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Review Article

Synergy of *Bradyrhizobium* spp. and Co-Inoculants to Enhance Fertiliser Efficiency and Soybean Yield in Acid-Stressed Soils: A Systematic Review

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ABSTRACT

Bradyrhizobium spp., as nitrogen-fixing bacteria, when combined with plant growth-promoting rhizobacteria such as *Azospirillum*, *Bacillus*, and *Pseudomonas*, alongside arbuscular mycorrhizal fungi (AMF), can sustain soil health and enhance soybean yields by working together to improve fertiliser efficiency, this approach has an impact on sustainable agriculture. Soybeans are a vital crop for soil regeneration in tropical agriculture, especially in regions with acidic soils. This systematic literature review evaluates how *Bradyrhizobium* and co-inoculants enhance biological nitrogen fixation, root nodule formation, and soybean growth. PRISMA guidelines and bibliometric analysis were employed to maintain scientific transparency and stringency. During the initial screening process, 12 out of 1,463 articles met the criteria, focusing on Rhizobiaceae-based inoculants and co-inoculation approaches in acidic soils. The results show that strategic co-inoculation significantly increased soybean yields by 8-88%, reduced reliance on chemical nitrogen fertilisers by approximately 30-50%, and enhanced nutrient use efficiency and root nodule formation. In addition to enhancing productivity, this technology has an impact on long-term soil rehabilitation, making it a vital component of climate-resilient and sustainable agriculture.

Keywords: Arbuscular mycorrhizal fungi, acidic soils, biofertiliser, co-inoculants, fertiliser efficiency, PGPR, soybean, symbiotic N-fixer

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INTRODUCTION

Soybean (*Glycine max* L.) is a legume crop which is highly beneficial due to its capability of enhancing soil fertility through symbiotic nitrogen fixation, supporting the sustainability of cropping systems by facilitating the improvement of soil quality. In addition to its agroecological role, soybean provides plant-based protein with high-quality, essential amino acids and vegetable oil, making it an important commodity for global food security, nutrition, and animal feed. Soybeans' position is strengthened by this role as a key element of both agricultural productivity and environmental sustainability. However, soybean productivity is frequently constrained by acid-stressed soils, which are widespread in tropical and subtropical regions. These soils are characterised by low pH, aluminium (Al) toxicity, phosphorus (P) fixation and deficiency, manganese toxicity, calcium and magnesium deficiencies, and impaired biological nitrogen fixation, all of which restrict root development, microbial activity, nutrient availability, and ultimately soybean growth and yield (Li et al., 2023; Zahran, 1999). Previous studies have reported that soybeans grown under acidic soil conditions exhibit significant reductions in root development, nodulation, nutrient uptake, and grain yield due to these combined stresses (Bedassa et al., 2022).

To overcome constraints on soybean production in acid-stressed soils, increasing research has focused on the synergistic use of nitrogen-fixing *Bradyrhizobium* spp. and microbial co-inoculants, particularly plant growth-promoting rhizobacteria (PGPR) such as *Bacillus, Azospirillum,* and *Pseudomonas*, as well as arbuscular mycorrhizal fungi (AMF). These microbial symbionts have synergistic roles in enhancing root growth habit, phosphorus and micronutrient solubilisation, and induction of plant hormones such as indole-3-acetic acid (IAA), which increases plant abiotic stress tolerance to aluminum toxicity, low pH, and phosphorus deficiency (Ahmad et al., 2018; Khan et al., 2023).

AMF, in particular, form symbiotic relationships with soybean roots and create a productive root surface area through networks of hyphae that facilitate water and nutrient uptake, especially under compacted, acidic soils or low-nutrient conditions. AMF also induce aggregation and cycling of soil organic matter, which helps overall soil health. In combination with PGPR and *Bradyrhizobium*, these microbial consortia create a more favorable rhizosphere, enhance nodulation efficiency, and significantly boost biological nitrogen fixation. Recent studies have shown that such co-inoculation practices significantly enhance soybean yields—reported increases of up to 40–80% depending on soil conditions, while reducing the reliance on chemical nitrogen fertilisers (Moretti et al., 2020). Region-specific strain identification, inoculant with optimally formulated inoculants, and validation on a field scale across various agroecological zones need to be focused on in future studies (Santos et al., 2019).

In their capacity to overcome the constraint of soybean (*Glycine max* L.) cultivation in acid-stressed soils, symbiosis between soybean roots and *Bradyrhizobium* species plays a critical role in sustaining biological nitrogen fixation (BNF). Through this symbiosis,

Bradyrhizobium infects root tissues and nodules, where atmospheric nitrogen is biologically converted to ammonia, supplying the plant with an available and renewable source of nitrogen. In acidic soils, *Bradyrhizobium* inoculant quality is generally impaired by its sensitivity to low pH, aluminum (Al) toxicity, and disrupted microbial communication, leading to weak nodulation and nitrogen fixing activity.

