ammonia is then incorporated into organic molecules, such as amino acids and proteins, within the plant [19].

In turn, *Azospirillum* and *Azotobacter* are free-living bacteria that also possess the nitrogenase enzyme, although they do not form nodules on roots. The N_2 molecules are converted into NH_3 inside the bacterial cells. The ammonia produced in the reaction can be released into the surrounding environment, increasing soil fertility [20]. BFN by rhizobacteria enhances soil quality, especially by providing a constant source of nitrogen [21].

Another essential element for the growth and development of plants is phosphorus (P). When phosphate-based fertilizers are applied to the soil, they are not always fully utilized by plants, and the excess phosphorus tends to bind to surrounding metallic cations, such as calcium (Ca^{2+}), iron (Fe^{3+}), and aluminum (Al^{3+}), forming insoluble phosphates. These phosphates (calcium phosphate, iron phosphate, and aluminum phosphate) have low solubility in water, limiting P availability to plants [22].

Bacillus, *Pseudomonas*, *Acinetobacter*, and *Pantoea* species play an important role in improving P availability in the soil, especially in its insoluble forms. These bacteria are referred to as PSBs

(phosphate-solubilizing bacteria) and produce and release several organic acids (formic, acetic, propionic, lactic, and succinic acids). The hydroxyl and carboxyl groups of the acids released by these bacteria react with phosphate minerals, dissolving and converting them into assimilable forms by the plants [23]. From the production of these organic acids, these bacteria also enhance the availability of other nutrients, such as potassium (K), which is one of the most crucial nutrients for plants. Potassium is typically applied in soluble forms, but it undergoes rapid fixation in the soil [24].

The combination of nitrogen-fixing and phosphorus and potassium-solubilizing bacteria presents an alternative for reducing the application of chemical inputs in agricultural fertilization, thereby rendering agriculture more sustainable and cost-effective [25].

2.2. Protection Against Oxidative Stress in Adverse Environmental Conditions

Rhizobacteria also play a crucial role in the mitigation of the oxidative stress effects on plants that occur due to an imbalance between the production of reactive oxygen species (ROS) and the inherent capacity of plants to neutralize them through antioxidant systems [26]. The accumulation of ROS, highly reactive molecules, results in oxidative damage to vital cellular components, including lipids, proteins, and nucleic acids in plant cells. Oxidative stress caused by ROS can lead to cellular deterioration, compromised photosynthetic efficiency, and inhibition of plant growth.

Various abiotic factors contribute to the establishment of this imbalance, such as high soil salinity, environmental pollutants, water deficiency, toxic substances, and even inherent characteristics of the environment [27].

Antioxidant enzymes such as glutathione reductase (GR), ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), monodehydroascorbate reductase (MDHAR), catalase (CAT), peroxidase (POX), and superoxide dismutase (SOD) neutralize ROS through oxidation, reduction, and dismutation processes of O₂ into H₂O₂. Rhizobacteria *Bacillus subtilis*, *Pseudomonas fluorescens*, *Pseudomonas putida*, among others, help modulate the plant's antioxidant defense system and enhance the activity of antioxidant enzymes [28]. Thus, plant tolerance to adverse conditions, e.g., drought, high temperatures, and pollution is enhanced, and plants that are more resilient when facing oxidative stress tend to maintain optimized nutrient absorption, reducing the need for excessive amounts of fertilizers [29].

2.3. Production of Phytohormones by Rhizobacteria

Phytohormones control plant growth, development, and responses to environmental stimuli. Some beneficial rhizobacteria possess the remarkable ability to synthesize and release phytohormones, which will positively influence plant growth and health [30].

Some examples are auxins and cytokinins, two phytohormones that work in a coordinated manner to stimulate the growth of both above-ground parts and roots. The increase in root development, for instance, leads to an expansion of the absorption area, enhancing the efficiency in resource uptake from the soil, and consequently promoting a more robust and healthier development of plants [31]. Gibberellins, another group of phytohormones of great importance, are responsible for stem elongation, leaf expansion, floral development, seed germination, and fruit development [32].

