

Effects of plant growth-promoting bacteria on maize performance: A systematic review and meta-analysis

Marcos Vinício Silva¹, Edimar Agnaldo Moreira² & Daniele Maria Marques¹

¹ Faculty of Sciences and Technologies of Campos Gerais, Course of Agronomy, Campos Gerais, Minas Gerais, Brazil

² Institute of Natural Sciences, Federal University of Alfenas (UNIFAL-MG), Alfenas, Minas Gerais, Brazil

Correspondence: Edimar Agnaldo Moreira, Institute of Natural Sciences, Federal University of Alfenas (UNIFAL-MG), Alfenas, Minas Gerais, Brazil. E-mail: edimar.moreira@unifal-mg.edu.br

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Abstract

Plant growth-promoting bacteria (PGPB) have been increasingly investigated as sustainable alternatives for improving crop productivity and reducing dependence on chemical fertilizers in agricultural systems. However, the effectiveness of microbial inoculation in maize remains variable across environmental and experimental conditions. This study aimed to quantify the overall effects of PGPB inoculation on maize performance and evaluate the influence of environmental and microbial factors on plant responses through a systematic review and meta-analysis. The review followed PRISMA 2020 guidelines and included experimental studies published between 2015 and 2026. A total of 23 studies providing sufficient statistical information met the eligibility criteria and were included in the quantitative synthesis. To ensure transparency and reproducibility, the complete dataset, PRISMA 2020 flow diagram, methodological quality assessment, and detailed search strategies are provided as supplementary materials. Effect sizes were calculated using the natural logarithm of the response ratio (lnRR) and analyzed using random-effects models. PGPB inoculation was generally associated with positive effects on maize performance, with an overall pooled effect size of $\lnRR = 0.3754$ (95% CI = 0.2989–0.4520; $p < 0.0001$), corresponding to an average increase of approximately 45.6% relative to non-inoculated controls. No detectable heterogeneity was observed among studies ($I^2 = 0.00\%$), indicating relatively consistent responses within the analyzed dataset. Moderator analyses demonstrated that the experimental environment significantly influenced the magnitude of plant responses, with greenhouse studies showing stronger positive effects than field experiments. No statistically significant differences were detected among inoculation types or bacterial taxa. Publication bias was not detected, and sensitivity analyses indicated that the pooled effect size was not disproportionately influenced by individual studies. Overall, the findings suggest that PGPB inoculation may represent a promising strategy for sustainable maize production, although the magnitude and consistency of responses remain dependent on environmental context and experimental conditions. The study also highlights the importance of integrating microbial functional traits, environmental filters, and microbiome interactions to improve the field-level performance of microbial inoculants in agricultural systems.

Keywords: rhizobacteria, bioinoculants, crop yield, plant–microbe interactions, sustainable agriculture.

Efeitos de bactérias promotoras de crescimento vegetal no desempenho do milho: Uma revisão sistemática e meta-análise

Resumo

As bactérias promotoras de crescimento vegetal (PGPB) têm sido amplamente investigadas como alternativas sustentáveis para aumentar a produtividade agrícola e reduzir a dependência de fertilizantes químicos em sistemas de cultivo. Entretanto, a eficiência da inoculação microbiana em milho permanece variável entre diferentes condições ambientais e experimentais. Este estudo teve como objetivo quantificar os efeitos gerais da

inoculação com PGPB sobre o desempenho do milho e avaliar a influência de fatores ambientais e microbianos nas respostas das plantas por meio de uma revisão sistemática e meta-análise. A revisão seguiu as diretrizes PRISMA 2020 e incluiu estudos experimentais publicados entre 2015 e 2026. Um total de 23 estudos com informações estatísticas suficientes atendeu aos critérios de elegibilidade e foi incluído na síntese quantitativa. Para garantir transparência e reprodutibilidade, o conjunto completo de dados, o fluxograma PRISMA 2020, a avaliação da qualidade metodológica e as estratégias detalhadas de busca foram disponibilizados como materiais suplementares. Os tamanhos de efeito foram calculados utilizando o logaritmo natural da razão de resposta ($\ln RR$) e analisados por meio de modelos de efeitos aleatórios. A inoculação com PGPB esteve geralmente associada a efeitos positivos sobre o desempenho do milho, com tamanho de efeito global de $\ln RR = 0,3754$ ($IC_{95\%} = 0,2989-0,4520$; $p < 0,0001$), correspondendo a um aumento médio de aproximadamente 45,6% em relação aos controles não inoculados. Não foi detectada heterogeneidade entre os estudos ($I^2 = 0,00\%$), indicando respostas relativamente consistentes dentro do conjunto de dados analisado. As análises de moderadores demonstraram que o ambiente experimental influenciou significativamente a magnitude das respostas das plantas, com estudos conduzidos em casa de vegetação apresentando efeitos positivos mais intensos do que em experimentos de campo. Não foram detectadas diferenças estatisticamente significativas entre os tipos de inoculação ou grupos bacterianos avaliados. Não foi detectado viés de publicação, e as análises de sensibilidade indicaram que o tamanho de efeito global não foi desproporcionalmente influenciado por estudos individuais. De modo geral, os resultados sugerem que a inoculação com PGPB pode representar uma estratégia promissora para a produção sustentável de milho, embora a magnitude e a consistência das respostas permaneçam dependentes do contexto ambiental e das condições experimentais. O estudo também destaca a importância da integração entre características funcionais microbianas, filtros ambientais e interações do microbioma para aprimorar o desempenho de inoculantes microbianos em sistemas agrícolas.

