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PLANT GROWTH-PROMOTING BACTERIA USED IN MAIZE CULTIVATION: A SYSTEMATIC LITERATURE REVIEW (2015–2025)

BACTÉRIAS PROMOTORAS DE CRESCIMENTO DE PLANTAS UTILIZADAS NA CULTURA DO MILHO: UMA REVISÃO SISTEMÁTICA DA LITERATURA (2015-2025)

BACTERIAS PROMOTORAS DEL CRECIMIENTO VEGETAL UTILIZADAS EN EL CULTIVO DE MAÍZ: UNA REVISIÓN SISTEMÁTICA DE LA LITERATURA (2015-2025)

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ABSTRACT

Maize (*Zea mays* L.) is one of the most economically important cereals worldwide, contributing significantly to the economies of many countries. Its production model relies heavily on synthetic fertilizers, which contribute to environmental degradation. Plant growth-promoting bacteria (PGPB) are among the sustainable alternatives used to partially replace these inputs, as they can enhance maize growth by optimizing nutrient uptake, increasing disease resistance, and promoting soil health. This study aimed to synthesize information from the last ten years (2015–2025) regarding PGPB applied to maize cultivation. Searches were conducted across five databases—PubMed, ScienceDirect, Scopus, Web of Science, and LILACS—identifying 1,333 articles. After the screening process, 65 articles were included in the review. The included studies were predominantly conducted in two countries: Brazil and China. The most frequently reported bacterial species were *Bacillus subtilis* (27%), *Azospirillum brasilense* (23%), and *Pseudomonas fluorescens* (12%). Among the functional traits, phytohormone production was the most frequent (75%), followed by biological nitrogen fixation (49%), phosphate solubilization (48%), and siderophore production (32%). Biofilm production (8%) was the least frequent trait. Classifying the articles by biostimulation category revealed that the assessment of growth and yield parameters (95%) predominated, whereas abiotic stress tolerance (22%) and biocontrol and crop protection (18%) were less frequent. This review demonstrates that several genera of plant growth-promoting bacteria have been proportionally under-studied in the field over the last

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decade, highlighting potential knowledge gaps regarding their effects on physiological and yield parameters in maize crops, particularly in the face of stress and global climate challenges.

Keywords: *Zea mays. Bacillus*. Sustainable Agriculture. Productivity. Yield.

RESUMO

O milho (*Zea mays* L.) é um dos cereais mais importantes economicamente em todo o mundo, contribuindo significativamente para as economias de muitos países. Seu modelo de produção depende de fertilizantes sintéticos que favorecem a degradação ambiental. As bactérias promotoras do crescimento vegetal estão entre as alternativas sustentáveis utilizadas para substituir parcialmente esses insumos, podendo melhorar o crescimento do milho por meio da otimização da absorção de nutrientes, aumento da resistência a doenças e promoção da saúde do solo. Este estudo teve como objetivo reunir informações dos últimos dez anos (2015-2025) sobre bactérias promotoras de crescimento utilizadas na cultura do milho. Foram realizadas buscas em cinco bases de dados: PubMed, ScienceDirect, Scopus, Web of Science e LILACS, onde foram identificados 1.333 artigos. Após a avaliação, 65 artigos foram incluídos na revisão. As referências estão distribuídas predominantemente em dois países, sendo eles Brasil e China. As espécies bacterianas mais frequentes foram *Bacillus subtilis* (27%), *Azospirillum brasilense* (23%) e *Pseudomonas fluorescens* (12%). Entre as características funcionais das bactérias, a produção de fitohormônios foi a mais frequente (75%), seguida pela fixação biológica de nitrogênio (49%), solubilização de fosfatos (48%) e produção de sideróforos (32%). A produção de biofilme (8%) foi a característica menos frequente. A classificação dos artigos de acordo com as categorias de bioestimulação promovidas pelas bactérias relatadas revelou que a avaliação de parâmetros de crescimento e produtividade (95%) foi predominante enquanto tolerância a estresses abióticos (22%) e biocontrole e proteção (18%) foram menos frequentes. Esta revisão revelou que diversos gêneros de bactérias promotoras de crescimento de plantas foram proporcionalmente pouco estudados em campo nos últimos dez anos, evidenciando possíveis lacunas de conhecimento sobre os seus efeitos nos parâmetros produtivos e fisiológicos na cultura do milho, principalmente diante de estresses e desafios climáticos globais.

