Application of phosphate-solubilizing bacteria in soybean cultivation: a mini-review

Alair Diniz da Costa Filho[1], Hellen Regina Fernandes Batista Ventura[2], Edson Luiz Souchie[1] & Matheus Vinicius Abadia Ventura[1,2]

[1] Microbiology Laboratory, Goiano Federal Institute, Rio Verde, Goiás, Brazil

[2] UniBRAS University Center of Rio Verde, Rio Verde, Goiás, Brazil

Correspondence: Alair Diniz da Costa Filho, Microbiology Laboratory, Goiano Federal Institute, Rio Verde, Goiás, Brazil. E-mail: dnzflho@gmail.com

Received: November 22, 2025 DOI: 10.14295/bjs.v5i2.843

Accepted: January 31, 2026 URL: https://doi.org/10.14295/bjs.v5i2.843

Abstract

Brazilian agriculture plays a strategic role in the national economy, with Brazil standing out as one of the world's leading soybean (*Glycine max* L.) producers. Despite its economic relevance, soybean productivity is constrained by several factors, including high production costs, dependence on non-renewable inputs, adverse climatic conditions, and particularly the low fertility of tropical soils, especially phosphorus (P) deficiency. In this context, the use of phosphate-solubilizing bacteria (PSB) emerges as a sustainable alternative to enhance phosphorus availability and uptake by plants, thereby reducing dependence on chemical phosphate fertilizers. This study aims to review the scientific literature on the application of PSB in soybean cultivation, emphasizing their mechanisms of action, effects on phosphorus uptake, and impacts on plant growth and productivity.

Keywords: soybean, phosphorus, phosphate-solubilizing bacteria, productivity, soil fertility.

Aplicação de bactérias solubilizadoras de fosfato na cultura da soja: uma mini-revisão

Resumo

A agricultura brasileira desempenha papel estratégico na economia nacional, destacando-se o Brasil como um dos maiores produtores mundiais de soja (*Glycine max* L.). Apesar de sua relevância econômica, a produtividade dessa cultura é limitada por diversos fatores, como elevados custos de produção, dependência de insumos não renováveis, condições climáticas adversas e, sobretudo, a baixa fertilidade dos solos tropicais, especialmente a deficiência de fósforo (P). Nesse contexto, o uso de bactérias solubilizadoras de fósforo (BSF) surge como uma alternativa sustentável para aumentar a disponibilidade e a absorção de P pelas plantas, reduzindo a dependência de fertilizantes fosfatados de origem química. Este trabalho tem como objetivo revisar a literatura científica acerca da aplicação de BSF na cultura da soja, com ênfase em seus mecanismos de ação, efeitos na absorção de fósforo e impactos sobre o crescimento e a produtividade da planta.

Palavras-chave: soja, fósforo, bactérias solubilizadoras de fosfato, produtividade, fertilidade do solo.

1. Introduction

Brazilian agriculture constitutes one of the most competitive and strategic sectors of the national economy, playing a fundamental role in job creation, food production, and making a significant contribution to the growth of the Gross Domestic Product (GDP). In this context, agricultural research plays a central role by fostering the development of technologies capable of consolidating efficient, sustainable, and resilient production systems, reconciling increased agricultural productivity in areas already open for cultivation with the reduction of environmental impacts associated with conventional production models, as well as the adoption of crop rotation practices (Barbosa; Brisola, 2024; Silva et al., 2023a; El Batti et al., 2023).

In line with this perspective, the Sustainable Development Goals (SDGs) established by the United Nations (UN), particularly SDG 2, advocate that by 2030 sustainable food production systems and resilient agricultural practices be implemented to increase productivity, preserve ecosystems, strengthen adaptation to climate change, and progressively improve soil quality, thereby supporting the continuity of life on Earth (UN, 2024; Olabi et al., 2025). Filho et al. (2023) discuss these guidelines in the context of climate change and its impacts on agriculture, while Suman et al. (2022) emphasize the need for innovative strategies that reduce dependence on synthetic chemical inputs and promote greater efficiency in the use of natural resources. Such strategies include products based on local microorganisms capable of exerting inhibitory effects on a wide range of agricultural pathogens, as well as microorganisms able to metabolize elements of agronomic interest across different groups of crops, ensuring the rational and sustainable use of soil resources.

Soybean (*Glycine max* (L.) Merrill) stands out as one of the most important crops for agribusiness, particularly in Brazil, where it has been consolidated as a major commodity in the country's trade balance (Medina, 2022). Brazil ranks among the world's leading soybean producers and exporters, and in the 2024/25 growing season, soybean cultivation covered approximately 49.01 million hectares, with an estimated production of 169.1 million metric tons and an average yield of 3,440 kg ha^{-1} (Conab, 2025). These figures highlight the economic importance of the crop while underscoring the challenges associated with maintaining and sustainably increasing productivity.

Technological advances related to soybean nutritional requirements have contributed to improved crop management and increased yields (Bevilaqua et al., 2002). Nevertheless, Brazilian agricultural systems are still strongly affected by the low natural fertility of soils, a common characteristic of tropical regions, which leads to the intensive use of mineral fertilizers. This practice significantly increases production costs, amplifies environmental impacts, and intensifies dependence on external and nonrenewable nutrient sources. Greschuk et al. (2023) emphasize that Brazilian soils have the potential to achieve higher productivity, provided that soil renewal processes and the use of nature-based strategies are effectively implemented.

Soybean productivity is influenced by multiple factors, including water availability, agricultural mechanization, soil acidity, photoperiod, and edaphoclimatic conditions. However, soil fertility represents one of the most decisive factors for crop performance, as macro- and micronutrients are essential for physiological and biochemical processes directly related to plant growth, development, and productivity (Javed et al., 2022; Greschuk et al., 2023).

Among the macronutrients, nitrogen (N), phosphorus (P), and potassium (K), P is the second most critical essential nutrient limiting agricultural productivity, particularly in Brazilian soils, due to its low natural availability (Luo et al., 2024). Phosphorus plays a fundamental role in physiological and reproductive processes, including its involvement in photosystems I and II, energy transfer, cellular metabolism, root development, and the formation of reproductive structures such as flowers, fruits, and seeds (Raij, 1991), as well as in plant responses to different sources of abiotic stress (Khan et al., 2023). Quantitatively, P accounts for approximately 2 g kg^{-1} of plant dry matter (Schachtman, 1998), and in soybean crops, an average of about 20 kg ha^{-1} of P is immobilized in the total plant biomass (Novais et al., 2007).