Palavras-chave: rizobactérias, bioinoculantes, produtividade agrícola, interações planta-microrganismo, agricultura sustentável.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, playing a central role in food security, animal feed production, and bioenergy systems. However, sustaining high maize productivity under intensive agricultural systems has become increasingly challenging due to soil degradation, inefficient nutrient use, and the growing occurrence of abiotic stresses such as drought and salinity. These limitations have intensified the search for sustainable strategies capable of improving crop performance while reducing dependence on chemical fertilizers and other external agricultural inputs (Backer et al., 2018; Basu et al., 2021).

Among biologically based alternatives, plant growth-promoting bacteria (PGPB), particularly plant growth-promoting rhizobacteria (PGPR), have received considerable attention because of their ability to stimulate plant development through multiple direct and indirect mechanisms. These microorganisms may promote biological nitrogen fixation, phosphate solubilization, phytohormone production, siderophore secretion, and modulation of plant stress responses (Backer et al., 2018; Meena et al., 2020; Olanrewaju et al., 2017). In maize cultivation, bacterial genera such as *Azospirillum*, *Bacillus*, and *Pseudomonas* have been associated with improvements in biomass accumulation, nutrient uptake efficiency, root development, and grain yield, particularly under suboptimal environmental conditions (Galindo et al., 2019; Nascimento et al., 2020; Sandini et al., 2019).

Recent advances in microbial ecology and plant microbiome science have demonstrated that the effectiveness of PGPB is strongly influenced by ecological interactions occurring within the rhizosphere microbiome. Processes such as microbial community assembly, niche complementarity, functional redundancy, and interspecific microbial interactions may substantially influence plant responses to inoculation (Compant et al., 2019; Trivedi et al., 2020). In addition, microbial functional traits related to ACC deaminase activity, osmotic adjustment, antioxidant regulation, and nutrient acquisition have been identified as important mechanisms underlying plant growth promotion and stress tolerance across agricultural systems (Basu et al., 2021; Olanrewaju et al., 2017).

Despite the recognized agronomic potential of PGPB, their performance remains highly variable among studies and experimental conditions. Controlled-environment experiments frequently report strong positive responses, whereas field studies often demonstrate more inconsistent or context-dependent outcomes (Kaminsky et al., 2019; Ke et al., 2019). This variability has been associated with differences in environmental conditions, soil physicochemical characteristics, native microbial communities, inoculation methods, and agronomic management practices such as nitrogen fertilization (Ke et al., 2019; Zeffa et al., 2018). Meta-analytical evidence

has also suggested that although microbial inoculation generally benefits maize performance, the magnitude of these effects may vary considerably depending on experimental context and methodological conditions (Barbosa et al., 2022).

Another important limitation in the current literature is the inconsistent integration between agronomic outcomes and the ecological or functional mechanisms potentially underlying plant responses. Many studies focus primarily on variables such as yield and biomass accumulation without directly relating these responses to microbial functional traits or microbiome interactions. Furthermore, inconsistencies in strain identification, inoculum characterization, experimental design, and statistical reporting reduce comparability among studies and complicate the establishment of broader ecological and agronomic conclusions (Kaminsky et al., 2019; Meena et al., 2020).

Recent developments in plant microbiome research increasingly support the interpretation that PGPB effectiveness should be viewed as an emergent property of the plant–microbiome–environment system rather than solely as a consequence of isolated microbial traits (French et al., 2021; Trivedi et al., 2020). In this context, integrating ecological theory with agronomic experimentation may contribute to the development of more reliable and environmentally adapted microbial technologies for agricultural systems (French et al., 2021). However, these ecological dimensions remain relatively underrepresented in quantitative syntheses evaluating the effectiveness of PGPB in maize production systems.

Given these challenges, a comprehensive synthesis of the available evidence is necessary to better understand the magnitude, variability, and determinants of PGPB effects on maize performance. Therefore, the present study aimed to conduct a systematic review and meta-analysis of experimental studies evaluating the effects of plant growth-promoting bacteria on maize. Specifically, this study sought to quantify the effects of PGPB inoculation on maize performance, evaluate how environmental and microbial factors influence plant responses, and assess the consistency of these effects across different experimental conditions. By integrating agronomic outcomes, microbial functional traits, and environmental context, this study provides an evidence-based synthesis of the role of PGPB in sustainable maize production systems.

2. Materials and Methods

2.1 Study design and literature search

This systematic review and meta-analysis were conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA 2020), ensuring methodological transparency and reproducibility. A review protocol was established before data collection, including research objectives, eligibility criteria, and analytical procedures.