Palavras-chave: *Zea Mays*. *Bacillus*. Agricultura Sustentável. Produtividade. Rendimento.

RESUMEN

El maíz (*Zea mays* L.) es uno de los cereales de mayor importancia económica a nivel mundial, contribuyendo significativamente a las economías de muchos países. Su modelo de producción depende de fertilizantes sintéticos que favorecen la degradación ambiental. Las bacterias promotoras del crecimiento vegetal se encuentran entre las alternativas sostenibles utilizadas para reemplazar parcialmente estos insumos, mejorando potencialmente el crecimiento del maíz mediante la optimización de la absorción de nutrientes, el aumento de la resistencia a enfermedades y la promoción de la salud del suelo. Este estudio tuvo como objetivo recopilar información de los últimos diez años (2015-2025) sobre las bacterias promotoras del crecimiento vegetal utilizadas en el cultivo de maíz. Se realizaron búsquedas en cinco bases de datos: PubMed, ScienceDirect, Scopus, Web of Science y LILACS, donde se identificaron 1333 artículos. Tras la evaluación, se incluyeron 65 artículos en la revisión. Los estudios incluidos se distribuyen predominantemente en dos países: Brasil y China. Las especies bacterianas más frecuentes fueron *Bacillus subtilis* (27%), *Azospirillum brasilense* (23%) y *Pseudomonas fluorescens* (12%). Entre las características funcionales de las bacterias, la producción de fitohormonas fue la más frecuente (75%), seguida de la fijación biológica de nitrógeno (49%), la solubilización de fosfatos (48%) y la producción de sideróforos (32%). La producción de biopelículas (8%) fue la característica menos frecuente. La clasificación de los artículos según las categorías de bioestimulación reveló que la evaluación de parámetros de crecimiento y rendimiento (95%) fue predominante, mientras que la tolerancia a estreses abióticos (22%) y el biocontrol y la protección (18%) fueron menos frecuentes. Esta revisión reveló que varios géneros de bacterias promotoras del crecimiento vegetal han sido proporcionalmente poco estudiados en el campo en los últimos diez años, lo que resalta posibles lagunas de conocimiento sobre sus efectos en los parámetros de rendimiento y fisiológicos en el cultivo de maíz, especialmente frente a los estreses y desafíos climáticos globales.

Palabras clave: *Zea Mays*; *Bacillus*; Agricultura soStenible. Productividad. Rendimiento.

INTRODUCTION

Maize (Zea mays L.) is one of the most important cereals in the world, being essential for food security (Albahri *et al.*, 2023), animal production (Gunjević *et al.*, 2023; Karnatam *et al.*, 2023), and as a raw material for various industrial sectors (Zhang *et al.*, 2021; Jiao *et al.*, 2022). Global production is led by the United States, China, and Brazil, which reflects the economic relevance of this crop (USDA, 2026). On the other hand, conventional maize production heavily relies on chemical fertilizers (Kong *et al.*, 2022). The continuous use of these inputs has contributed to significant environmental impacts, such as soil degradation, water resource contamination, and increased greenhouse gas emissions (Kopittke *et al.*, 2025). This makes it necessary to adopt sustainable alternatives to reconcile high productivity with minimal environmental impact.