Other phytohormones produced by rhizobacteria, such as abscisic acid, prove to enhance plant tolerance to stress conditions like drought and high temperatures. Abscisic acid regulates stomatal movements, contributing to the containment of water loss [30]. Furthermore, salicylic acid triggers the plant's defense system, providing increased resistance to pathogens and pests [33].

2.4. Production of ACC Deaminase

Ethylene is a gaseous hormone produced by plants and plays a vital role in their development and adaptation to adverse conditions. During biotic stresses, such as pathogen attacks, the increase in ethylene levels triggers a series of defense responses, including the production of phytoalexins and the activation of resistance genes [34]. Similarly, in abiotic stresses such as drought and salinity, ethylene assists plants in survival by adjusting growth, closing stomata to reduce water loss, and

promoting the synthesis of antioxidant enzymes to combat oxidative stress. However, when ethylene levels exceed what is needed, undesirable effects can occur, such as inhibition of root and stem growth, reduction in photosynthetic rate, and even induction of premature senescence. Additionally, excess ethylene can lead to premature leaf and flower drop, compromising the plant's ability to photosynthesize and reproduce. Therefore, precise regulation of ethylene levels is crucial to ensure optimal growth and development of plants [35].

Some PGPR produce ACC deaminase, an enzyme that reduces ethylene concentrations in the plant by cleaving the precursor aminocyclopropane carboxylic acid (ACC) into ammonia and α -ketobutyrate. This mechanism helps reduce damage caused by various stresses, particularly environmental ones, such as in saline soils [36], heavy metals [37], and water stress [38].

2.5. Chemical Signals: Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are chemical substances widely released by most living organisms. Rhizobacteria can produce certain VOCs that promote growth promotion and the induction of systemic resistance [39].

These substances are released by bacteria into the surrounding environment and encompass a variety of categories, including alcohols, benzenoids, aldehydes, alkenes, acids, esters, terpenoids, and ketones. These compounds act as chemical signals, enabling bidirectional communication (between plants and microorganisms in the rhizosphere). Among the genera of rhizobacteria identified as VOC producers are species of *Bacillus*, *Serratia*, *Enterobacter*, and *Pseudomonas* [40].

The multiple categories of compounds and the intricate biochemical pathways involved in their signaling make the complete elucidation of these mechanisms a challenge. However, studies indicate that microbial VOCs are associated with promoting plant growth, possibly by modulating the synthesis and/or metabolism of phytohormones produced by rhizobacteria or by the plants themselves [30].

2.6. Production of Siderophores

Siderophores are secreted molecules that can be used both as biofertilizers and/or biocontrollers. As biofertilizers, they optimize the availability of iron in the root zone, and at the same time, their biocontroller activity relies on competing with phytopathogens for access to iron [41].

From a structural perspective, a typical siderophore presents one or more well-known functional groups such as hydroxamate, catecholate, or carboxylate. These functional groups establish bonds with iron ions, forming stable complexes. Although siderophores are widely recognized for their affinity with iron, it is important to emphasize that some of these organic molecules can also form complexes with other metals, including zinc, copper, manganese, and other metals [42].

There are two theories regarding how plants absorb iron from microbial siderophores. According to the first theory, siderophores with high redox potential donate iron (Fe^{2+}) to the plant's transport system after being reduced. This happens when siderophores with Fe^{3+} are transported to the roots, where reduction occurs in the apoplast, retaining Fe^{2+} and increasing iron concentrations in the roots. Following the second theory, microbial siderophores can bind to iron in the soil and exchange ligands with plant phytosiderophores, a process dependent on various factors such as complex stability, concentrations, and root environment conditions [43].

In addition, the high affinity of siderophores for iron results in limiting the access of this element by other microorganisms, suppressing the population of phytopathogenic agents in the rhizosphere. The reduction in disease incidence strengthens plant health and reduces the need for high doses of chemical control agents [44].

3. Plant Growth-Promoting Fungi (PGPF)

Some genera of saprophytic fungi present in the rhizosphere are capable of promoting growth by colonizing the plant's roots, primarily through increased nutrient absorption, phytohormone production, and induction of systemic resistance. Among the most common are *Aspergillus*, *Fusarium*,

Penicillium, *Piriformospora*, *Phoma*, and *Trichoderma* [45]. Here, we focus on fungi from *Trichoderma* genus and arbuscular mycorrhizal fungi (AMF). The latter are obligatory symbionts of plant roots and have a notable effect on nutrient acquisition and resistance to abiotic stress [46] (Table 2).