These problems have been resolved using co-inoculation methods involving *Bradyrhizobium* spp., plant growth-promoting rhizobacteria such as *Azospirillum, Bacillus,* and *Pseudomonas*, and arbuscular mycorrhizal fungi (AMF). These microbial combinations enrich the rhizosphere environment through phytohormone (auxin) synthesis, phosphorus solubilisation, siderophore production, soil aggregation, and promotion of root elongation. They also indirectly reduce abiotic stresses and increase the colonisation ability and nitrogen fixation capacity of *Bradyrhizobium*. Co-inoculation also improves root system architecture by enhancing nutrient and water uptake under stress. Different studies have proven the synergistic effect of such a microbial mixture. Jabborova et al. (2021) noted that co-inoculation improved nodulation by 56% and shoot biomass by 48% under drought stress. Wei et al. (2023) documented that combining PGPR with *Bradyrhizobium* enhanced soybean yield by 32% in long-term trials, while Marinković et al. (2024) observed a yield increase of 44% under both stressed and non-stressed conditions. On different soils and ecosystems, these findings all reveal quantitative yield boosts ranging from 20% to 56%. These benefits result not only from enhanced nitrogen fixation and nutrient mobilisation but also from enhanced tolerance to abiotic stress. Most importantly, by supplying a significant portion of the plant's nitrogen demand biologically, co-inoculation helps reduce inorganic nitrogen fertiliser use, minimise environmental impact, and lower input costs. Therefore, co-inoculation with PGPR and arbuscular mycorrhizal fungi (AMF) alongside *Bradyrhizobium* is a sustainable, scalable, and climate-resilient method to increase soybean productivity in tropical agroecosystems with varying conditions and stresses such as soil acidity.

Despite numerous studies evaluating the role of *Bradyrhizobium* spp. and a wide variety of co-inoculants in enhancing soybean growth, recent evidence remains disjointed across multiple combinations of microbes, measured agronomic parameters, and environmental conditions. The majority of research projects have focused on specific aspects of plant growth or single inoculant; on the other hand, a comprehensive synthesis of the synergistic effects of *Bradyrhizobium* spp. combined with plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and other beneficial microorganisms under acid-stressed soil conditions is still lacking. Moreover, identification of the most effective microbial consortium approaches for enhancing nodulation efficiency, nutrient uptake, fertiliser use efficiency, and sustainable soybean production has received lack of attention. Therefore, a systematic synthesis of the current evidence is needed to bridge these knowledge gaps and provide evidence-based recommendations for future research and practical agricultural applications.

Despite the increasing number of studies investigating the application of *Bradyrhizobium* spp. and microbial co-inoculants for soybean cultivation under acid-stressed soil conditions, several important research problems remain unresolved. The present review addresses the following research problems: (1) The most effective microbial consortium combinations, particularly the synergistic interactions between *Bradyrhizobium* spp., plant growth-promoting rhizobacteria (PGPR), and arbuscular mycorrhizal fungi (AMF), have not been systematically evaluated with respect to nodulation efficiency, nutrient uptake, fertiliser use efficiency, and soybean productivity; (2) The lack of an integrated synthesis of current findings limits the development of evidence-based inoculation strategies to support sustainable soybean cultivation in acid-affected tropical agroecosystems.

This systematic literature review aims to critically evaluate and summarise recent research on the contribution of *Bradyrhizobium* spp. and co-inoculants to enhancing soybean (*Glycine max* L.) growth in acidic soil conditions. The study specifically examines the synergistic effects of co-inoculation on nutrient uptake, root nodule formation, and yield improvement, identifying the most effective microbial combinations and application strategies to enhance inoculant efficacy and fertiliser use efficiency. The supreme objective is to provide insights based on evidence to sustain long-term and resilient soybean cultivation in tropical agroecosystems affected by environmental adversity such as acidic soil pressure.

MATERIALS AND METHODS

Literature Search Strategy

Literature search was carried out comprehensively using Scopus and ScienceDirect. The search utilised combinations of keywords such as "*Bradyrhizobium*", "Symbiotic nitrogen fixation", "Co-inoculants", "Biofertiliser PGPR", "Fertiliser efficiency", "Soybean productivity", and "Acid soils". The Boolean search strategy and the resulting outcomes are summarised in Table 1.

Table 1
Search strategy used to gather applicable research articles

Search Strategy	Scopus	ScienceDirect
Bradyrhizobium AND Soybean	78	20
Nitrogen fixation AND PGPR	43	31
Soybean AND Acidic soils	22	50
PGPR AND fertiliser AND efficiency	22	53
Co-inoculation AND Soybean AND acidic soils	0	276
Co-inoculants AND fertiliser efficiency	13	57
Soybean Productivity AND fertiliser efficiency	48	750
Total Articles		1463

Data Retrieval for Bibliometric Analysis

Metadata was fetched exclusively from Scopus and ScienceDirect using the same combination of keywords in the bibliometric analysis. The retrieval was restricted to English-language articles with a year of publication between 2020 and 2024. Bibliographic data were exported in RIS format and analysed using VOSviewer version 1.6.19 to map keyword co- occurrences, thematic clusters, and temporal trends. The minimum benchmark of five keyword co-occurrences with a 60% relevance score was applied to highlight key research trends in relation to the enhancement of soybean productivity through microbial approaches under acidic soil stress conditions.