Phosphorus deficiency severely compromises shoot and root growth, reduces nodulation and the activity of nitrogen-fixing nodules, limits water and nutrient uptake, and results in reduced leaf area, lower flowering, and poor pod formation, ultimately leading to significant yield losses (Oliveira et al., 2011). Furthermore, in tropical soils, a large proportion of P applied via fertilizers is rapidly immobilized through adsorption and precipitation reactions with iron (Fe^{2+}) and aluminum (Al^{3+}) oxides—a phenomenon known as phosphorus fixation—which reduces its agronomic efficiency and necessitates increasing fertilizer application rates (Raij, 1991; Yi et al., 2023). Chemically unavailable nutrients accumulate in the soil matrix and negatively interfere with the physiological processes of agriculturally important plants. As discussed, this phenomenon is common in tropical soils, including those in Brazil (Pavinato; Cipriano, 2025).

In this context, the use of phosphate-solubilizing bacteria (PSB) has emerged as a promising and environmentally sustainable strategy to enhance P availability in different soil types. These microorganisms act by solubilizing insoluble forms of P, primarily through the production of organic acids, enzymes, and other metabolites, thereby facilitating nutrient uptake by plants and contributing to the reduction of conventional phosphate fertilizer use. Phosphorus-solubilizing microorganisms (PSM) belong to a class of beneficial microbes with specific functional traits, such as the ability to mobilize inorganic and organic P compounds. Although bacteria represent the main group within this category, recent studies have reported an increasing use of fungi and archaea with similar functional characteristics (Li et al., 2021).

The application of PSBs has increased steadily in recent years, and numerous studies have reported positive outcomes regarding their efficiency in metabolizing phosphate fertilizers in soil and promoting physiological processes in agriculturally important plants, making this approach effective for improving phosphorus use efficiency (Luo et al., 2024). PSBs are known to exert their effects primarily in the rhizosphere (Figure 1), where they colonize plant roots and constitute an important component of plant growth-promoting bacteria. Non-labile phosphorus sources converted by PSBs become labile and thus available for root uptake (Kour et al., 2023). In addition, PSB are capable of reducing rhizosphere pH through the secretion of low-molecular-weight organic acids, such as citric and lactic acids, which effectively solubilize insoluble phosphate compounds (Ahuja et al., 2007; Luo et al., 2024; Oba et al., 2024). Studies investigating PSBs for their ability to produce phosphatases and other enzymes involved in the soil phosphorus cycle have expanded, enabling a better understanding of the synergistic interactions among microorganisms, phosphorus, and plants (Chen et al., 2021; Yu et al., 2022; Luo et al., 2024).

In light of the above, this study aims to review the scientific literature on the application of phosphate-solubilizing bacteria (PSB) in soybean cultivation, with emphasis on their mechanisms of action, effects on phosphorus uptake, and impacts on plant productivity, within the framework of sustainable approaches adopted in modern agricultural systems.

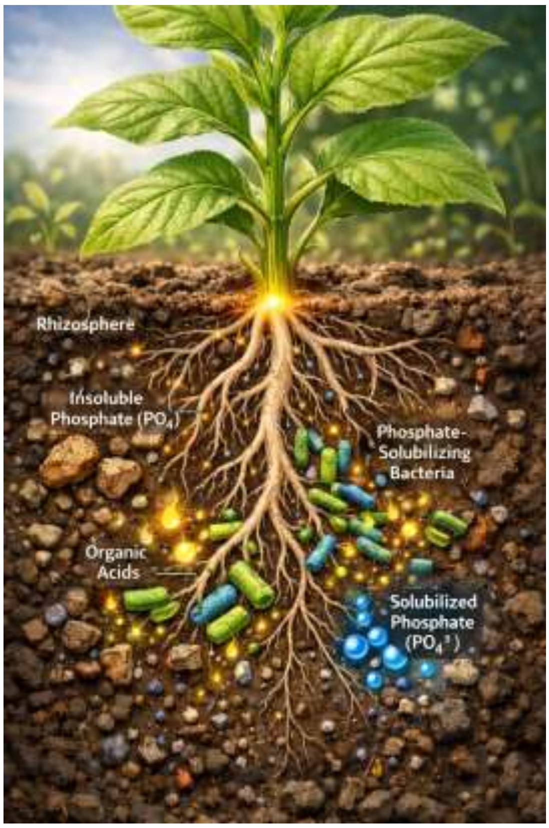

Figure 1. Schematic representation of the rhizosphere showing the interaction between plant roots and phosphate-solubilizing bacteria. These microorganisms release organic acids that promote the solubilization of insoluble phosphate compounds (PO_4^-), converting them into soluble forms (PO_4^{3-}) available for plant uptake, thereby enhancing phosphorus availability and root nutrition. Source: Authors, 2025.

2. Phosphorus and tropical agriculture

2.1 Phosphorus problem in soil

Phosphorus (P) is characterized as an essential and indispensable element for plants; however, in soils, it is commonly found associated with complexes containing oxides such as iron (Fe_2O_3), silica (SiO_2), or aluminum (Al_2O_3), predominantly in non-labile forms. Consequently, large amounts of phosphate fertilizers are applied annually for soybean production in highly weathered soils, as observed in extensive regions of Brazil (Viruel et al., 2014). The application of P at high rates in weathered soils is justified by the strong fixation of this element, which results in low levels of available P, especially in soils with a predominance of sesquioxide minerals (Büll et al., 1998; Novais; Smyth, 1999).

As briefly discussed, P is one of the essential macronutrients involved in several physiological processes in plants during both vegetative and reproductive stages, being considered the second most important element after N (Walpola; Yoon, 2012; Sarmah; Sarma, 2022). The agronomic efficiency of phosphate fertilizers may be influenced by phosphate sources, soil properties, application methods, and the cultivated plant species (Chien; Menon, 1995).