Table 2. Some examples of PGPF growth promotion mechanisms.

Specie	Mechanism of growth promotion	Culture	Reference
<i>Trichoderma</i> sp.	Phosphate solubilization	Soybean (<i>Glycine max</i>)	[47]
<i>Trichoderma</i> sp.	VOCs production	<i>Arabidopsis thaliana</i>	[48]
<i>T. koningiopsis</i>	VOCs production	<i>Arabidopsis thaliana</i>	[49]
<i>T. viride</i>	VOCs production	Tomato (<i>Solanum lycopersicum</i>)	[50]
<i>T. asperellum</i>	Phosphate solubilization and phytohormone production	Cucumber (<i>Cucumis sativus</i>)	[51]
<i>Rhizophagus clarus</i>	Increase of P and N content	Soybean (<i>Glycine max</i>) and Cotton (<i>Gossypium hirsutum</i>)	[52]
<i>Glomus. intraradices</i>	Salt tolerance	Wheat (<i>Triticum aestivum</i>)	[53]
<i>Rhizophagus irregularis</i>	Drought tolerance	Maize (<i>Zea mays</i>)	[54]
Mix of <i>Rhizophagus clarus</i> , <i>R. intraradices</i> , <i>Septoglomus deserticola</i> , <i>Funneliformis mosseae</i>	Water déficit tolerance	Soybean (<i>Glycine max</i>)	[55]
<i>Rhizophagus irregularis</i> , <i>Funneliformis mosseae</i> , and <i>Funneliformis geosporum</i>	High temperature tolerance	Soybean (<i>Glycine max</i>)	[56]

3.1. *Trichoderma* spp. as Biocontrol Agents and Fertilizers

Fungi of the genus *Trichoderma* have remarkable abilities in the biological control of pathogenic fungal agents that harm plant growth. This activity in controlling fungi is well-documented in the literature and various mechanisms of action are described.[57].

This effect can occur through direct or indirect mechanisms. Direct mechanisms rely on competition for resources, such as space and nutrients. *Trichoderma* spp. colonize surfaces and substrates, occupying spaces and consuming nutrients.

It limits the growth of pathogens, restricting their establishment in plants. Chitinases and Beta-1,3-glucanases produced by *Trichoderma* spp. are vital keys to its action against other fungi. The

production of these enzymes is part of the process known as mycoparasitism, where, upon recognizing chemical signals from the cell wall of the pathogen, *Trichoderma* hyphae grow towards and wrap around the hyphae of the pathogenic fungus. They then initiate the secretion of enzymes that degrade and create pores in the cell wall, through which *Trichoderma* obtains nutrients [58,59].

Regarding indirect mechanisms, the activation of the plant's defense system is observed. This is because *Trichoderma* spp. emit chemical signals that stimulate the production of defensive compounds in plants, such as phytoalexins and enzymes [60,61].

Organic compounds, such as VOCs, are also produced by *Trichoderma* spp. and influence the germination of fungal spores, inhibiting their development. VOCs produced by *Trichoderma koningiopsis* T-51 inhibited the mycelial growth of *Botrytis cinerea* by 73.78% and of *Fusarium oxysporum* by 43.68%. Additionally, there was a reduction in conidial germination and a delay in germ tube elongation [49].

It is important to highlight that the production of metabolites can vary between different species and strains of *Trichoderma*, as well as the environmental conditions. These metabolites play critical roles in the ecology of *Trichoderma* and their interactions with plants and other microorganisms, consolidating their role in controlling plant diseases and promoting soil health. Additionally, these fungi also play a vital role in improving nutrient and water uptake [62–64].

Out of 251 *Trichoderma* isolates from the Amazon rainforest soil, 49 demonstrated phosphate solubilization capacity. It was observed the production of organic acids, such as lactic acid, fumaric acid, ascorbic acid, malic acid, gluconic acid, D-isocitric acid, phytic acid, and citric acid. Additionally, two strains showed growth-promoting activity in soybean plants in a greenhouse setting [47]. High solubilization activity and growth promotion were also confirmed for *T. asperellum* UFT 201 in soybean cultivations in a greenhouse, and these results were later replicated in a field experiment [65,66].