Systematic Literature Review Using PRISMA

This systematic literature review conforms to the PRISMA 2020 guidelines. Articles were retrieved from Scopus and ScienceDirect using the same combination of keywords; 1,463 articles were identified at the initial stage, and 12 articles were considered qualified for in-depth textual analysis. Mendeley Reference Manager was used to remove the duplicates, and screening based on titles and abstracts was used as well. The article selection and screening process is illustrated in Figure 1. If the articles addressed the role of *Bradyrhizobium* spp.

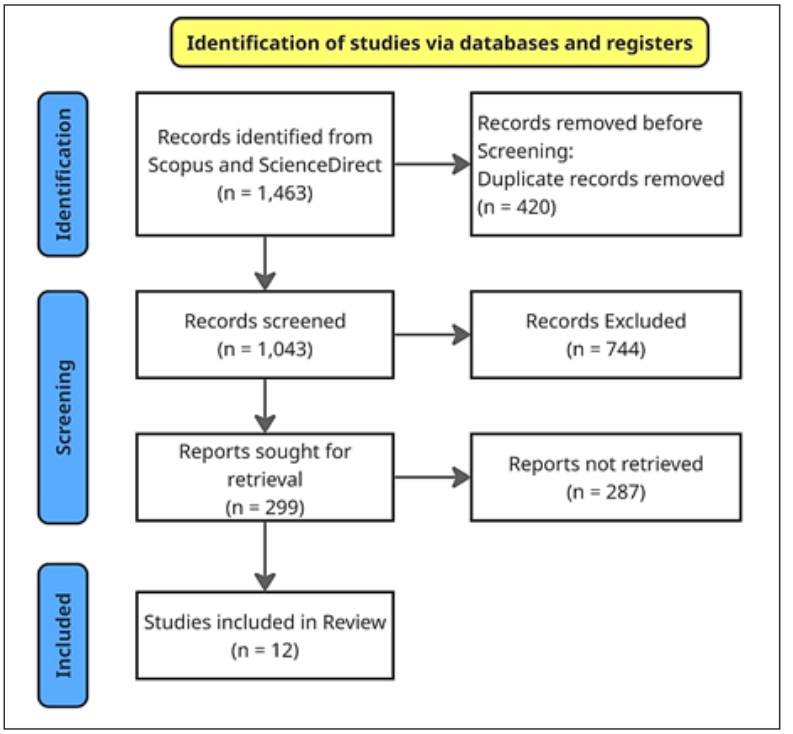

Figure 1. The PRISMA flow diagram outlining the stages of article selection for the systematic literature review

and co-inoculants in soybean growth in acidic soils and demonstrated measurable impacts on nutrient uptake, nodulation, or crop yield, they were included. The selection criteria are summarised in Table 2. These 12 articles are further summarised in Table 3 and form the ultimate evidence foundation, which presents the microbial agents, their functional roles, and the documented impacts under environmental adversity such as acidic soil stress.

Table 2
Approach used to gather applicable research articles

Criteria	Inclusion	Exclusion
Relevance topics	Journal focused on the application of *Bradyrhizobium* and co-inoculants in or relevant to soybean cultivation in acid soils	Journal without a core focus on the application of *Bradyrhizobium* and co-inoculants in or relevant to soybean cultivation in acid soils
Date of publication	2020-2024	< 2020
Type of publications	Research article	Book chapters, Encyclopedia, News, Conference abstracts
Language of publication	English	All other languages
Databases	Scopus and ScienceDirect	Articles that are not indexed by Scopus

RESULTS AND DISCUSSION

Bibliometric Analysis

Bibliometric analysis was undertaken using VOSviewer to uncover emerging themes and research trends from the past five years. Visual representations, including binary counting, were employed to create co- occurrence maps of document keywords. To identify 49 key keywords through diverse search methods, the minimum co-occurrence threshold for document keywords in the research articles was set at 5, with 60% relevance.

The network visualisation illustrates the connectivity among key concepts in soil microbiology, plant growth-promoting rhizobacteria (PGPR), and sustainable agriculture. The thematic groups are differentiated by colour: blue includes microbial agents linked with PGPR, green covers soybean plants' physiological responses, and red reflects agronomic management practices.

The blue colour (PGPR group) covers terms such as *Pseudomonas, Bacillus*, IAA production, and bioinoculant. The role of symbiotic microbes in stimulating plant growth under abiotic stress is represented by these terms; research by Ashwin et al. (2022) and Widodo et al. (2022) is in line with these findings, which substantiated that rhizobacterial inoculation enhances phosphorus solubilisation, root nodule formation, chlorophyll content, and seedling vigour. The green colour (soybean group) covers terms such as tolerance, abiotic stress, and seed germination. It emphasises that combining *Azospirillum brasilense* and *Bradyrhizobium* inoculation is important to enhance productivity under

Table 3
Microbial contributions to soybean cultivation under acid-stressed soil conditions