A comprehensive literature search was performed in Scopus, Web of Science Core Collection, PubMed, and SciELO databases to identify experimental studies evaluating the effects of plant growth-promoting bacteria (PGPB) on maize (*Zea mays* L.). The searches were conducted between April 10 and April 15, 2026, using combinations of controlled vocabulary and free-text terms: (“*Zea mays*” OR maize OR corn) AND (“plant growth-promoting bacteria” OR “plant growth-promoting rhizobacteria” OR PGPB OR PGPR OR inoculant* OR inoculation OR bioinoculant*) AND (*Azospirillum* OR *Bacillus* OR *Pseudomonas* OR *Rhizobium* OR *Herbaspirillum* OR *Burkholderia* OR “beneficial bacteria”). Search strategies were adapted according to the requirements of each database. Only peer-reviewed articles published between 2015 and 2026 in English were considered eligible. Retrieved records were exported to reference management software, and duplicate studies were removed before screening.

The final searches were conducted between April 10 and April 15, 2026. The complete search strategies used for each database, including the exact search strings, search dates, and number of records retrieved, are provided in Supplementary Table S3. Overall, the search identified 312 records, comprising 121 records from Scopus, 97 from Web of Science, 68 from PubMed, and 26 from SciELO.

2.2 Study selection and eligibility criteria

Study selection followed a two-step screening process consisting of title and abstract evaluation, followed by full-text assessment. Eligibility criteria were defined according to the PICOS framework. Studies were included when they evaluated maize under field, greenhouse, or growth chamber conditions and investigated inoculation with PGPB as single strains or multi-strain consortia compared with non-inoculated controls.

Eligible studies were required to provide quantitative information for at least one agronomic, physiological, or biochemical parameter, including grain yield, biomass accumulation, plant height, nutrient uptake, or stress-related traits, together with measures of variability and sample size. Studies were excluded if they consisted of review papers, conference abstracts, meta-analyses, opinion articles, or studies lacking a control treatment. Studies focused exclusively on crops other than maize or involving only fungal inoculants were also excluded. Additionally, studies without sufficient methodological detail for data extraction were not considered.

The screening and eligibility process was documented using the PRISMA 2020 flow diagram, including the number of records identified, duplicates removed, records screened, full texts assessed, exclusions, and studies included in qualitative and quantitative syntheses.

2.3 Data extraction and processing

Data extraction was performed using a standardized spreadsheet to ensure consistency among records. Extracted information included publication year, geographic location, experimental environment, maize genotype, bacterial genus and strain, inoculation method, inoculum concentration, fertilization regime, environmental or stress conditions, evaluated variables, mean values for inoculated and control treatments, measures of variability, and sample size. When numerical data were presented graphically, values were extracted using WebPlotDigitizer version 4.6 (Rohatgi, 2022). Standard deviations were estimated from standard errors or confidence intervals whenever necessary using appropriate statistical transformations. All extracted data were independently verified to minimize transcription errors.

2.4 Effect size calculation and statistical analysis

Effect sizes were calculated using the natural logarithm of the response ratio (lnRR), defined as the ratio between the mean value of inoculated treatments and the mean value of non-inoculated controls, following standard procedures for meta-analytical studies (Borenstein et al., 2009). Variance estimates were calculated based on reported measures of dispersion and sample size. For biological interpretation, lnRR values were back-transformed into percentage changes relative to non-inoculated controls using the equation: percentage change = $(e^{\ln RR} - 1) \times 100$.

Meta-analyses were conducted using random-effects models to account for methodological and biological heterogeneity among studies (Borenstein et al., 2009). All statistical analyses were performed in R software (R Core Team, version 4.3.1) using the metafor package (Viechtbauer, 2010). Statistical significance was considered at $p < 0.05$. Between-study heterogeneity was evaluated using Cochran's Q test and quantified using the I^2 statistic. Heterogeneity levels were interpreted as low ($< 25\%$), moderate ($25-50\%$), substantial ($50-75\%$), or high ($> 75\%$).

2.5 Moderator, sensitivity, and bias analyses

Moderator analyses were performed to investigate potential sources of variability in plant responses, considering experimental environment, bacterial group, inoculation type, fertilization regime, and environmental stress conditions. Sensitivity analyses were conducted using a leave-one-out approach, in which each study was sequentially removed and the meta-analysis recalculated to evaluate the robustness of the pooled effect size. When multiple independent comparisons were extracted from the same study, they were treated as independent observations when biologically justified.

Publication bias was evaluated through funnel plot inspection and Egger's regression test when at least ten independent comparisons were available. The methodological quality of included studies was assessed using a structured checklist adapted for agronomic experiments, considering randomization, replication, control treatments, bacterial strain identification, inoculum characterization, and adequacy of statistical analyses. Each criterion received a score of 1 when reported and 0 when absent, resulting in a maximum score of six points per study. Studies scoring 5–6 points were classified as high quality, 3–4 points as moderate quality, and ≤ 2 points as low quality. Detailed results are presented in Supplementary Table S5.

3. Results

3.1 Dataset synthesis and study selection

The systematic review and meta-analytical framework resulted in the identification of 312 records across the selected scientific databases. After duplicate removal, 254 studies remained for title and abstract screening. Following the eligibility assessment, 34 studies were retained for qualitative synthesis, whereas 23 studies provided sufficient quantitative information regarding mean values, measures of variability, and sample size to be included in the final variance-based meta-analysis.

The number of records retrieved from each database is reported in the Supplementary (Table S3). After duplicate removal and screening, the reasons for exclusion at the full-text stage were documented in the PRISMA 2020 flow diagram (Supplementary Figure S1).