The combination of these action mechanisms confers significant benefits to the plant. After selecting four strains with positive inhibitory activity against *F. oxysporum*, phosphate solubilization, and IAA production, an evaluation of tomato seed inoculation confirmed an increase in chlorophyll levels, aerial part length, fresh and dry weight of both the aerial part and roots, and a reduction in wilt disease caused by *F. oxysporum* ranging from 10 to 30% [67].

3.2. Arbuscular Mycorrhizal Fungi: Extensions of Roots in Soil

AMF have a symbiotic relationship with plant roots [62]. Intracellular hyphae form arbuscules, specialized structures that penetrate the root epidermis to exchange nutrients with hosts [68]. AMF provide many benefits to plants, such as increased photosynthetic rates, improved soil quality, influence on atmospheric CO₂ fixation [69], enhanced nutrient absorption (particularly P), increased water uptake, protection against pathogens, assistance in obtaining micro and macronutrients [70].

The benefits arise from AMF functioning as extensions of roots, penetrating other parts of the rhizosphere. Additionally, their hyphae are thinner compared to roots, allowing them to access a greater soil volume. For protection against water deficit, AMF hyphae enhance access to small soil pockets [71]. Also, the presence of phytohormones like abscisic acid modulates plant mechanisms related to water deficit, such as aquaporins and transpiration [72].

AMF can also increase flood tolerance, improving growth and assisting in phosphorus absorption through osmotic adjustment performed by the fungi [73].

Heat stress is also attenuated by AMF, which increases nutrient and water absorption, along with improved photosynthetic rates. Other effects are the accumulation of proline and sugars, sodium reduction, increased carbon and homeostasis [74]. These mechanisms, aiding in extreme temperature tolerance, also contribute to salinity tolerance [75]. Therefore, AMF plays a pivotal role in terrestrial ecosystems' microbiomes, helping host plants and ecosystem maintenance [76].

Among its roles in plant health regarding enhanced nutrient obtention, P absorption is the most thoroughly described and recognized as the primary regulator of the association. In conditions of high available concentrations of this mineral in the soil, the plant tends to reduce its investment in the association, whereas, under conditions of low availability, plant investment is higher. This

enhanced P absorption occurs directly, through the absorption and transport of P via the hyphae to the arbuscules, and indirectly, by stimulating phosphate-solubilizing bacteria in the soil [77].

This stimulation occurs in the region known as the mycorrhizosphere, which is the zone around roots colonized by mycorrhizal fungi, directly influenced by hyphal and root exudation [78]. Composed of hyphae with a diameter of approximately 0.2 μm , much finer than roots but significantly denser, the mycorrhizosphere is broader than the rhizosphere and acts as a matrix, facilitating interactions between bacteria and fungi. Extraradical fungal hyphae form the hyphosphere, a region influenced by AMF hyphae, that bring about physical, chemical, and biological alterations. Examples of these alterations include soil particle aggregation and the direct delivery of water to the host plant [79,80].

Fungal hyphae release carbon-rich compounds promoting bacterial growth, and, on the other hand, hyphae can also produce compounds that signal or inhibit other microorganisms' growth [81], affect soil pH, maintain a liquid film, and serve as bacterial concentration nodes, creating a microbiome that supports soil maintenance [82].

Through hyphal exudation of signaling molecules and compounds, AMF can influence the surrounding soil, modifying the local microbiota, referred to as the hyphosphere effect. It can also impact weathering, where exudates act as chelators, destabilizing mineral surfaces [83,84]. Thus, the hyphosphere provides an excellent habitat for other microorganisms, supporting the soil microbiome and influencing various soil processes [85].

4. Co-Inoculation of Beneficial Microorganisms

In recent years, there has been increased interest in combining microorganisms with similar activities but different mechanisms of action. This management strategy has been primarily studied in the control of diseases caused by nematodes, fungi, and insects, resulting in a reduction in the use of chemical products and a lower selection of resistant pathogens [86,87].

The interaction between growth-promoting microorganisms does not always result in the improvement of plant development or the biocontrol of pathogens; it is subject to several factors, such as the genetic variability of native bacteria, hosts, and environmental factors, such as light, temperature, and the organic matter of the soil [88].