In the Brazilian Cerrado environment, the adequate supply of macro- and micronutrients, particularly P, is an indispensable tool for achieving high crop yields (Silva et al., 2025a). This is mainly because Cerrado soils are generally acidic, contain significant levels of iron and aluminum oxides, and exhibit low nutrient availability, especially P (Torres et al., 2023). In addition, this nutrient is subject to retention by chemical forms of Fe, Si, and Al oxyhydroxides, which are common minerals in tropical soils, thereby restricting adequate phosphorus uptake by plant root systems (Malavolta, 2006; Goldberg, 2008; Yi et al., 2023).

Crop productivity depends on P availability for photosynthesis (Veneklaas et al., 2012). Thus, phosphate fertilization practices are not only essential for obtaining high yields but may also contribute to increasing phosphorus content in seeds. The agronomic efficiency of phosphate fertilizers depends on several factors, including the physical and chemical properties of the soil, climatic conditions, and the crop species. Therefore, understanding the processes involved in P dynamics in the soil and its interactions with different soil components, as well as the forms through which this nutrient becomes available to plants, is fundamental for determining fertilization requirements and, consequently, defining appropriate fertilizer rates and application methods (Raij, 2011).

Therefore, efforts should be made to improve P uptake and utilization by plants, which can be achieved through pH management and the use of microorganisms that enhance P availability (Inui, 2009; Ibrahim et al., 2022). According to Oliveira (2009), "phosphorus is an essential element for soybean cultivation, and inadequate levels of this nutrient affect the entire plant development"; thus, it is accurate to state that, in the absence of P, soybean plants fail to develop adequately to achieve satisfactory productivity.

2.2 Mechanism of P solubilization

Phosphorus-solubilizing bacteria play a fundamental role in increasing the availability of this nutrient to plants, especially in tropical soils, where a large proportion of phosphorus occurs in insoluble forms. These microorganisms use different biochemical and physiological mechanisms to release P from the soil.

The acidification of the rhizosphere is an important mechanism by which phosphorus is solubilized from unavailable mineral sources and may also enhance the activity of some phosphate-solubilizing enzymes (Rathinasabapathi et al., 2018). Among the mechanisms used by microorganisms to transform poorly soluble phosphates into soluble forms are processes such as the release of metabolites, extracellular enzymes, and organic acids, acidification processes, exchange reactions, and chelation (Abreu et al., 2017).

The mechanisms proposed by which plant growth-promoting bacteria (PGPB) can improve the nodulation activity of Rhizobium include: production of binding proteins in the cell membrane (Burns et al., 1981), production of antimicrobial agents (Li; Alexander, 1988), and stimulation of root colonization by mycorrhizal fungi, resulting in changes in root morphology (Meyer; Linderman, 1986).

The use of microorganisms in soybean cultivation has been known for many years, mainly through the use of Bradyrhizobium sp., which carries out the process of biological nitrogen fixation, and more recently through coinoculation, involving Bradyrhizobium sp. and Azospirillum brasilense. These bacteria are responsible for meeting nitrogen demand and promoting root hair growth, respectively, in soybean crops (Hungria et al., 2007; Hungria, 2013; Hungria; Nogueira, 2019).

2.3 Phosphate-solubilizing microorganisms and their development in soybean crops

Pests in soybean cultivation cause billions of reais in losses annually, significantly compromising crop productivity. Chemical control using insecticides remains the most common practice; however, excessive use of these products has led to serious issues, including environmental contamination, food residue accumulation, and increased pest resistance (Shome et al., 2022; Machado, 2024). In this context, biological control emerges as a sustainable and efficient alternative based on the use of natural enemies of pests. These include predatory insects, parasitoids, and microorganisms such as fungi, bacteria, and viruses. In addition to being effective, biological control does not leave toxic residues and helps preserve environmental quality (Song et al., 2022; Silva et al., 2023b).

Thus, biological control is considered an essential tool in modern agriculture. Bioinputs applied in soybean cultivation are composed of fungi, bacteria, or viruses used in the management of insect pests and phytopathogens. Fungi and bacteria, beyond their direct role in biological control, can establish beneficial symbiotic relationships with plants, enhancing growth, nutrient uptake, and resistance to biotic and abiotic stresses (Wahab et al., 2023).

According to Wagemans et al. (2022), virus-based bioinputs have a more specific application, being exclusively targeted at insect pest control, where they selectively infect and reduce pest populations. Therefore, these products represent sustainable alternatives to chemical pesticides, promoting greater balance in soybean production systems. Fungi used in bioinputs can be classified into different groups. Entomopathogenic fungi, such as *Beauveria bassiana*, *Cordyceps* (*Isaria*) *javanica*, *Cordyceps* (*Isaria*) *fumosorosea*, and *Metarhizium anisopliae*, are employed in the control of insect pests like the whitefly (*Bemisia tabaci*) and the two-spotted spider mite (*Tetranychus urticae*). Mycopathogenic fungi, including *Trichoderma harzianum* and *Trichoderma asperellum*, are used to control fungal diseases such as damping-off and root rot (*Rhizoctonia solani*) and white mold (*Sclerotinia sclerotiorum*). Nematophagous fungi, such as *Pochonia chlamydosporia* and *Purpureocillium* (*Paecilomyces*) *lilacinum*, are applied to manage nematodes like *Meloidogyne* spp. and *Pratylenchus brachyurus* (Coutinho, 2018; Loureiro et al., 2020).

Plant–microorganism interactions are highly complex and dynamic, making their control and predictability in agricultural systems challenging (Copeland et al., 2025). Additionally, due to methodological variability and experimental limitations, many findings in this field remain contradictory. Nevertheless, the exploration of microbial processes is promising for improving phosphorus mobilization in soils (Mendes; Reis Junior, 2003).

According to Alves et al. (2002), Silva et al. (2023b), and Li et al. (2024), inoculation with phosphorus-solubilizing microorganisms promotes positive effects on phosphorus content in the aerial parts of perennial plants, indicating enhanced uptake of labile soil phosphorus in the presence of these microorganisms. These findings highlight the potential of specific microbial strains for use in inoculant production technologies for agribusiness.