Microbial Agent	Functional Role	Benefit in Acid-Stressed Soils	Impact on Soybean Productivity (with Reference)
Bradyrhizobium japonicum, *Bradyrhizobium elkanii*, and *Sinorhizobium fredii*	Symbiotic nitrogen fixation; Host-specific Nod factor & T3SS signalling	Increase resistance to low pH, high temperature, salinity and high nitrate	Delay of nodule senescence & increased nitrogen fixation resulting in higher yields (Li et al., 2020)
Bradyrhizobium spp. and *Azospirillum brasilense*	Biological Nitrogen Fixation and Plant Growth Promotion (e.g., nutrient uptake, stress tolerance)	Improves resilience under tropical acidic conditions	Nodulation increased by up to 350%; yield rose on average by 8% and up to 80% in certain cases (Prando et al., 2024)
Pseudomonas sp. (PSB Lampung-2)	Phosphate solubilising	Increases P availability under low pH and Al toxicity	Increase yield by 45% (greenhouse) and 27% (field) with PSB + P fertiliser (Widodo et al., 2022)
Cupriavidus, *Klebsiella*, and *Proteobacteria*	Phosphorus mineralisation via acid phosphatase (AcP) and phoC gene	Enhances P availability and root-associated nutrient cycling	Improved adaptation and phosphorus acquisition under P-deficient acidic soil (Chen et al., 2024)
Rhizobium and Arbuscular Mycorrhizal Fungi (AMF)	Biological Nitrogen Fixation and boosts phosphorus uptake via mycorrhiza	Enhanced nodulation and nutrient uptake in acidic soils	Increase grain yield up to 356%, shoot biomass up to 140% and nodules up to 676% (Kamau et al., 2020)
Arbuscular Mycorrhizal Fungi (AMF), *Rhizobium, Talaromyces verruculosus,* and *Paraburkholderia soli*	N-fixation, P-uptake, and microbiome recruitment	Enhances Al stress tolerance, improves root and shoot biomass, especially in Al-sensitive genotypes; increases N uptake, synergistic with AMF in improving N cycling and enzyme activity	Increases shoot biomass by 112% and root biomass by 217% in Al-sensitive soybean (BD2); Promotes growth in both Al-tolerant and Al-sensitive soybean; Improves N and C accumulation; Enhances N content and biomass when combined with AMF (Wen et al., 2023)
Rhizobia (including *Bradyrhizobium*)	Symbiotic nitrogen fixation, root architecture modification, and acid adaptation	Root adaptation to phosphorus deficiency and aluminium toxicity	Potential to increase P and SNF efficiency in acid-tolerant varieties (Li et al., 2023)

Table 2 (*continued*)

Microbial Agent	Functional Role	Benefit in Acid-Stressed Soils	Impact on Soybean Productivity (with Reference)
Azospirillum brasilense, Arthrobacter crystallopoietes, Bacillus aryabhattai, and *Paenibacillus peoriae*	PGPR: P solubilisation, N fixation, hormone production	Biochar as a carrier increased pH and microbial stability in acidic sandy soils (pH 4.4); enhanced abundance and survival of PGPR	Maize biomass increased 2.6-3.2×, although not on soybean; mechanism and microbes are relevant (Kari et al., 2021)
Bradyrhizobium spp.	C-N transport in nodules, activation of β-1,3-glucanase enzyme	Regulation of nodule metabolic efficiency in acid soil via Mg	Increases nitrogen fixation symbiosis efficiency in soybeans (Cao et al., 2022)
Duddingtonia flagrans, Pochonia chlamydosporia, and *Bradyrhizobium japonicum*	Nematode biocontrol and increased nutrient uptake	Controlling *Meloidogyne javanica*, increasing nutrient intake in soil with nutrient decrease and high biotic stress	Increase root nutrients, nodulation, and soybean performance (Balbino et al., 2021)
Bradyrhizobium diazoefficiens (USDA110 & CB1809)	Nodule respiratory and SNF metabolic adaptations	Respiratory adaptation in conditions of P deficiency	Increases nitrogen efficiency even in P-deficient soils (Sulieman et al., 2024)
Bradyrhizobium japonicum, Bradyrhizobium diazoefficiens, Azospirillum brasilense, and *Bacillus subtilis*	Nitrogen fixation, growth hormone (IAA), antioxidants, and LCO metabolites	Increase drought resilience and efficiency in photosynthesis	Increase photosynthesis, nodulation and soybean yield up to 12.2% (Moretti et al., 2021)