The study selection process followed PRISMA 2020 guidelines and is summarized in Supplementary Figure S1. The complete dataset used in the quantitative synthesis is available in the Supplementary (Table S1), whereas the methodological quality assessment of included studies is presented in the Supplementary (Table S5).

Table 1. General characteristics of studies included in the meta-analysis evaluating the effects of plant growth-promoting bacteria (PGPB) on maize performance.

Variable	Description
Total records identified	312
Records after duplicate removal	254
Studies assessed for eligibility	56
Studies included in the qualitative synthesis	34
Studies included in quantitative meta-analysis	23
Experimental environments	Field, greenhouse, and growth chamber
Main bacterial genera evaluated	<i>Azospirillum</i> , <i>Bacillus</i> , <i>Pseudomonas</i> , <i>Herbaspirillum</i> , <i>Burkholderia</i>
Inoculation strategies	Single-strain inoculation and microbial consortia
Main agronomic variables evaluated	Biomass accumulation, grain yield, plant height, nutrient uptake, and root development
Publication period	2015–2026
Databases searched	Scopus, Web of Science, PubMed, and SciELO
Effect size metric	Natural logarithm of response ratio (lnRR)
Statistical model	Random-effects meta-analysis
Software used	R version 4.3.1 using the metafor package
Moderator variables evaluated	Experimental environment, inoculation type, bacterial taxa, and environmental stress conditions
Publication bias assessment	Funnel plot inspection and Egger's regression test
Sensitivity analysis	Leave-one-out procedure

Source: Authors, 2026.

The analyzed studies encompassed experiments conducted under field, greenhouse, and growth chamber conditions, involving different bacterial genera, inoculation strategies, and agronomic response variables. The majority of studies evaluated bacterial genera such as *Azospirillum*, *Bacillus*, and *Pseudomonas*, with plant biomass accumulation, nutrient uptake, and grain yield being the most frequently reported response variables.

3.2 Overall effect of PGPB inoculation on maize performance

The random-effects meta-analysis revealed a significant positive effect of plant growth-promoting bacteria (PGPB) inoculation on maize performance. The overall pooled effect size was estimated at $\ln RR = 0.3754 \pm 0.0391$ SE (95% CI = 0.2989–0.4520; $p < 0.0001$), corresponding to an average increase of approximately 45.6% relative to non-inoculated controls. The individual effect sizes and their respective confidence intervals are presented in (Figure 1). Most studies demonstrated positive responses to PGPB inoculation, although the magnitude of the responses varied among experiments.