One of the earliest phosphorus-solubilization technologies developed in Brazil is BiomaPhos, a liquid inoculant recommended for seed treatment and in-furrow application. After application, the bacteria colonize and multiply in the rhizosphere, establishing interactions with the plant root system. During this process, strains BRM 119 (*Bacillus megaterium*) and BRM 2084 (*Bacillus subtilis*) produce various organic acids, promoting phosphorus solubilization in the soil (Bittencourt et al., 2024; Massucato et al., 2025).

Overall, the use of bioinputs represents a strategic and sustainable alternative for pest and disease management in soybean cultivation, reducing reliance on chemical pesticides and their negative impacts. Microorganisms such as fungi, bacteria, and viruses show high potential in biological control while also providing additional benefits, including phosphorus solubilization and plant growth promotion (Boro et al., 2022). Innovative technologies like BiomaPhos reinforce the practical applicability of these solutions in agribusiness, contributing to increased productivity, environmental sustainability, and competitiveness of soybean production in Brazil (Barbosa et al., 2025).

2.4 Benefits and limitations of the use of these bacteria as a sustainable bioinput

The use of PSB has been highlighted as a promising alternative to reduce dependence on chemical fertilizers, improve phosphorus use efficiency, and promote sustainable agricultural practices. One of the main benefits highlighted is the reduction in chemical inputs, such as fertilizers and synthetic pesticides, which are associated with negative impacts on the environment and human health (Altieri; Nicholls, 2017; Silva et al., 2025b). Studies show that these bacteria can increase phosphorus availability in the soil, stimulate soybean growth and productivity, and also contribute to improving plant resistance to biotic and abiotic stresses (Silva, 2023a; Zhu et al., 2024; Feng et al., 2024). In addition, recent reviews Table 1 indicate that PSB exhibit multiple mechanisms of action, such as the production of organic acids, phosphatases, siderophores, and exopolysaccharides, resulting in consistent gains in plant growth and quality (Silva, 2023a; Pan; Cai, 2023).

On the other hand, some limitations must be considered. The effectiveness of these microorganisms under field conditions still shows inconsistent results, since environmental factors such as pH, moisture, temperature, and soil composition directly influence their survival and activity (Zhu et al., 2024). Reviews also point out that although many isolates show high solubilization capacity under *in vitro* conditions, this response does not always translate efficiently into real agricultural systems, representing a challenge for large-scale application (Khan et al., 2007). Thus, although PSB represents a sustainable bioinput with great potential for modern agriculture, especially in soybean cultivation, further advances in field research, formulation strategies, and integration with other agricultural practices are necessary to maximize its efficiency (Liu-Xu et al., 2024).

Table 1. Field and laboratory studies on the application of PSB in soybean.

Author/Year	Theme	Main Results
Crespo et al. (2024)	Persistence of *Metarhizium* in the soil	Good efficacy in the control of soybean pests; high persistence in the soil
Tall; Meyling (2018)	Plant growth promotion by *Beauveria bassiana*	Positive effects on soybean growth, dependent on nutritional conditions
Pereira et al. (2020)	Control of the brown stink bug *Euschistus heros*	*Beauveria bassiana* is effective in reducing this pest in soybean crops.
Rodríguez-Gómez et al. (2018)	Compatibility of insecticides with entomopathogenic fungi	Some insecticides are compatible with *Beauveria* and *Metarhizium*, indicating potential for integrated pest management
Duarte et al. (2019)	Virulence of fungi against *Helicoverpa armigera*	*Metarhizium* and *Beauveria* showed high mortality of this pest in soybean crops

Source: Authors, 2025.

2.5 Effect of PSB on growth, productivity, and phosphorus economy in soybean cultivation

The effects of inoculation with phosphorus-solubilizing microorganisms (PSB) in soybean have been widely evaluated in different regions of the world. Akhila et al. (2025) reported that the use of PSB microorganisms in soybean, including *Pseudomonas fluorescens* and *B. subtilis*, increased growth parameters, productivity, nutrient content, and uptake, as well as soil microbial and enzymatic activity. In addition, in this study, cultivation costs and net returns were evaluated and were significantly higher with the application of 60 kg P_2O_5 ha^{-1} combined with inoculation of *B. subtilis*. The interaction between 60 kg P_2O_5 and Bacillus subtilis resulted in greater root biomass.

Rao et al. (2024) evaluated growth parameters of *G. max* under the application of phosphorus at 62.5 kg ha^{-1} via vermicompost combined with PSB (10 kg ha^{-1}) and observed improved agronomic performance in this crop, with significant increases in plant height, number of branches, dry matter accumulation, and yield components, including number of pods, grain yield, and haulm production. These results were statistically similar to those obtained with phosphorus applied at the same rate via poultry manure combined with PSB. In contrast, phosphorus application via pongamia cake resulted in the lowest growth and yield values. From an economic perspective, the highest net returns and benefit–cost ratio were observed with the use of poultry manure combined with PSB, whereas pongamia cake showed the lowest economic indicators.

Several microorganisms, including both bacteria and fungi, have the ability to solubilize phosphate, promoting significant gains in the vegetative and reproductive parameters of soybean. In addition to increasing the availability of labile phosphorus in the soil, these microorganisms also contribute to protecting plants against phytopathogen attacks, thereby strengthening the production system. Inoculation with *Rhizobium japonicum* and

Pseudomonas striata showed significant effects on soybean productivity, grain quality, and plant nutrition. Even when associated with reduced mineral fertilizer application, the use of these inoculants resulted in yields statistically comparable to those obtained with 100% of nitrogen and phosphorus doses. The combination of *R. japonicum* and *P. striata* with 50% N and 75% P increased grain protein and oil contents and improved plant nodulation.

Additionally, an increase in soil nitrogen content was observed with *R. japonicum* inoculation, along with greater phosphorus availability with *P. striata*, highlighting the potential of these microorganisms to reduce dependence on chemical fertilizers without compromising crop productivity, as demonstrated in the study conducted by Shome et al. (2022). Despite these benefits, the response to PSB inoculation can vary according to soil type, existing microbial communities, and environmental conditions. Some studies suggest limited effects under specific soil and climate contexts, indicating that PSB responses are sometimes inconsistent across locations and years. Therefore, while PSB shows great potential for improving phosphorus economy in soybean cultivation and supporting sustainable agricultural practices, broader field validation and integration strategies are necessary to reliably translate these benefits into commercial agronomic systems (Timofeeva et al., 2022).