These interactions are classified as synergistic, antagonistic, or non-interactive/additive, according to the observed effect. Synergy occurs when a combined effect is observed, meaning that co-inoculation provides a greater effect compared to the application of these agents individually. On the other hand, in antagonism, this effect is negative, whereas in non-interactive interactions, there is no impact compared to the isolated application of each microorganism [89].

An example of a synergistic interaction is the co-inoculation between AMF and PGPR, which has been examined by several studies, especially nitrogen-fixing bacteria (NFB). In general, gains in biomass and minerals were achieved, particularly in nitrogen and phosphorus rates [73,90].

The activity of AMF and NFB in the rhizosphere is essential for plant nutrition, and various factors contribute to a tripartite symbiosis. These microorganisms do not compete for the same colonization sites, indicating coexistence and possibly functional interactions. Furthermore, the inoculation of AMF has already been shown to be important in establishing NFB and improving nodulation, as nodulation is dependent on high levels of P, which can be increased by AMF colonization (Meena et al., 2018). It is also worth noting the importance of the correct combination of strains to achieve synergy in the co-inoculation of these microorganisms [91] (Table 3).

Table 3. Benefits of inoculating microorganisms.

Species	Culture	Benefits	References
<i>Bradyrhizobium diazoefficiens</i> and <i>Rhizobium tropici</i>	Common beans (<i>Phaseolus vulgaris</i>)	Growth promotion and grain yield	[92]
<i>Bradyrhizobium japonicum</i> and <i>Azospirillum brasilense</i>	Soybean (<i>Glycine max</i>)	Increased yield components, grain yield and seed quality	[93]
<i>Pseudomonas fluorescens</i> and <i>Azospirillum brasilense</i>	Tomato (<i>Solanum lycopersicum</i>)	Increased yield and fruit quality	[94]
<i>Bradyrhizobium</i> sp. and <i>Trichoderma</i> sp.	Cowpea (<i>Vigna unguiculata</i>)	Increased the growth rate, biomass and photosynthetic pigments	[95]
<i>B. licheniformis</i> and <i>B. subtilis</i>	Cucumber (<i>Cucumis sativus</i>)	Alleviated Salt Stress	[96]
<i>B. subtilis</i> , <i>B. megaterium</i> and <i>Rhizophagus intraradices</i>	Soybean (<i>Glycine max</i>)	Increase leaf nutrient and in yield	[97]
<i>Rhizophagus irregulares</i> and <i>Bradyrhizobium</i> sp.	Mung bean (<i>Vigna radiata</i>)	Growth promotion and alleviated water stress	[90]

5. Biological Inoculants Registered in Brazil

According to the Brazilian Ministry of Agriculture (MAPA), there are 636 inoculants with 713 registrations (some inoculants are registered for more than one crop) in Brazil, covering 37 crops, ranging from vegetables such as lettuce, cabbage, and potatoes, but primarily grains [98]. Approximately 50% of these registrations are designated for soybean cultivation, the most widely planted crop in the country, covering an area of about 45 million hectares [99]. Bean and maize, also among the most planted crops in the country, have 73 and 70 registrations respectively. Jack bean (35), peanut (36), and wheat (23) close the list of crops with the most inoculant registrations. The remaining registrations are divided among the remaining 31 crops, with lettuce standing out with 8 (Figure 2).