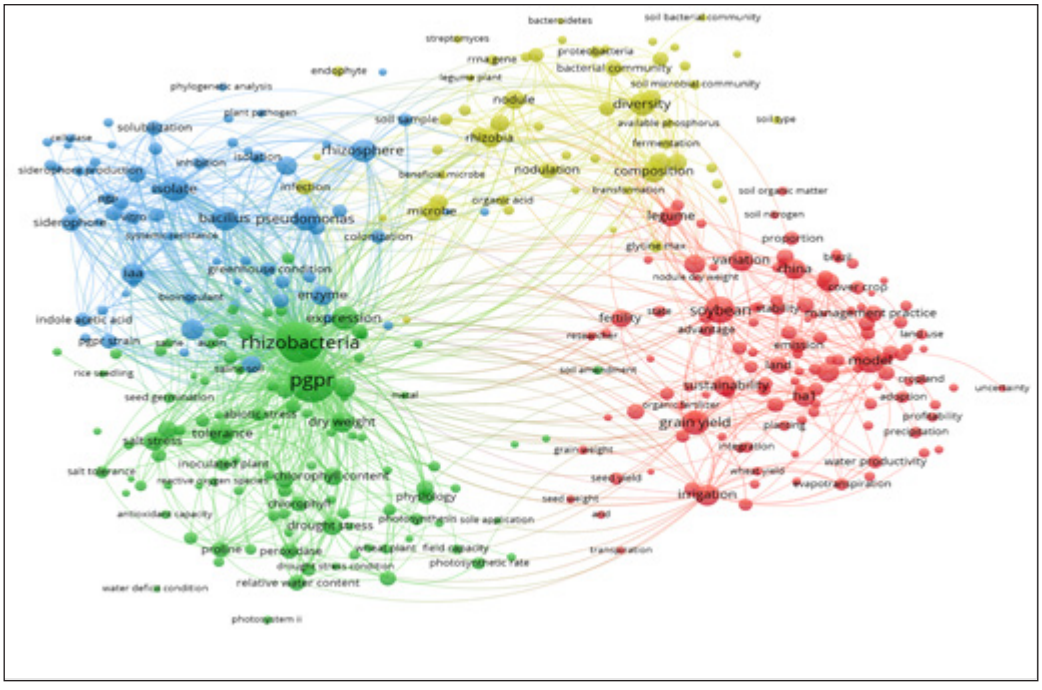

Figure 2. Network visualisation of the co-occurrence mapping of pertinent keywords related to research on the use of *Bradyrhizobium*, PGPR, and AMF to enhance soybean growth and fertiliser efficiency in acid soils

acidic soil stress (Prando et al., 2024). The red colour includes agronomic terms such as sustainability, irrigation, and land use, indicating the fusion of microbial inoculants with nutrient management and climate-resilient agricultural practices. Research by Ferdous et al. (2024) has further supported this statement; it reported *Rhizobium*'s survival improvement in conservation systems, and Zhang et al. (2023) identified precision agriculture as a primary driver in enhancing inoculant efficiency.

Generally, Figure 2 visualises the developing interconnection between microbial inputs, plant physiological responses, and environmental management strategies. Visualisation reinforces the relevance of co- inoculation technology for the sustainability of soybean production in tropical agroecosystems with acidic soil stress.

Figure 3 visualises the publication timeframe of the terms included in the analysis. The most recent publications are illustrated with keywords represented in yellow, with the colour changing from green to blue to illustrate older publication dates. Based on the visualisation, many articles were published in early to mid-2022, including the utility of *Bradyrhizobium* and co-inoculants to enhance soybean plant growth in acidic stress condition, which is aligned with this network visualisation, indicating that researchers studying this topic is still lacking.

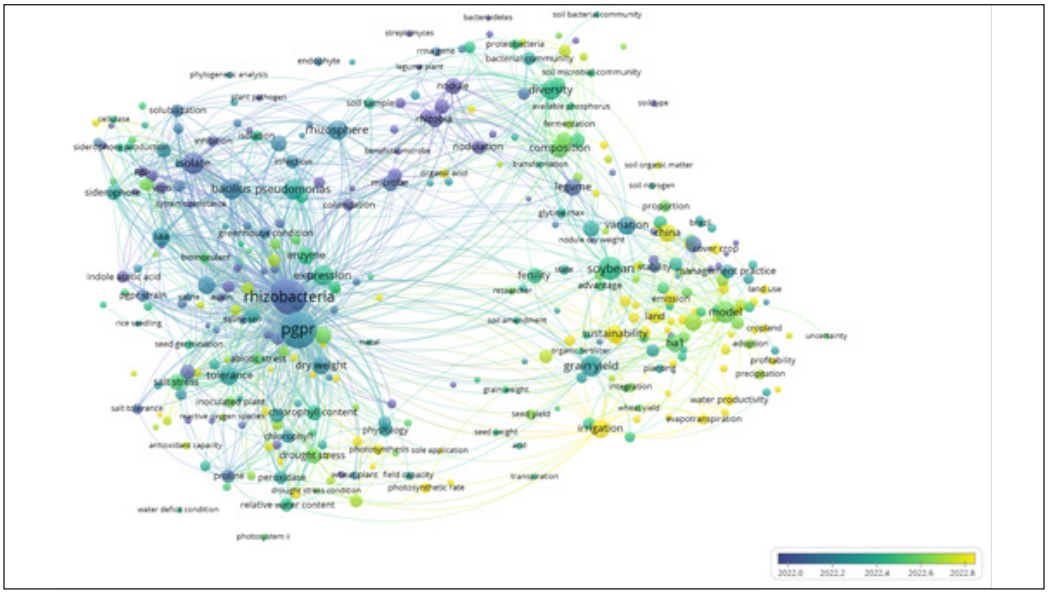

Figure 3. Mapping of co-occurrence of textual data provided in the titles and abstracts of the research articles used in this study