Plant growth-promoting bacteria (PGPB) represent a viable alternative for sustainable agriculture (Kumari *et al.*, 2023). These microorganisms exert several positive effects on plants through direct and indirect mechanisms (Hasan *et al.*, 2024), including the production of phytohormones (Orozco-Mosqueda *et al.*, 2023), phosphate solubilization (Timofeeva *et al.*, 2022), and biological nitrogen fixation (Aasfar *et al.*, 2024). They can also synthesize siderophores (Sun *et al.*, 2022) and induce systemic resistance against phytopathogens (Yang *et al.*, 2023). Several bacterial strains from this group have demonstrated potential for mitigating abiotic stresses, such as drought and salinity (Gupta *et al.*, 2022), conditions that are increasingly frequent due to global climate change (Bouabdelli *et al.*, 2022; Khamidov *et al.*, 2022).

The use of these bacteria in maize cultivation has been widely investigated, primarily under field conditions, to evaluate direct impacts on productivity (Ocwa *et al.*, 2024), biomass, and grain yield (Galindo *et al.*, 2022). Species of Bacillus, Azospirillum, and Pseudomonas are widely reported due to their functional versatility, broad environmental distribution, and ease of bioinoculant formulation. Despite this, most studies focus on immediate agronomic responses, with little attention given to aspects related to grain nutritional quality, yield stability under stress, and the diversification of explored bacterial genera.

Systematic reviews help synthesize available knowledge, reveal temporal trends, and point out scientific gaps that require further research. This study aimed to conduct a systematic literature review published between 2015 and 2025 regarding the use of growth-promoting bacteria in maize cultivation. The research focused on field experiments, analyzing the temporal and geographic distribution of studies, the main bacterial genera and species investigated, as well as functional traits and biostimulation categories.

METHODOLOGY

This study is a systematic review following the guidelines proposed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher *et al.*, 2010; Page *et al.*, 2021). Data collection was conducted through searches in five different international electronic databases: PubMed, ScienceDirect, Scopus, Web of Science, and Latin American and Caribbean Health Sciences Literature (LILACS). The search was limited to English-language articles published between 2015 and 2025, using a combination of the following keywords and Boolean operators: (Zea mays OR maize OR corn) AND (plant growth-promoting rhizobacteria OR PGPR OR plant growth-promoting bacteria) AND (growth OR yield OR productivity OR biomass OR dry weight OR plant height OR germination OR improve OR salt tolerance OR drought tolerance OR stress tolerance).

The article inclusion criteria were: research studies; application of individual bacteria or bacterial consortia; and analysis of the effects of bacteria on maize growth, development, and productivity. The exclusion criteria were: review articles, book chapters, and studies involving microorganisms other than bacteria.

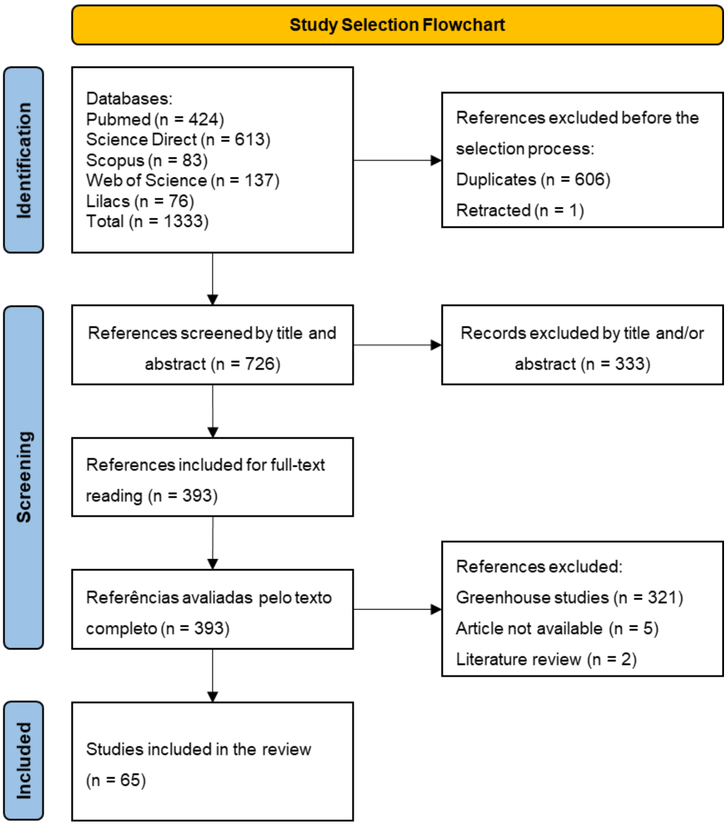
The screening process consisted of evaluating titles and abstracts, followed by the full-text reading of potentially eligible studies, performed independently by two reviewers. The selected articles were analyzed, and a data matrix was built using Microsoft Excel 2021 software (Microsoft Corporation, USA), incorporating information such as title, authors, publication year, country of origin, inoculated bacteria, reported functional traits, and observed plant biostimulant effects, to subsequently organize them into graphs and tables for comparative analysis, following approaches used in systematic reviews in the field (Diniz *et al.*, 2024).