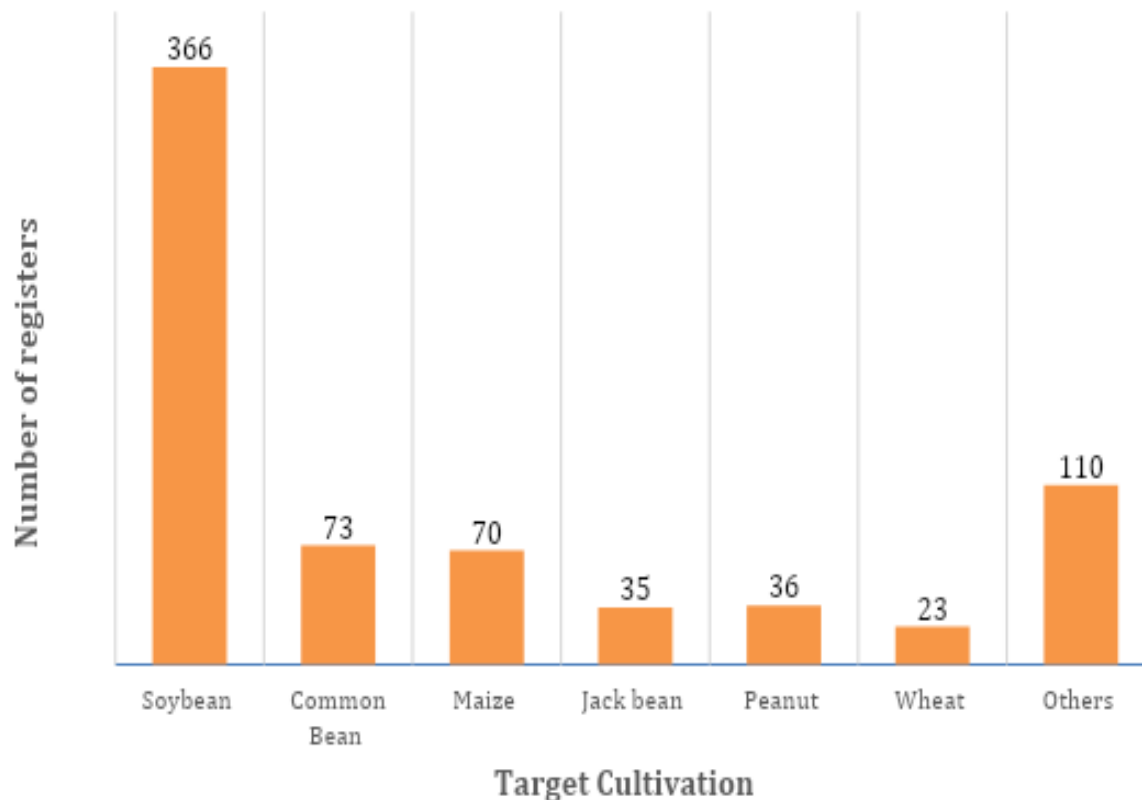


Figure 2. – Number of inoculants registered for the main crops in Brazil.

Among these registrations, 622 consist of formulations with a single microorganism, with a significant portion being NFB such as *Bradyrhizobium* spp., *Azospirillum brasilense*, and *Rhizobium* spp. For soybeans, for example, there are 189 registrations of products with *Bradyrhizobium japonicum*, 57 for *Bradyrhizobium Elkhani*, and 52 with the co-inoculation of *B. japonicum* and *B. elkhani*. For beans, 65 out of 73 registrations are for *Rhizobium tropici* and 6 for *Azospirillum brasilense*. In maize cultivation, 45 out of 70 registrations contain *A. brasilense* [98]. The introduction of these inoculants, which began in 1964, played a pivotal role in rendering Brazil competitive in grain production and reducing the necessity for nitrogen fertilization. In recent years, formulations with co-inoculation of two NFB strains have also been implemented, resulting in increased yields compared to individual inoculation. This co-inoculation strategy is anticipated to gain further prominence in the coming years [100]. According to Telles et al. (2023), during the 2019/2020 harvest season, the co-inoculation technology of *Bradyrhizobium* spp. and *A. brasilense* was employed in 25% of all soybean-cultivated areas in Brazil, resulting in a cost-saving of 15.2 billion dollars through the replacement of urea application with biological nitrogen fixation. Additionally, it generated an estimated profit of 914 million dollars [101].