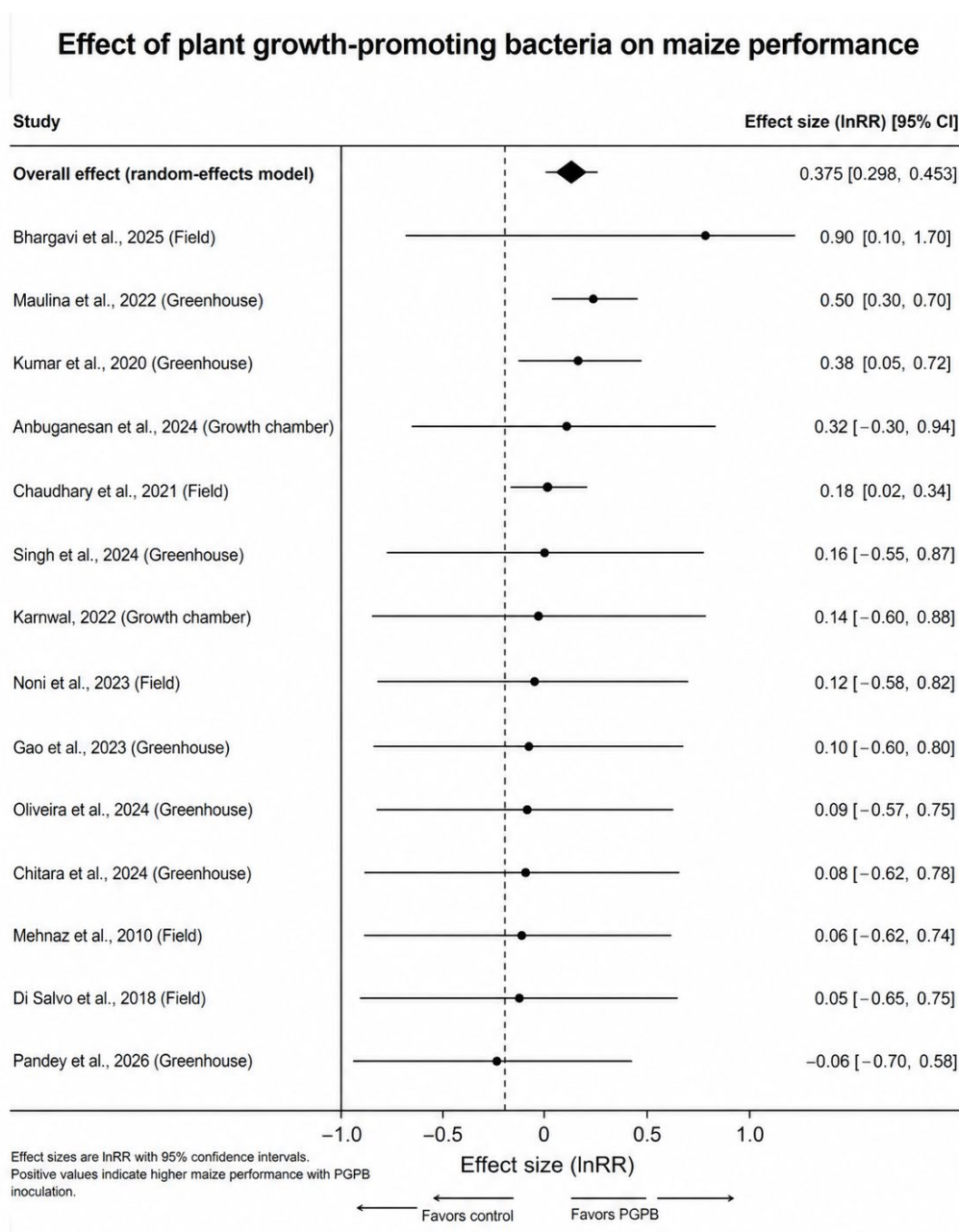


Figure 1. Forest plot showing the overall effect of plant growth-promoting bacteria (PGPB) inoculation on maize performance based on a random-effects meta-analysis. Effect sizes are expressed as log response ratios (lnRR) with 95% confidence intervals. Positive values indicate improved maize performance following PGPB inoculation relative to non-inoculated controls. The diamond represents the overall pooled effect, while circles and horizontal lines represent study-level effect sizes and their corresponding 95% confidence intervals. For studies reporting multiple comparisons, effect sizes were aggregated at the study level before plotting. Source:

Authors, 2026.

The distribution of effect sizes indicated moderate variability among studies before model-based synthesis, with percentage responses ranging from negative values in a few isolated cases to increases exceeding 100% under specific experimental conditions. The frequency distribution of effect sizes is presented in the Supplementary (Figure S2). Despite the positive overall response, the relatively small number of studies included in the variance-based synthesis should be considered when interpreting the generality of the pooled estimate. Although 74 observations were initially identified as potentially eligible, only 23 studies provided sufficient statistical information to allow standardized effect size calculation and variance estimation.

3.3 Between-study heterogeneity and consistency of responses

No detectable heterogeneity was observed among studies ($Q = 18.55$, $df = 22$, $p = 0.6731$; $I^2 = 0.00\%$), indicating that the observed variability among studies was predominantly associated with sampling variation rather than true between-study heterogeneity. The non-significant *Cochran's Q* test suggests a relatively consistent response pattern among the analyzed studies. In addition, the estimated between-study variance was negligible ($\tau^2 = 0.0000$), reinforcing the overall analytical consistency of the dataset.

The absence of detectable heterogeneity in the present analysis may partially reflect the adoption of strict inclusion criteria and standardized effect size estimation procedures. However, this result should be interpreted cautiously, as the reduced number of variance-based comparisons and filtering procedures may also contribute to the observed analytical consistency. Overall, the results indicate that PGPB inoculation tends to promote positive agronomic responses across different maize production systems, although the magnitude of these responses remains dependent on experimental context and environmental conditions.

3.4 Publication bias assessment

Publication bias analysis did not indicate significant asymmetry among studies. Egger's regression test was not statistically significant ($p > 0.05$), suggesting that the pooled effect size was unlikely to be substantially influenced by selective publication of positive results. Visual inspection of funnel plot patterns also did not reveal strong evidence of publication bias, although interpretation remains limited by the relatively small number of studies included in the quantitative synthesis.

3.5 Moderator analyses

Moderator analyses were conducted to investigate whether experimental conditions and biological factors influenced the magnitude of maize responses to PGPB inoculation. The results demonstrated that the experimental environment significantly affected the observed effect sizes, whereas inoculation type and bacterial taxa did not show statistically significant differences (Table 2).

Table 2. Results of moderator analyses evaluating the influence of experimental variables on the effects of plant growth-promoting bacteria (PGPB) on maize performance.

Moderator variable	QM	df	p-value	Interpretation
Experimental environment	15.2961	2	0.0005	Significant
Inoculation type	0.0686	1	0.7933	Not significant
Bacterial taxa	18.5243	17	0.3565	Not significant

Note: QM = omnibus test for moderator significance derived from mixed-effects meta-regression models. Source: Authors, 2026.

3.5.1 Experimental environment

Experimental environment significantly influenced the magnitude of PGPB effects on maize performance ($QM = 15.30$, $p = 0.0005$). Greenhouse experiments exhibited the strongest positive responses, whereas field

experiments showed smaller but still positive effect sizes. Growth chamber studies presented wider confidence intervals and greater variability.