RESULTS

The search for articles in the PubMed, ScienceDirect, Scopus, Web of Science, and LILACS databases resulted in the identification of 1,333 records (Figure 1). After removing 606 duplicates and one retracted article, 726 references remained for title and abstract screening. At this stage, 333 records were excluded for failing to meet the inclusion criteria, leaving 393 articles for full-text evaluation.

During the detailed analysis, 328 studies were excluded: 321 because they were conducted exclusively in greenhouses, five due to the unavailability of the full text, and two because they were literature reviews. At the end of the process, 65 studies fully met the inclusion criteria and were considered for this systematic review.

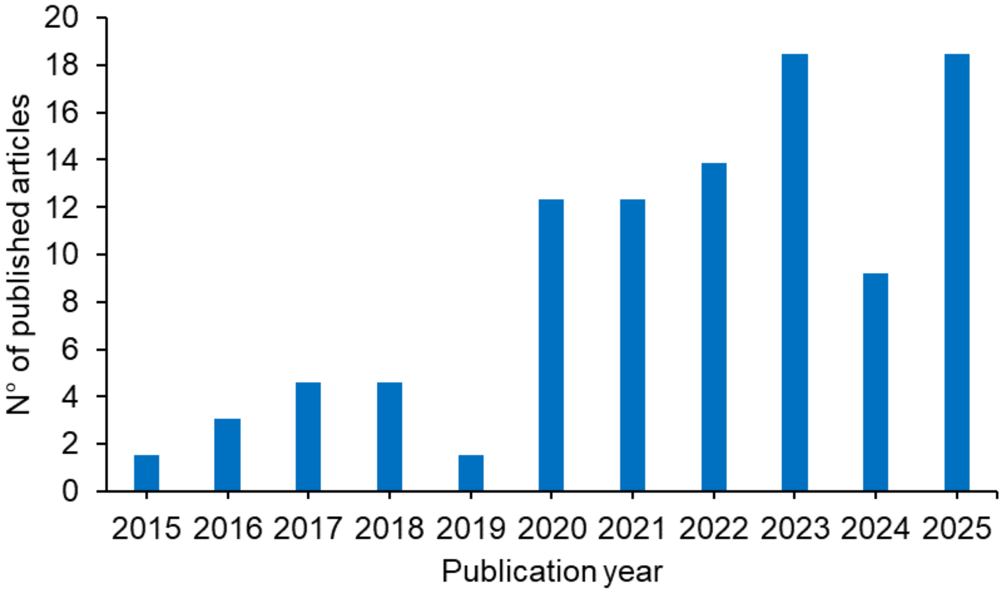
Figure 1 Study selection and screening flowchart



Source: Prepared by the authors.

The temporal distribution of studies experimentally evaluating the effects of PGPB on maize revealed a progressive increase in the number of publications over the analyzed period (Figure 2). Between 2015 and 2019, the representation of studies was low, with annual figures remaining below 5%. From 2020 onwards, a significant rise in the number of articles was observed, particularly in 2023 and 2025, which accounted for the largest proportions of publications.