Analyzing a subset of the most important crops (Table 4), in addition to NFB, there are also registrations of plant growth-promoting rhizobacteria (PGPR) from the genus *Bacillus*, and *Pseudomonas fluorescens*. In certain cases, co-inoculation between two strains is implemented, such as *B. subtilis* and *B. megaterium* for soybean, maize, and bean crops, *B. megaterium* and *Lysinobacillus* sp for maize, strains that promote growth by providing phosphorus availability, and *B. licheniformis* and *B. aryabhatai* act on increasing stress tolerance in maize. In addition to *P. fluorescens* and *Azospirillum brasilense* for maize and soybean crops, there are also strains of *B. subtilis* and *B. elkhani* for soybean. In these latter two cases, there are co-inoculation of strains with different activities, biological nitrogen fixation, and phosphorus solubilization. Co-inoculation with three strains is also observed, such as *B. subtilis*, *B. amyloliquefaciens*, and *B. pumilus* for promoting growth in soybean and maize, and *P. fluorescens*, *B. amyloliquefaciens*, and *Priestia megaterium*; *B. subtilis*, *B. elkhani*, and *Paraburkodelia nodosa* for soybean. This last species, introduced in the year 2024 to the market, isolated only in Brazilian

soils so far, exhibits nitrogen fixation activity, among other beneficial interactions such as phosphate solubilization, hormone production, siderophore synthesis, and ACC deaminase activity [102].

In terms of fungi, the number of registrations is reduced to 5 registrations of *Trichoderma* for soybean and 5 registrations of AMF for soybean and maize. Among these, one formulation contains eight strains (4 *T. harzianum*; 3 *T. asperelloides*, and 1 *T. koningiopsis*), which are registered for soybean, alongside the other *Trichoderma* products. As for AMF, the registrations are for soybean and maize, containing a strain of *Rhizophagus intraradices* or a double inoculation with *Rhizoglossum intraradices* and *Claroideoglossum claroideum* (Table 4).

Table 4. Genus of microorganisms registered for the main crops in Brazil, organized in single inoculation or co-inoculation.

Cultura	Gênero	Single inoculation	Co-inoculation
Soybean (<i>Glycine max</i>)	<i>Bradyrhizobium</i> sp.	246	<i>B. Japonicum</i> + <i>B. Elkani</i> (52) <i>B. Japonicum</i> + <i>A. brasilense</i> (4)
	<i>Azospirillum</i> sp.	28	<i>A. brasilense</i> + <i>P. fluorescense</i> (2)
	<i>Bacillus</i> sp.	8	<i>B. megaterium</i> + <i>B. subtilis</i> (2)
	<i>Pseudomonas</i> sp.	6	<i>B. subtilis</i> + <i>B. elkani</i> (3)
	<i>Trichoderma</i> sp.	5	<i>R. intraradices</i> + <i>Claroideoglossum claroideum</i> (2)
	<i>Rhizophagus</i> sp. (<i>Rhizoglossum</i>)	5	<i>B. subtilis</i> + <i>B. amyloliquefacens</i> + <i>B. pumilus</i> (1) <i>P. fluorescense</i> + <i>B. amyloliquefacens</i> + <i>Priestia megaterium</i> (1)
Common beans (<i>Phaseolus vulgaris</i>)	<i>Rhizobium</i> sp.	65	<i>Bacillus megaterium</i> + <i>Bacillus subtilis</i> (1)
	<i>Azospirillum</i> sp.	6	
	<i>Bacillus</i> sp.	1	
Maize (<i>Zea mays</i>)	<i>Azospirillum</i> sp.	41	<i>B. megaterium</i> + <i>B. subtilis</i> (2) <i>A. brasilense</i> + <i>P. fluorescense</i> (2)
	<i>Bacillus</i> sp.	8	<i>B. megaterium</i> + <i>Lysinobacillus</i> sp. (1)
	<i>Rhizophagus</i> sp. (<i>Rhizoglossum</i>)	5	<i>B. licheniformis</i> + <i>B. aryabhatai</i> (2) <i>B. Japonicum</i> + <i>A. brasilense</i> (2)
	<i>Pseudomonas</i> sp.	3	<i>R. intraradices</i> + <i>Claroideoglossum claroideum</i> (2)
	<i>Methylobacterium</i> sp.	1	<i>B. subtilis</i> + <i>B. amyloliquefacens</i> + <i>B. pumilus</i> (1)
Peanut (<i>Arachis hypogaea</i>)	<i>Bradyrhizobium</i> sp.	36	-
Jack bean (<i>Canavalia ensiformis</i>)	<i>Bradyrhizobium</i> sp.	35	-
Wheat (<i>Triticum aestivum</i>)	<i>Azospirillum</i> sp.	23	-

Brazil's biological product market is experiencing substantial growth, NFB based inoculants well-established in the production of various crops, most notably maize and soybeans. Nonetheless, the adoption of inoculants with alternative growth-promoting mechanisms remains in its early stages.