3. Conclusions

Phosphorus availability is a critical factor for soybean development and yield, particularly in Cerrado soils, where the natural scarcity of this nutrient and its strong fixation by soil minerals make phosphate fertilization indispensable. In this context, PSBs have emerged as promising biological alternatives, contributing not only to improved phosphorus-use efficiency but also to the sustainability of agricultural production systems. The diverse biochemical mechanisms employed by these microorganisms, such as the secretion of organic acids, phosphatases, and other chelating compounds, enhance phosphorus solubilization and availability, thereby stimulating plant growth and indirectly supporting biological nitrogen fixation.

Although numerous laboratory and field studies have demonstrated the potential agronomic benefits of PSBs, their performance under real farming conditions remains variable. This variability is largely associated with edaphoclimatic factors, soil chemical characteristics, microbial competition, and limitations related to inoculant formulation and survival in the soil environment. Consequently, the effectiveness of PSB is strongly dependent on proper strain selection, compatibility with soil and crop management practices, and the development of more stable and efficient formulations.

In this sense, advances in applied research, including long-term field trials, multi-strain consortia, and integrated nutrient management strategies, are essential to enhance the consistency and reliability of PSB-based technologies. Overall, the use of bioinputs such as PSBs represents a strategic approach to reducing dependence on chemical phosphate fertilizers, increasing soybean productivity, and promoting the environmental sustainability of Brazilian agriculture, aligning agricultural practices with the principles of sustainable intensification.

Phosphorus-solubilizing bacteria have emerged as a promising biological strategy to enhance phosphorus availability in soils where a large fraction of phosphorus remains in insoluble forms, limiting plant uptake and crop productivity. PSB can mobilize bound phosphorus through the secretion of organic acids and phosphatases, thereby converting unavailable phosphorus into forms that plants can readily absorb. This process not only improves nutrient acquisition but also supports key physiological functions related to growth and yield in crops such as *G. max* due to phosphorus's role in energy transfer, cell division, and reproductive development (Shome et al., 2022).

Beyond nutrient solubilization, PSB have been reported to promote growth by producing plant growth regulators (e.g., indole-3-acetic acid) and siderophores, which can further stimulate root development and nutrient uptake capacity. Experimental evidence from soybean rhizosphere research has shown that PSB strains belonging to genera such as *Bacillus* and *Pseudomonas* increased soil acid phosphatase activity and available phosphorus content, leading to enhanced plant uptake of phosphorus and better overall stand performance in controlled conditions (Song et al., 2022).

4. Acknowledgments

The authors thank the Goiano Federal Institute, Rio Verde campus, CEBIO, CNPq, CAPES, FAPEG, and FUNAPE.

5. Authors' Contributions

Alair Diniz da Costa Filho: conceptualization, resources, formal analysis, investigation, methodology, and writing – original draft. *Edson Luiz Souchie*: supervision, funding acquisition, project administration, and writing – review & editing.

6. Conflicts of Interest

No conflicts of interest.

7. Ethics Approval

Not applicable.

8. References

Abreu, C. S., Figueiredo, J. E. F., Oliveira, C. A., Santos, V. L., Gomes, E. A., Ribeiro, V. P., Barros, B. A., Lana, U. G. P., & Marriel, I. E. (2017). Maize endophytic bacteria as mineral phosphate solubilizers. *Genetics and Molecular Research*, 16(1), 1-13. http://dx.doi.org/10.4238/gmr16019294

Ahuja, A., Ghosh, S. B., & D'Souza, S. F. (2007). Isolation of a starch utilizing, phosphate solubilizing fungus on buffered medium and its characterization. *Bioresource Technology*, 98(17), 3408-3411. https://doi.org/10.1016/j.biortech.2006.10.041

Akhila, G., Raghuveer, M,M Ranjitha, S., Krishna Chaitanya, A. (2025). Effect of phosphorous levels and PSB strains on growth, yield and nutrient uptake of soybean (*Glycine max* L.). *Plant Archives*, 25(2), 2182.

Alves, L., Mendonza, E. A., & Silva Filho, G. N. (2002). Microrganismos solubilizadores de fosfatos e o crescimento de pinus e eucalipto. *Revista Brasileira de Ciência do Solo*, 36(4), 939-947. https://doi.org/10.1590/S0100-06832002000400011

Barbosa, V. C. R., & Brisola, M. V. (2024). Além dos campos: as prospecções tecnológicas sustentáveis da EMBRAPA para o agronegócio brasileiro. *Revista de Economia e Sociologia Rural*, 62(3), e270441. https://doi.org/10.1590/1806-9479.2023.270441pt

Barbosa, M. F., Sales, R. M. M., Galarza, F. A. D., Kruger, C. Q., Fávaro, L. C. L., & Quirino, B. F. (2025). Biological resources driving productivity: bioinputs for sustainable plant agriculture in Brazil. *Sustainable Microbiology,* 2(3). https://doi.org/10.1093/sumbio/qvaf011

Bevilaqua, G. A. P., Silva Filho, P. M., & Possenti, J. C. (2002). Aplicação foliar de cálcio e boro e componentes de rendimento e qualidade de sementes de soja. *Ciência Rural*, 32(1), 31-34.

Bittencourt, C. D., Messias, M., Wendland, A., & Brito, E. P. (2024). Phosphate-solubilizing inoculant improves agronomic performance of common bean with reduced phosphate fertilizer dose. *Journal of Soil Science and Plant Nutrition*, 24, 5815-5828. https://doi.org/10.1007/s42729-024-01943-2

Boro, M., Sannyasi, S., Chettri, D., & Verma, A. K. (2022). Microorganisms in biological control strategies to manage microbial plant pathogens a review. *Archives of Microbiology*, 204. https://doi.org/10.1007/s00203-022-03279-w

Büll, L. T., Forli, F., Tecchio, M. A., & Corrêa, J. C. (1998). Relação entre fósforo extraído por resina e resposta da cultura do alho vernalizado à adubação fosfatada em cinco solos com e sem adubação orgânica. *Revista Brasileira de Ciência do Solo*, 22(3), 459-470. https://doi.org/10.1590/S0100-06831998000300012