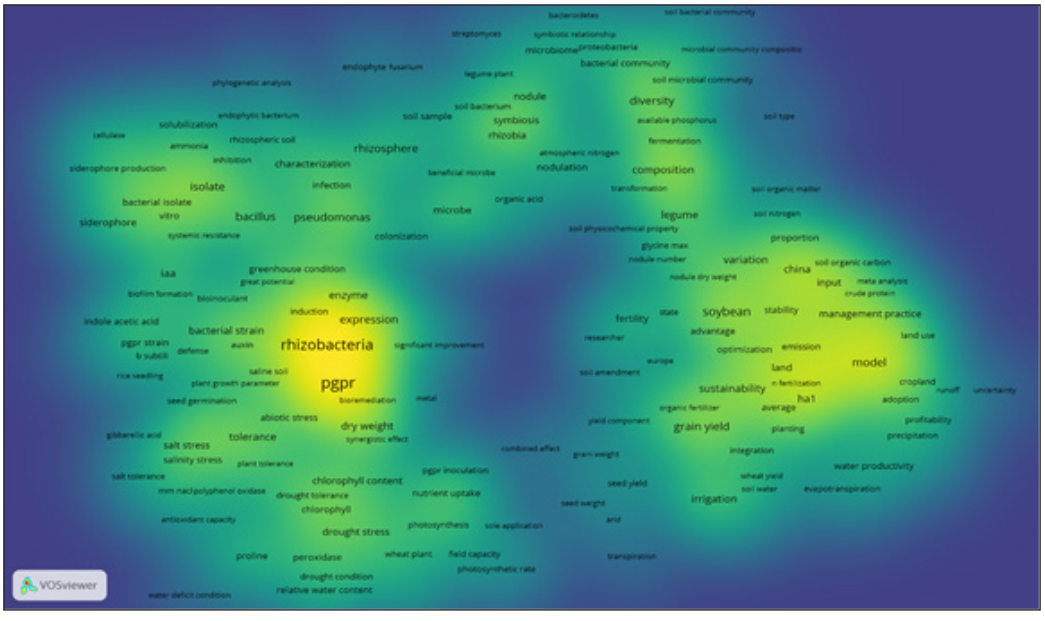

Figure 4. Overlay visualisation of publication year mapping related to research on soybean farming under acid soil stress

Keyword appearance by publication year overlaid in Figure 4, showing that most articles attentive to co-inoculation approaches and acidic stress adaptation were published

between 2022 and 2024, indicating a growing research trend and potential gap for deeper on-farm applications.

PRISMA Result

12 selected studies provide a comprehensive summary regarding the evidence reinforcing the synergistic effects of co-inoculation between *Bradyrhizobium* spp. and a wide variety of co-inoculants such as PGPR, AMF, PSB, and fungal biocontrol agents in boosting soybean growth and nutrient efficiency under acidic soil stress.

Field-scale experiments across diverse regions of Brazil have demonstrated an increase in root nodule formation and crop yields of up to 80% subsequent to inoculation with *Azospirillum brasilense* (Prando et al., 2024). Research in Kenya showed that the combined application of *Rhizobium* and arbuscular mycorrhizal fungi (AMF) promoted superior root nodule development, as well as enhanced phosphorus uptake and biomass accumulation in acidic soils (Kamau et al., 2020). The utility of *Bradyrhizobium liaoningense* combined with *Ambispora leptoticha* plays a role in higher drought stress tolerance, resulting in statistically meaningful gains in plant biomass and an 88% increase in grain yield (Ashwin et al., 2022). *Bacillus*, *Pseudomonas*, and *Paenibacillus* as phosphate-solubilising bacteria support phosphorus supply and crop productivity, thus decreasing dependency on chemical phosphate fertilisers (Chen et al., 2024; Widodo et al., 2022). Recent molecular studies have also explained that nutrient-poor acidic soils are a contributing factor in enhancing biological nitrogen fixation efficiency through respiration alterations and increased magnesium absorption into root nodules (Cao et al., 2022; Sulieman et al., 2024).

Research explains that the application of soil amendments and co-inoculation can enhance soybean crop response to acidic stress conditions through diverse mechanisms. Co-inoculation between *Bradyrhizobium* and plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum* and *Bacillus* can enhance photosynthetic efficiency and soybean yields (Moretti et al., 2021). PGPR with biochar enhances microbial adaptiveness and root biomass in acidic sandy soils, thus boosting nitrogen utilisation (Kari et al., 2021). Advantageous microorganisms suppress nematodes and soil-borne pathogens, contributing to plant health. Fungal biocontrol agents such as *Duddingtonia flagrans* and *Purpureocillium* spp. have been presented to enhance root health and nutrient absorption, boosting soybean performance in acidic stress conditions (Balbino et al., 2021; Haarith et al., 2021).