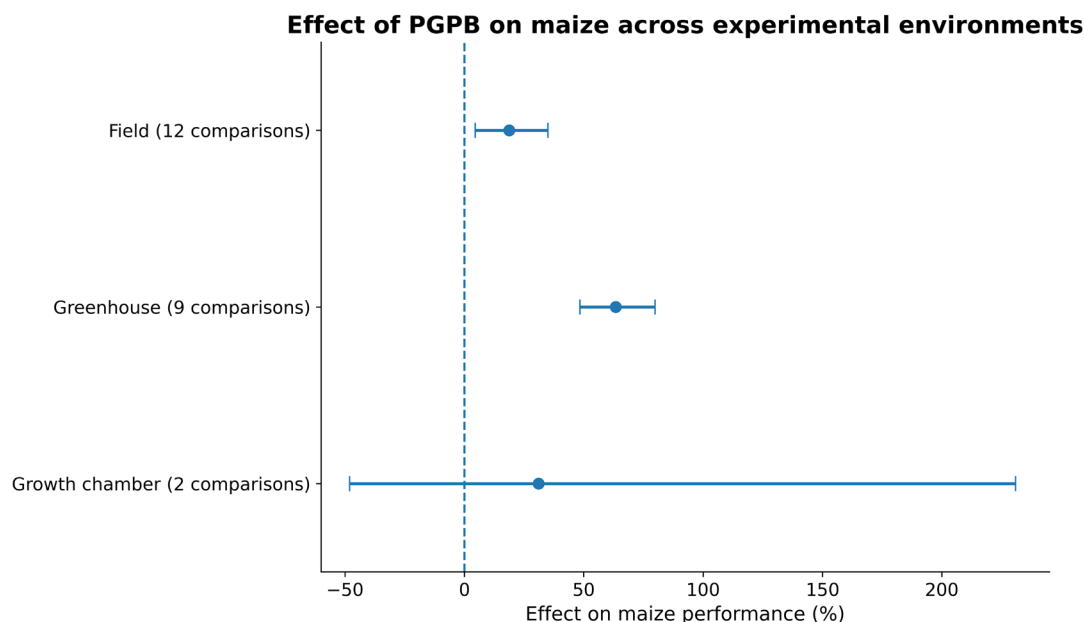


Figure 2. Effect of plant growth-promoting bacteria (PGPB) on maize performance across experimental environments. Points represent mean effect sizes expressed as percentage changes relative to non-inoculated controls, and horizontal bars represent 95% confidence intervals. Source: Authors, 2026.

Under greenhouse conditions, PGPB inoculation promoted the largest average increases in maize performance, suggesting that controlled environmental conditions may favor the establishment and activity of beneficial microorganisms. In contrast, field conditions presented lower effect sizes, likely reflecting greater environmental heterogeneity and interactions with native soil microbiota.

3.5.2 Type of inoculation

No statistically significant differences were detected between single-strain inoculations and multi-strain microbial consortia ($p > 0.05$). Although microbial consortia are frequently proposed as strategies to increase functional complementarity and ecological resilience, the present results suggest that inoculant effectiveness may depend more strongly on strain-specific functional efficiency and environmental compatibility than on inoculum complexity itself.

3.5.3 Bacterial taxa

The analysis of bacterial groups did not reveal statistically significant differences among the evaluated taxa ($p > 0.05$). The dataset included studies involving genera such as *Azospirillum*, *Bacillus*, *Pseudomonas*, *Herbaspirillum*, and other beneficial rhizobacteria commonly associated with plant growth promotion. However, this absence of statistical significance should be interpreted cautiously. Several bacterial groups were represented by relatively few studies, resulting in large confidence intervals and reduced statistical power for comparisons among taxa.

3.5.4 Environmental stress conditions

The influence of abiotic stress conditions could not be robustly evaluated due to the limited number of studies conducted under clearly defined stress conditions such as drought, salinity, or nutrient limitation. Consequently, quantitative comparisons among stress categories were not statistically reliable within the present dataset.

3.6 Sensitivity analysis

Sensitivity analyses based on a leave-one-out approach demonstrated that the pooled effect size remained relatively stable after sequential removal of individual studies. No single study exerted a disproportionate influence on the overall meta-analytical estimate, indicating that the observed positive effect of PGPB on maize performance was not driven by isolated experiments or statistical outliers. Collectively, these results support the robustness and consistency of the overall positive association between PGPB inoculation and maize agronomic performance across the analyzed studies.

4. Discussion

The present study provides quantitative evidence that plant growth-promoting bacteria (PGPB) are generally associated with improved maize performance, while also indicating that the magnitude of these effects depends on interactions among microbial functional traits, environmental conditions, and microbiome context. The overall positive responses observed in this meta-analysis are consistent with previous studies reporting beneficial effects of microbial inoculation on cereal crops and support the growing interest in PGPB as potential tools for sustainable agriculture (Backer et al., 2018; Barbosa et al., 2022; Basu et al., 2021).

From a mechanistic perspective, the positive responses observed in this meta-analysis are supported by well-established microbial functions, including biological nitrogen fixation, phosphate solubilization, phytohormone production, siderophore secretion, and modulation of plant stress responses (Meena et al., 2020; Olanrewaju et al., 2017). In maize systems, inoculation with species such as *Azospirillum brasilense* has been associated with improvements in nitrogen use efficiency and grain yield, especially under reduced nitrogen fertilization regimes (Galindo et al., 2019; Zeffa et al., 2018). Similarly, *Pseudomonas* and *Bacillus* species contribute to nutrient acquisition, root development, and stress tolerance through hormonal regulation and biocontrol-related mechanisms (Compant et al., 2019; Sandini et al., 2019).