Cabrera, E. V. R., Espinosa, Z. Y. D., & Pino, A. F. S. (2024). Use of phosphorus-solubilizing microorganisms as a biotechnological alternative: A review. *Microorganisms*, 12(8), 1591. https://doi.org/10.3390/microorganisms12081591

Charana, B., & Yoon, M-H. (2012). Prospectus of phosphate solubilizing microorganisms and phosphorus availability in agricultural soils: A review. *African Journal of Microbiology Research*, 6(37), 6600-6605. https://doi.org/10.5897/AJMR12.889

Chen, J., Zhao, G., Wei, Y., Dong, Y., Hou, L., & Jiao, R. (2021). Isolation and screening of multifunctional phosphate solubilizing bacteria and its growth-promoting effect on Chinese fir seedlings. *Scientific Reports,* 11, 9081. https://doi.org/10.1038/s41598-021-88635-4

Chien, S. H., & Menon, R. G. (1995). Factors affecting the agronomic effectiveness of phosphate rock for direct application. *Fertilizer Research*, 41, 227-234.

Conab. (2025). Companhia Nacional de Abastecimento, safra de grãos 2024/25. Available: https://www.gov.br/conab/pt-br/assuntos/noticias/producao-de-graos-na-safra-2025-26-esta-estimada-em-354-4-milhoes-de-toneladas. Accessed on January 27, 2026.

Copeland, C., Schulze-Lefert, P., & Ma, K-W. (2025). Potential and challenges for application of microbiomes in agriculture. *The Plant Cell*, 37(8). https://doi.org/10.1093/plcell/koaf185

Coutinho, R. R. (2018). *Pochonia chlamydosporia*: controle de Meloidogyne javanica em soja, associação com culturas de cobertura e interação com bactérias fixadoras de nitrogênio e com o pH do solo. Tese (Doutorado em Fitopatologia) - Universidade Federal de Viçosa. Viçosa, Brasil, 91 f.

Crespo, Â. L. B. et al. (2024). Assessment of soil persistence and field efficacy of *Metarhizium* applied for soybean insect pest control. *Journal of Fungi*, 10(3), 216, 2024. https://doi.org/10.3390/jof10030216.

Dey, G., Banerjee, P., Sharma, R. K., Maity, J. P., Etesami, H., Shaw, A. K., Huang, Y-H., Huang, H-B., & Chen, C-Y. (2021). Management of phosphorus in salinity-stressed agriculture for sustainable crop production by salt-tolerant phosphate-solubilizing bacteria – A review. *Agronomy*, 11, 1552. https://doi.org/10.3390/agronomy11081552

Duarte, A. L. A. (2019). Virulência de fungos entomopatogênicos contra *Helicoverpa armigera* em soja. *Revista Caatinga*, 32(2), 425-434. https://doi.org/10.1590/1983- 21252019v32n215rc

El Batti, M. M., Machado, P. G., Hawkes, A., & Ribeiro, C. O. (2023). Land use polices and their effects on Brazilian farming production. *Journal of Nature Conservation*, 73, 126373. https://doi.org/10.1016/j.jnc.2023.126373

Feng, Y., He, J., Zhang, H., Jia, X., Hu, Y., Ye, J., Gu, X., Zhang, X., & Chen, H. (2024). Phosphate solubilizing microorganisms also improve plant disease resistance, adaptability, and survival. *Frontiers in Microbiology*, 14. https://doi.org/10.3389/fmicb.2023.1320853

Filho, W. L., Salvia, A. L., Dinis, M. A. P., & Mifsud, M. (2023). The central role of climate action in achieving the United Nations' sustainable development goals. *Scientific Reports*, 13, 20582. https://doi.org/10.1038/s41598-023-47746-w

Goldberg, S. (2008). Interaction of aluminum and iron oxides and clay minerals and their effect on soil physical properties: A review. *Communications in Soil Science and Plant Analysis*, 20(11-12), 1181-1207. https://doi.org/10.1080/00103629009368144

Greschuk, L. T., Demattê, J. A. M., Silvero, N. E. Q., & Rosin, N. A. (2023). Asoil productivity system reveals most Brazilian agricultural lands are below their maximum potential. *Scientific Reports*, 13, 14103. https://doi.org/10.1038/s41598-023-39981-y

Hungria, M., & Nogueira, M. A. (2019). Tecnologias de inoculação da cultura da soja: mitos, verdades e desafios. *In*: Boletim de Pesquisa 2019/2020, 50-62 p.

Hungria, M., Campo, R. J., & Mendes, I. C. (2007). A importância do processo de fixação biológica do nitrogênio para a cultura da soja: componente essencial para a competitividade do produto brasileiro. Embrapa Soja. Documentos, 283, 80 p.

Hungria, M., Nogueira, M. A., & Araujo, R. S. (2013). Co-inoculation of soybeans and common beans with rhizobia and *Azospirilla*: strategies to improve sustainability. *Biology and Fertility of Soils*, 49(7), 791-801. https://doi.org/10.1007/s00374-012-0771-5

Ibrahim, M., Iqbal, M., Tang, Y-T., Khan, S., Guan, D-X., & Li, G. (2022). Phosphorus mobilization in plant-soil environments and inspired strategies for managing phosphorus: A review. *Agronomy*, 12(10), 2539. https://doi.org/10.3390/agronomy12102539

Javed, A., Ali, E., Afzal, K. B., Osman, A., & Riaz, S. (2022). Soil fertility: Factors affecting soil fertility, and biodiversity responsible for soil fertility. *International Journal of Plant, Animal and Environmental Sciences*, 12, 021-033. https://doi.org/10.26502/ijpaes.202129

Khan, F., Siddique, A. B., Shabala, S., Zhou, M., & Zhao, C. (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants*, 12(15), 2861.

https://doi.org/10.3390/plants12152861

Khan, M. S., Zaidi, A., & Wani, P. A. Role of phosphate-solubilizing microorganisms in sustainable agriculture – A review. *Agronomy for Sustainable Development*, 27, 29-43. https://doi.org/10.1051/agro:2006011