Diverse studies have synthesised that microbial co-inoculation enhances soybean adaptation to acidic stress conditions through nutrient uptake, improved rhizosphere diversity, and stress resilience. Diverse rhizobial consortia, including *Bradyrhizobium*, *Rhizobium*, *Pararhizobium*, and *Sinorhizobium*, have been shown to foster microbial diversity and nodulation potential in acidic, no-till agricultural systems (Ferdous et al., 2024). Functional analyses of soybean rhizosphere microbiota further demonstrate that

beneficial bacteria possess traits associated with acid-stress mitigation, nutrient cycling, and enhanced nitrogen acquisition (Wen et al., 2023). These findings are supported by studies showing that PGPR improve stress tolerance, nitrogen uptake, chlorophyll content, root development, and nitrogen metabolism under acidic conditions, ultimately resulting in greater nutrient use efficiency and soybean productivity (Li et al., 2020; Shaffique et al., 2023; Sudarshna & Sharma, 2024).

The studies emphasised that integrating *Bradyrhizobium* spp. with co-inoculants (specifically PGPR, AMF, and PSB) can overcome agronomic-limiting factors in acidic stress conditions effectively. This combination improves biological nitrogen fixation (BNF), phosphorus solubilisation, abiotic stress resilience, and nutrient absorption, enhancing crop tolerance and efficiency in nutrient use. Consistently, results present increased soybean productivity throughout the studies, ranging from 8% to 88%, and boost long-term enhancements in soil health, rhizosphere microbial activity, and nutrient cycling as well.

In general, the findings firmly suggest that co-inoculation reduces dependency on chemical nitrogen fertilisers, especially in acidic stress conditions and low external input farming systems, even though the level of this reduction was not quantified explicitly in most of the 12 studies evaluated. This deduction is supported by other studies beyond the main dataset, which show that integration between *Bradyrhizobium* and PGPR can reduce nitrogen fertiliser use by 30-50% without sacrificing crop yields (de Souza et al., 2015; Zahran, 1999). These results emphasise that microbial-based solutions for soybean yield in tropical regions are ecologically efficient and sustainable. Regrettably, application at the field scale remains high-risk; to overcome this, key obstacles regarding stability in formulation, strain compatibility, and adaptability to various agro-ecological environments are addressed. This underscores the need for formulating local inoculants and integrated nutrient management systems.

Functional Role of *Bradyrhizobium* spp. and Co-Inoculants in Enhancing Soybean Productivity and Soil Fertility under Acid-Stressed Conditions

Synergistic interactions between *Bradyrhizobium* and other co-inoculants (such as *Bacillus, Azospirillum*, *Pseudomonas*, and arbuscular mycorrhizal fungi) play a key functional role in enhancing soybean growth and soil fertility, especially in acidic stress conditions, as presented in various studies. These microorganisms contribute to various fundamental biological processes, including symbiotic nitrogen fixation, phosphorus solubilisation, phytohormone production, and abiotic stress mitigation, all of which are highly relevant to plant activity under stressful soil conditions. The symbiotic relationship between *Bradyrhizobium* and soybean roots has made it widely recognised. *Bradyrhizobium* develops root nodules that provide plots for biological nitrogen fixation (BNF).

Nevertheless, acidic stress conditions result in low pH, aluminium (Al) toxicity, and phosphorus (P) deficiency, which deteriorate nitrogenase enzyme activity and root nodule development. These suppressive factors can be mitigated by co-inoculants—they provide functional support that enhances microbial efficacy and rhizosphere conditions.

Manganese and aluminium toxicity can be ameliorated by particular PGPR through diverse mechanisms. PGPR secrete organic acids, which can chelate Al^{3+} ions, thus reducing their toxicity levels and biological availability that accumulates in the rhizosphere. In addition, insoluble phosphorus compounds are dissolved by organic acids released by phosphate-solubilising bacteria, while suppressing the formation of Al-P chelates, thus increasing the presence of solubilised phosphate in soil under acidic stress conditions. Exopolysaccharides (EPS) are synthesised by some PGPR, which sequester toxic metal ions and shield root surfaces from direct aluminium contact. Moreover, indole-3-acetic acid (IAA) stimulates root growth, enabling plants to maintain water absorption and nutrients in spite of the presence of toxic metals, while siderophore synthesis enhances microbial activity and micronutrient uptake within the rhizosphere (Shaffique et al., 2023; Widodo et al., 2022). For example, using *Azospirillum brasilense* for co-inoculation was proven to enhance nodulation by up to 350% and soybean production by up to 80%, especially under tropical conditions that induce acidic stress (Prando et al., 2024). Likewise, nutrient solubilisation, siderophore, and IAA production are facilitated by *Pseudomonas* spp. and *Bacillus*, promoting root growth and nutrient absorption (Shaffique et al., 2023; Widodo et al., 2022).

AMF's function, especially *Ambispora leptoticha*, enhances nitrogen fixation through boosted phosphorus uptake and interactions between root and soil as well. Ashwin et al. (2022) presented that integration between rhizobia and AMF enhanced drought resilience significantly, seed production, and shoot dry matter in acid soils, confirming the ecological collaboration between these microbes. Additionally, studies by Wen et al. (2023) presented that inoculation with AMF and other fungi with stress resilience, such as *Talaromyces verruculosus,* is able to induce aluminium stress resilience, restructure root-interacting microbiomes, and enhance nitrogen and carbon accumulation in soybean tissue. Co-inoculants enhance sustainable soil fertility as well; they enhance enzymatic activity within soils, diversity in microbial communities, and nutrient cycling, especially nitrogen and phosphorus cycling, which is usually altered in acidic soils. For example, improved rhizobial survival and efficacy in acidic no-till soils are recorded in Ferdous et al. (2024), meaning that co-inoculation enhances soil microbial resilience and viability.