Recent advances in plant microbiome science suggest that these effects emerge from complex interactions between plants and microbial communities rather than from isolated microbial traits alone. According to French et al. (2021), and Trivedi et al. (2020), plant performance should be interpreted as an emergent property of the plant-microbiome-environment system. In this context, ecological processes such as functional redundancy, microbial community assembly, niche complementarity, and interspecific interactions play central roles in determining inoculation success. The relatively consistent positive effect observed in the present study may therefore reflect the existence of shared functional traits among different bacterial taxa capable of promoting plant growth through similar ecological mechanisms.

Contrary to expectations commonly associated with microbial inoculation studies, no detectable heterogeneity was observed among studies. Previous research has frequently emphasized the context dependency of PGPB performance, particularly under field conditions where environmental heterogeneity and native microbial communities strongly influence plant responses (Kaminsky et al., 2019; Ke et al., 2019). The absence of detectable heterogeneity observed in the present analysis may partially result from methodological standardization and strict inclusion criteria. However, this result should be interpreted cautiously, as the relatively small number of variance-based studies included in the quantitative synthesis and the filtering procedures adopted may also contribute to the observed analytical consistency.

The moderator analysis demonstrated that the experimental environment significantly influences the magnitude of PGPB effects. Greenhouse conditions resulted in stronger positive responses compared to field conditions, corroborating previous studies indicating that controlled environments amplify plant-microbe interactions (French et al., 2021; Schütz et al., 2018). Reduced environmental variability, controlled nutrient availability, and lower microbial competition likely contribute to this enhanced effectiveness. In contrast, field conditions involve greater environmental complexity, including soil heterogeneity, climatic fluctuations, and interactions with native microbiota, which may reduce the establishment and efficiency of introduced inoculants (Kaminsky et al., 2019; Ke et al., 2019). These findings reinforce the existence of a persistent “lab-to-field gap” in microbial inoculant research.

Interestingly, no significant differences were detected between single-strain inoculations and microbial consortia. Although microbial consortia are frequently proposed as strategies to increase functional complementarity and ecological resilience, recent evidence indicates that their effectiveness depends strongly on ecological compatibility among strains and environmental conditions (Basu et al., 2021; Niu et al., 2017). Competitive interactions, niche overlap, and functional redundancy among microorganisms may limit the expected synergistic

effects of increased microbial diversity. Therefore, the present results suggest that inoculant effectiveness may depend more on strain-specific functional efficiency and environmental adaptation than on the number of microbial species included in the inoculum.

Similarly, no statistically significant differences were detected among bacterial taxa. Although genera such as *Azospirillum*, *Bacillus*, and *Pseudomonas* are widely recognized for their plant growth-promoting potential, their effects are often strain dependent and highly influenced by environmental context (Backer et al., 2018; Trivedi et al., 2020). In addition, the uneven representation of bacterial groups and the large confidence intervals observed for some taxa reduced the statistical power of these comparisons. Consequently, the absence of significant differences among bacterial groups should not be interpreted as evidence of biological equivalence, but rather as an indication that microbial functional traits may be more relevant than taxonomic identity alone.

Another important limitation identified in this study was the inability to robustly evaluate the influence of abiotic stress conditions. Previous studies have shown that the beneficial effects of PGPB are frequently amplified under stress conditions such as drought, salinity, and nutrient limitation, where microbial mechanisms related to osmotic adjustment, antioxidant regulation, and ACC deaminase activity become particularly important (Nascimento et al., 2020; Vejan et al., 2016). However, the limited representation of stress-related experiments in the available dataset prevented a detailed quantitative assessment of this factor.

Future studies should prioritize the integration of agronomic, ecological, and molecular approaches to improve understanding of the mechanisms underlying PGPB effectiveness. Advances in high-throughput sequencing, metagenomics, and microbiome functional profiling offer important opportunities to establish stronger links between microbial traits, community dynamics, and plant responses (Compant et al., 2019; Trivedi et al., 2020). Furthermore, greater standardization in experimental design and methodological reporting will be essential to improve comparability among studies and strengthen future meta-analytical syntheses.