An illustrative instance of this emerging trend is the utilization of AMF and PSB. Analogous to NFB in the context of nitrogen fertilization, AMF and PSB have the potential to revolutionize phosphate fertilization practices in Brazil. More than 50% of phosphorus fertilizers applied in Brazilian soils are imported, generating a variable cost according to the dollar exchange rate and are poorly utilized. It is believed that only 30% of this phosphorus is absorbed by plants, with a significant portion of the surplus accumulating in the soil. Brazilian soils contain elevated concentrations of P in insoluble forms, a consequence of decades of fertilization in iron (Fe) and aluminum (Al)-rich soils, culminating in the rapid immobilization of this vital nutrient. It is estimated that by 2018, Brazil has accumulated a staggering 33.4 teragrams (Tg) of phosphorus in its soil. This estimation is derived from an analysis of the ratio between phosphorus inputs from organic manure and mineral fertilizers and the phosphorus harvested by crops annually, dating back to 1967—a seminal year that marks the commencement of intensive phosphate fertilizer application. This accumulated phosphorus reservoir possesses an estimated economic value of US\$ 22 billion [103].

The inoculation of AMF and PSB is an important alternative to enhance the efficiency of phosphorus (P) absorption, reducing the need for application and utilizing the soil's legacy P [103,104]. However, the application of these microorganisms is still not widely disseminated in Brazil. For example, AMF products available are imported and do not utilize native strains from the country, highlighting a gap in investment in technologies for strain research and the development of production systems for these microorganisms.

Like phosphate fertilizers, potassium fertilizers are largely imported, around 97%, a percentage that has been increasing in recent years due to the accelerated growth of agriculture [99]. It is estimated that the efficiency of applied potassium (K) in the soil is 66%, with a considerable portion remaining stocked up in the soil and 13% lost through erosion and leaching processes [105]. Brazil is a country with extensive areas of mineral resources; rocks containing potassium have the potential as a source of this nutrient for agriculture. However, strategies are needed for the rapid release of this nutrient for plant uptake [106,107].

The exploration of strains with high K solubilization activity and the development of biological products focusing on the availability of this nutrient is a gap to be filled in the Brazilian market. Obviously, Brazil's solution to its dependency on the importation of chemical inputs is not solely the use of biological products, but also increased input production, as envisioned in the National Fertilizer Plan, aiming to reduce imports from 85% to 45% by 2050 [108].

Other inoculants that are expected to see increased registrations in the coming years are stress mitigators. The effects of adverse weather conditions are already being felt in Brazilian agriculture. According to the National Supply Company (Conab), the estimate for the harvest in the 2023/24 season is 8% lower compared to the previous season, a reduction of around 25.7 million tons. This loss of productivity is directly related to the delayed onset of rains in the Midwest, Southeast, and Matopiba regions, high temperatures, irregular and poorly distributed rainfall, and periods of drought lasting more than 20 days. In addition to the impacts on productivity, these effects may, in the long term, affect the cultivable regions for Brazil's main crops, reducing areas suitable for soybean and maize cultivation [109]. Currently, there are already efficient strains on the Brazilian market for reducing water stress, registered for soybean and maize crops. However, given the magnitude of the economic impact that these climate changes can cause, there is a trend towards increased investment in research and development of biological products to mitigate the effects of climate change on agriculture and a greater variety of strains and formulations covering more cultures.

6. Conclusion

The use of PGPR and PGPF as biological inoculants in Brazilian agriculture has proven to be efficient and capable of generating cost savings for the production system, as evidenced by the individual or co-inoculated use of *Bradyrhizobium* spp. and *Azospirillum brasilense*. Given the current challenges faced in agricultural production in Brazil, such as costs and impacts related to the application of chemical fertilizers and losses due to climate change, there is a trend towards increased registration and application of inoculants that are effective in reducing fertilization and increasing

plant tolerance to environmental stresses. In this scenario, AMF have great potential, as they not only play an important role in nutrient acquisition but also can help reduce the impact of abiotic stress.

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