Kour, D., Kour, H., Khan, S. S., Khan, R. T., Bhardwaj, M., Kailoo, S., Kumari, C., Rasool, S., Yadav, A. N., & Sharma, Y. P. (2023). Biodiversity and functional attributes of rhizospheric microbiomes: Potential tools for sustainable agriculture. *Current Microbiology*, 80(6), 192. https://doi.org/10.1007/s00284-023-03300-5

Li, J., Lu, J., Wang, H., Fang, Z., Wang, X., Feng, S., Wang, Z., Yuan, T., Zhang, S., & Ou, S (2021). A comprehensive synthesis unveils the mysteries of phosphate-solubulizing microbes. *Biological Reviews*, 96(6), 2771-2793. https://doi.org/10.1111/brv.12779

Li, C., Zheng, Z., Zhao, Y., Wang, H., Li, P., Xu, J., Jiao, J., Xu, L., Hu, F., & Li, H. (2024). Phosphate-solubilizing microorganisms stimulate physiological responses of perennial ryegrass to phosphorous deficiency with assistance of straw compost. *Agronomy*, 14(5), 1008. https://doi.org/10.3390/agronomy14051008

Liu-Xu, L., González-Hernández, A. I., Camañes, G., Vicedo, B., Scalschi, L., & Lorens, E. (2024). Harnessing green helpers: Nitrogen-fixing bacteria and other beneficial microorganisms in plant-microbe interactions for sustainable agriculture. *Horticulturae*, 10(6), 621. https://doi.org/10.3390/horticulturae10060621

Loureiro, E. S., Dias Neto, J. A., Pessoa, L. G. A., Adão, D. V., Dias, P. M., Pereira Filho, A. A., & Mateus, J. A. F. (2020). Manejo de *Pratylenchus brachyurus* com *Trichoderma harzianum* e *Purpureocillium lilacinum* na cultura da soja. *Research, Society and Development*, 9(7), e124973828. http://dx.doi.org/10.33448/rsd-v9i7.3828

Luo, D., Shi, J., Li, M., Chen, J., Wang, T., Zhang, Q., Yang, L., Zhu, N., & Wang, Y. (2024). Consortium of phosphorus-solubilizing bacteria promotes maize growth and changes the microbial community composition of rhizosphere soil. *Agronomy*, 14(7), 1535. https://doi.org/10.3390/agronomy14071535

Machado, A. W. (2024). Controle biológico de pragas na soja. Agrolink. Available at: Agrolink – Integrated pest management in soybean. Accessed on: August 30, 2025.

Malavolta, E. (2006). Manual de nutrição de plantas. São Paulo, Ceres. 638 p.

Massucato, L. R., Silva, M. B., Mosela, M., Watanabe, L. S., Afonso, L., Marcos, A. W., Nogueira, A. F., SOUsa, N. V., Fendrich, R. C., & Gonçalves, L. S. A. (2025). Enzymatic activity and organic acid profile of phosphate-solubilizing bacterial inoculants and their agronomic effectiveness in soybean. *Microorganisms*, 13(9), 2016. https://doi.org/10.3390/microorganisms13092016

Medina, G. S. (2022). The economics of agribusiness in developing countries: Areas of opportunities for a new development paradigm in the soybean supply chain in Brazil. *Frontiers in Sustainable Food Systems*, 6. https://doi.org/10.3389/fsufs.2022.842338

Mendes, I. C., & Reis Júnior, F. B. (2003). Microrganismos e disponibilidade de fósforo (P) nos solos: uma análise crítica. Embrapa, Documentos 85, Planaltina.

Meyer, J. R., & Linderman, R. G. (1986). Response of subterranean clover to dual inoculation with vesicular-arbuscular mycorrhizal fungi and a plant growth-promoting bacterium, *Pseudomonas putida*. *Soil Biology and Biochemistry*, 18(2), 185-190. https://doi.org/10.1016/0038-0717(86)90025-8

Novais, F. R., & Smyth, T. J. (1999). Fósforo em solo e planta em condições tropicais. Viçosa: UFV, 399 p.

Novais, F. R., Álvarez, V. H., Barros, N.F., Fontes, R. L., Cantarutti, R. B., & Neves, J. C. L. (2007). Fertilidade do solo. Viçosa: SBCS, 1017 p.

Oba, L. X. S., Mattos, L. M., Paiva, G. F., Carrasco, N. F., Santos, E. F., & Mota, L. H. C. (2024). Planting fertilization and *Metarhizium anisopliae* inoculation in the initial growth of sugarcane. *Revista de Agricultura Neotropical*, 11(1), e7712. https://doi.org/10.32404/rean.v11i1.7712

Olabi, A. G., Shehata, N., Issa, U. H., Mohamed, O. A., Mahmoud, M., Abdelkareem, M. A., & Abdelzaher, M. A. (2025). The role of green buildings in achieving the sustainable development goals. *International Journal of Thermofluids*, 25, 101002. https://doi.org/10.1016/j.ijft.2024.101002

Oliveira Júnior, A., Prochnow, L. I., & Klepker, D. (2011). Soybean yield in response to application of phosphate rock associated triple superphosphate. *Scientia Agricola*, 68(3), 376-385.

Oliveira, C. A., Alves, V. M. C., Casado, I. E., Gomes, E. A., Scotti, M. R., Carneiro, N. P., Guimarães, C. T., Schaffert, R. E., & Sá, N. M. H. (2009). Phosphate solubilizing microorganisms isolated from rhizosphere of maize cultivated in an oxisol of the Brazilian Cerrado Biome. *Soil Biology and Biochemistry*, 41(9), 1782-1787. https://doi.org/10.1016/j.soilbio.2008.01.012

Pan, L., & Cai, B. (2023). Phosphate-solubilizing bacteria: advances in their physiology, molecular mechanisms and microbial community effects. *Microorganisms*, 11(12), 2904. https://doi.org/10.3390/microorganisms11122904

Pavinato, P. S., & Cipriano, P. E. (2025). Optimizing phosphorus use in tropical soils for sustainable farming. *Soil Science Cases*. https://doi.org/10.1079/soilsciencecases.2025.0009

Raij, B. V. (2011). Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute, Piracicaba, 420 p.

Raij, B. V. (1991). Fertilidade do solo e adubação. São Paulo: Ceres; Piracicaba: Potafos, 181-202 p.