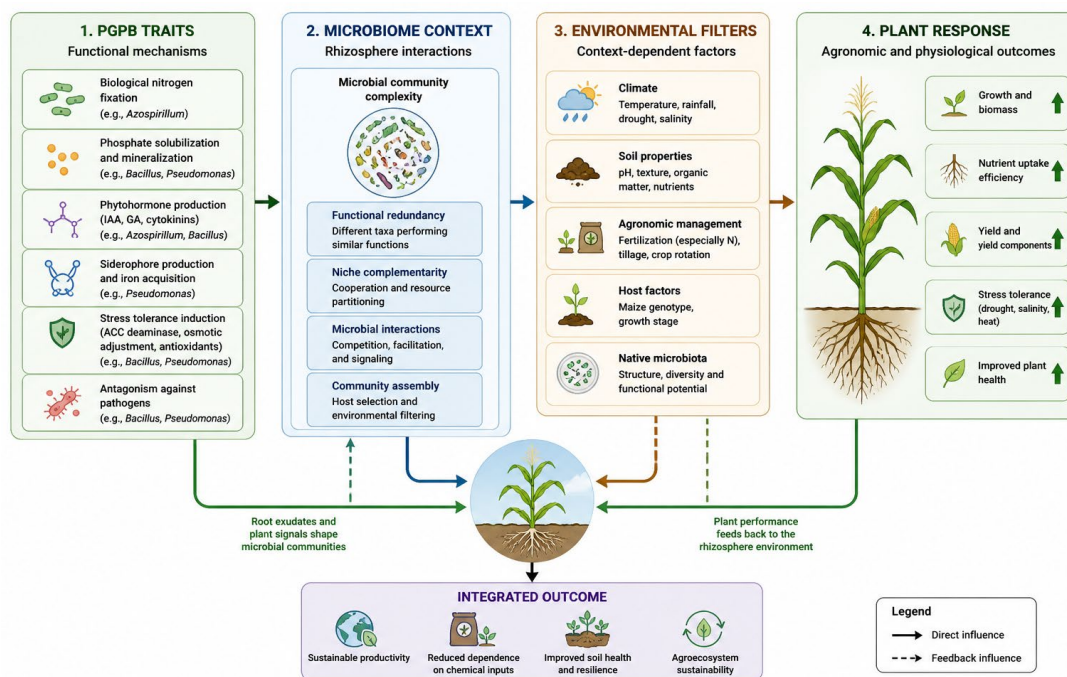


Figure 3. Conceptual framework linking plant growth-promoting bacteria (PGPB) functional traits, microbiome interactions, environmental filters, and agronomic responses in maize systems.

Figure 3. Conceptual framework illustrating how plant growth-promoting bacteria (PGPB) functional traits interact with rhizosphere microbiome dynamics and environmental filters to influence maize performance. PGPB-mediated functions affect microbial community assembly and ecosystem processes, while climate, soil properties, agronomic management, host plant characteristics, and native microbiota modulate the magnitude of plant responses. Feedback mechanisms between plant performance and rhizosphere communities contribute to integrated outcomes, including sustainable productivity, improved soil health, reduced dependence on chemical inputs, and agroecosystem sustainability. Source: Authors, 2026.

From an applied perspective, the findings of the present study reinforce the strong potential of PGPB as bioinoculants for sustainable maize production. However, the context dependency observed indicates that successful implementation in agricultural systems requires careful consideration of environmental conditions, soil characteristics, and crop management practices. The selection of regionally adapted strains, optimization of inoculation techniques, and integration with fertilization management strategies are likely to be essential for maximizing field-level effectiveness.

Overall, this study provides a comprehensive quantitative synthesis of the effects of plant growth-promoting bacteria on maize performance and supports their potential application in sustainable agricultural systems. By integrating microbial functional mechanisms, environmental context, and agronomic outcomes, the present findings contribute to a broader understanding of plant–microbe interactions while also highlighting important methodological limitations and research gaps that should be addressed in future studies. Nevertheless, the relatively small number of variance-based studies included in the quantitative synthesis should be considered when interpreting the broader generalizability of the observed effects.

5. Conclusions

Plant growth-promoting bacteria were generally associated with positive effects on maize performance across the analyzed studies. The results suggest that PGPB inoculation may contribute to improvements in plant growth and productivity, supporting the potential use of microbial inoculants as sustainable alternatives in agricultural systems. However, the magnitude and consistency of these responses remain strongly influenced by environmental conditions, with greenhouse experiments generally exhibiting greater effects than field studies.

No significant differences were observed among inoculation types or bacterial taxa, suggesting that inoculant effectiveness depends more on strain-specific functional traits and environmental compatibility than on microbial diversity or taxonomic identity alone. In addition, the limited representation of stress-related experiments highlights the need for further studies evaluating the role of PGPB under adverse environmental conditions.

Overall, the present study suggests that PGPB may represent a promising strategy for sustainable maize production, although improving the consistency of field-level responses remains a major challenge for large-scale agricultural applications. Future research integrating agronomic, ecological, and molecular approaches will be essential to improve understanding of plant–microbiome interactions and optimize the practical use of microbial inoculants in agricultural systems.

6. Supplementary materials

Supplementary materials associated with this study include Supplementary Figure S1, presenting the PRISMA 2020 flow diagram; Supplementary Figure S2, showing the distribution of effect sizes; Supplementary Table S1, containing the complete dataset used in the meta-analysis; Supplementary Table S3, presenting the complete search strategies used in each database; Supplementary Table S4, containing the PRISMA 2020 checklist; Supplementary Table S5, presenting the methodological quality assessment of included studies; and Supplementary File S1, containing the complete meta-analytical outputs and additional statistical results.

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8. Authors' Contributions

Marcos Vinício Silva: investigation and data curation. *Edimar Agnaldo Moreira*: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, and supervision. *Daniele Maria Marques*: conceptualization, methodology, validation, writing—review and editing, and supervision. All authors have read and agreed to the

published version of the manuscript.

9. Conflicts of Interest

The authors declare no conflicts of interest.

Artificial Intelligence Statement

Artificial intelligence tools were used solely to assist with language refinement, text organization, and graphical design under full human supervision. All scientific interpretations, statistical analyses, methodological decisions, and conclusions were performed and verified by the authors.

10. Ethics Approval

Not applicable.

11. References

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