The functional characteristics explained above indicate that microbial co-inoculation is not only a long-term method for enhancing soybean performance in acidic stress conditions but also a highly effective approach to restoring degraded land and boosting agroecosystem health. Their biological mechanisms facilitate short-term yield increases as well as the sustainable improvement of soil microbial balance, fertility, and structure.

Challenge and Future Innovative Technology

Challenges remain in translating experimental efficacy into enhanced field adaptation, particularly in acidic stress conditions, in spite of the significant ecological and agronomic advantages of co-inoculation techniques. The main challenge is inconsistency in microbial performance under a wide variety of edaphic and climatic conditions. Acidic soils are commonly characterised by limited microbial activity, low pH, aluminium toxicity, and phosphorus deficiency. These factors inhibit the colonisation, survival, and symbiotic performance of the inoculated microbes. *Bradyrhizobium* and co-inoculants can become less effective under extreme conditions due to disrupted signalling pathways, limited nutrient mobility, and interference from indigenous soil microorganisms. For instance, a Rhizobium strain that performs well in laboratory analyses may exhibit low nitrogen fixation efficiency and poor nodulation when subjected to field stresses. Furthermore, most commercial inoculants are developed as generic products lacking specific adaptation to particular locations or crop varieties. Such mismatches often result in suboptimal microbial performance, particularly when not combined with appropriate agronomic practices, such as the addition of organic matter or pH adjustment.

In addition, challenges such as short shelf life, low carrier stability, and inefficient delivery systems hinder microbial performance in the field. Traditional application methods expose inoculants to desiccation and UV degradation, or result in inoculant death prior to root colonisation due to competition with antagonistic soil microbes. These limitations can be overcome through advanced technologies capable of maximising inoculant performance. Nanoencapsulation is one such technology, involving the loading of microbial cells into protective nanocarriers. This approach protects microbes from environmental stress, controls their release in the root zone, and enhances microbial survival and colonisation capabilities. Zhang et al. (2023) demonstrated that nano-formulated inoculants exhibit stronger adhesion and greater persistence on roots under acidic conditions. Other areas of research include the development of native strains selected or engineered for enhanced tolerance to acidity, aluminium toxicity, and nutrient stress. Genomic and functional metagenomic data can accelerate the identification of stress-tolerant microbial candidates. Sulieman et al. (2024) and Cao et al. (2022) have described how the regulation of nodulation efficiency and nodule respiration mechanisms can be managed to improve *Bradyrhizobium* performance in soils subject to phosphorus stress.

Integration between microbial inoculation and precision agriculture tools, such as automated seed coating, GIS-based soil mapping, and location-specific nutrient implementation can boost the targeting exactness of inoculants while reducing waste. Farmers are able to match specific microbial consortia to specific soil conditions with these technologies, thus increasing input use. Even though microbial co-inoculation has been shown to enhance soybean production and boost soil health, its extensive implementation

requires a breakthrough in formulation, strain resilience, and application precision. Bridging the gap between practice and research will be vital to realising the full potential of co-inoculants in sustainable agriculture, especially in tropical regions under acidic stress.

CONCLUSION

This result presents the functional synergism of *Bradyrhizobium* spp. and co-inoculants such as *Azospirillum*, *Bacillus*, *Pseudomonas*, and arbuscular mycorrhizal fungi (AMF) in soybean yield and soil fertility improvement against acid stress. Co-inoculation methods in different agroecosystems greatly improved nodulation efficiency, nutrient levels, drought stress, and biological nitrogen fixation with soybean yield increments ranging from 8% to 88%. These positive effects are elicited through microbial activities like indole-3-acetic acid (IAA) and siderophore production, phosphorus solubilisation, modulation of root architecture, and soil microbiome enrichment. Along with short-term agronomic effects, these microbiomes also confer long-term soil health through enzymatic activity, microbial community structure diversity, and nutrient cycling, further establishing their roles as soil-regenerative technologies.

IMPLICATION OF THE STUDY

Generally, co-inoculation with *Bradyrhizobium* was found to be climate-resilient, sustainable, and efficient in enhancing fertiliser use efficiency as well as soybean yield in acid-sensitive tropical soils. Advancing these technologies locally through local innovation will be paramount in realising their full capacity in facilitating agroecological restoration and food security.

LIMITATION AND RECOMMENDATION FOR FUTURE RESEARCH

Generally, co-inoculation with *Bradyrhizobium* was found to be climate-resilient, sustainable, and efficient in enhancing fertiliser use efficiency as well as soybean yield in acid-sensitive tropical soils. Advancing these technologies locally through local innovation will be paramount in realising their full capacity in facilitating agroecological restoration and food security.

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