Rao, G. E., Nagarjun, P., Lakshmipathi, R. N., & Seddiqui, M. (2024). Effect of different source of organic phosphorus and PSB on growth and productivity of soybean (*Glycine max* (L.) Merril. *International Journal of Research in Agronomy*, 7(12), 526-533. https://doi.org/10.33545/2618060X.2024.v7.i12Sh.2255

Rathinasabapathi, B., Liu, X., Cao, Y., & Ma, L.Q. (2018). Phosphate-solubilizing Pseudomonads for improving crop plant nutrition and agricultural productivity. *In*: Crop Improvement Through Microbial Biotechnology, 363-372 p. https://doi.org/10.1016/B978-0-444-63987-500018-9

Sarmah, R., Sarma, A. K. (2022). Phosphate solubilizing microorganisms: A review. *Communications in Soil Science and Plant Analysis*. https://doi.org/10.1080/00103624.2022.2142238

Sohome, S., Barman, A., & Solaiman, Z. M. (2022). *Rhizobium* and phosphate solubilizing bacteria influence the soil nutrient availability, growth, yield, and quality of soybean. *Agriculture*, 12(8), 1136. https://doi.org/10.3390/agriculture12081136

Silva, D. S., Arima, E. Y., dos Reis, T. N. P., & Rattis, L. (2023a). Temperature effect on Brazilian soybean yields, and farmers' responses. *International Journal of Agricultural Sustainability*, 21(1). https://doi.org/10.1080/14735903.2023.2173370

Silva, L. I., Pereira, M. C., Carvalho, A. M. X., Buttrós, V. H., Pasqual, M., & Dória, J. (2023b). Phosphrous-solubilizing microorhanisms: A key to sustainable agriculture. *Agriculture*, 13(2), 462. https://doi.org/10.3390/agriculture13020462

Silva, T. P., Pinto, L. A. S. R., Pliveira, C. C. L., Ferreira, R., Trogello, E., & Pereira, M. G. (2025a). Phosphorus fractions in different management systems in the Cerrado Goiano. *Ambiente & Água – An Interdisciplinary Journal of Applied Science*, 20, e3057. https://doi.org/10.4136/ambi-agua.3057

Silva, J. M., Dalbon, V. A., Alves, A. C., Ataíde, C. B., Santos, T. M. C., Costa, M. E. L., & Montaldo, Y. C. (2025b). Bioinputs in sustainable agriculture: benefits, challenges, and pathways for resilient farming systems. *Asian Journal of Research in Crop Science*, 10(20, 85-97.

Song, C., Wang, W., Gan, Y., Wang, L., Chang, X., Wang, Y., & Yang, W. (2022). Growth propotion ability of phosphate-solubilizing bacteria from the soybean rhizosphere under maize-soybean. *Journal of the Science of Food and Agriculture*, 102(4), 1430-1442. https://doi.org/10.1002/jsfa.11477

Suman, J., Rakshit, A., Ogireddy, S. D., Singh, S., Gupta, C., & Chandrakala, J. (2022). Microbiome as a key player in sustainable agriculture and human health. *Frontiers in Soil Science*, 2. https://doi.org/10.3389/fsoil.2022.821589

Tall, S., & Meyling, N. V. (2018). Probiotics for plants? Growth promotion by the entomopathogenic fungus *Beauveria bassiana* depends on nutrient availability. *Microbial Ecology*, 76(1), 1002-1008. https://doi.org/10.1007/s00248-018-1180-6

Timofeeva, A., Galyamova, M., & Sedykh, S. (2022). Prospect of using phosphate-solubilizing microorganisms as natural fertilizers in agriculture. *Plants*, 11(16), 2119. https://doi.org/10.3390/plants11162119

Torres, J. L. R., Costa, D. D. A., Pereira, M. G., Guardieiro, L. V. F., Loss, A., Lourenzi, C. R., Gonzalez, A. P., Carvalho, M., & Vieira, D. M. S. (2023). Phosphorus fractionations and availability in areas under different management systems in the cerrado. *Agronomy*, 13(4), 966. https://doi.org/10.3390/agronomy13040966

UN. (2024). Sustainable Development, The 17 Goals, United Nations. Available at: https://sdgs.un.org/goals. Accessed in: January 22, 2026.

Viruel, E., Erazzú, L. E., Martinez, L. C., Ferrero, M. A., Lucca, M. E., & Sineriz, F. (2014). Inoculation of maize with phosphate solubilizing bacteria: effect on plant growth and yield. *Journal of Soil Science and Plant Nutrition*, 14(4), 819-831. http://dx.doi.org/10.4067/S0718-95162014005000065

Wagemans, J., Holtappels, D., Vainio, E., Rabiey, M., Marzachi, C., Herrero, S., Ravanbakhsh, M., Tebbe, C. C., Ogliastro, M., Ayllón, M. A., & Turina, M. (2022). Going viral: Virus-based biological control agents for plant protection. *Annual Review of Phytopathology*, 60, 21-42. https://doi.org/10.1146/annurev-phyto-021621-114208

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., & Reddy, S. P. P. (2023). Role or arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stress. *Plants*, 12(17), 3102. https://doi.org/10.3390/plants12173102

Yi, C., Zhu, J., Chen, L., Huang, X., Wu, R., Zhang, H., Dai, X., & Liang, J. (2023). Speciation of iron and aluminium in relation to phosphorus sorption and supply characteristics of soil aggregates in subtropical forests. *Forests*, 14(9), 1804. https://doi.org/10.3390/f14091804

Yo, H., Wu, X., Zhang, G., Zhou, F., Harvey, P. R., Wang, L., Fan, S., Xie, X., Li, F., Zhou, H., Zhao, X., & Zhang, X. (2022). Identification of the phosphorus-solubilizing bacteria strain JP233 and its effects on soil phosphorus leaching loss and crop growth. *Frontiers in Microbiology*, 13. https://doi.org/10.3389/fmicb.2022.892533

Zhu, Y., Xing, Y., Li, Y., Jia, J., Ying, Y., & Shi, W. (2024). The Role of Phosphate-Solubilizing Microbial Interactions in Phosphorus Activation and Utilization in Plant–Soil Systems: A Review. *Plants*, 12(19), 2686. https://doi.org/10.3390/plants13192686

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.