Figure 2 - Temporal distribution of selected articles by year of publication

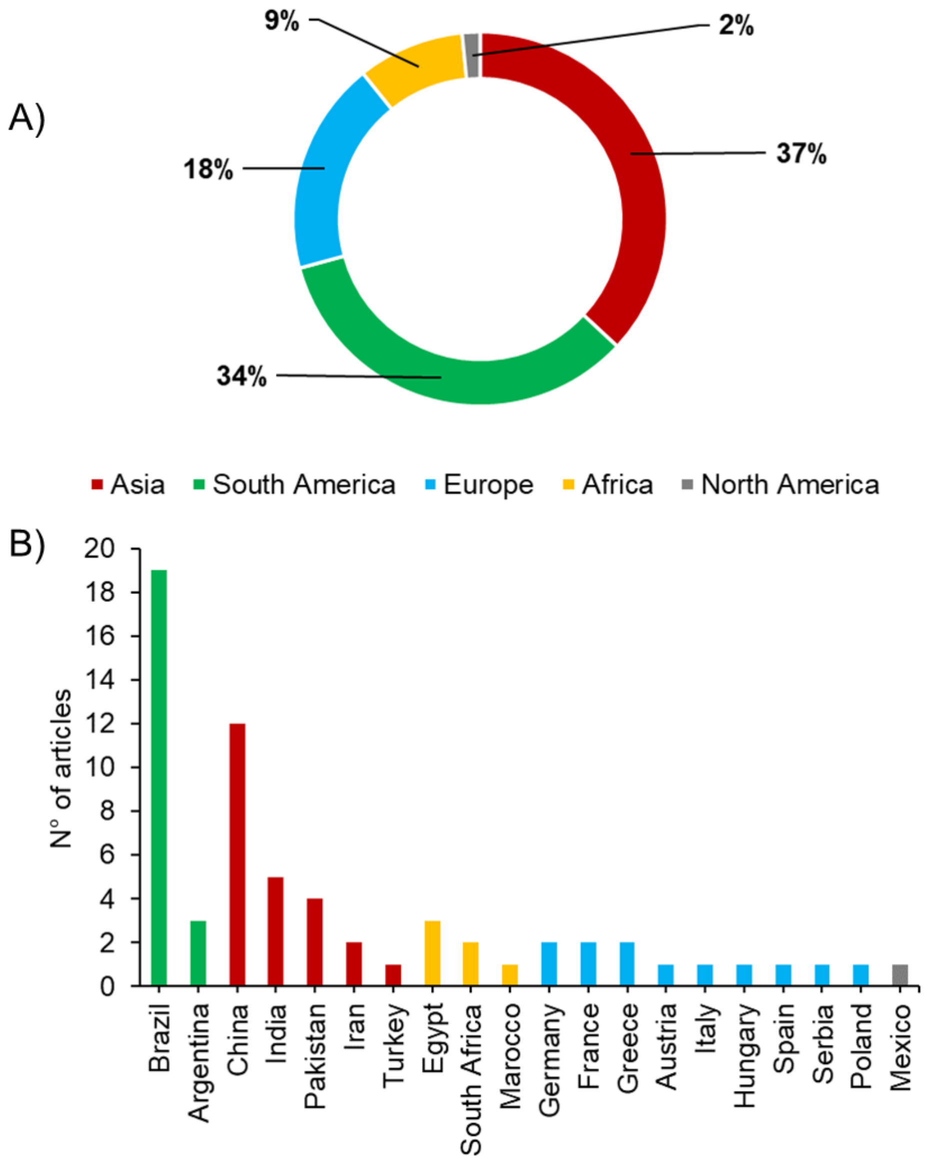


Source: Prepared by the authors.

The geographic distribution of the selected articles revealed that a larger proportion of studies was conducted in Asia, accounting for 37% of the total surveyed (Figure 3A). South America follows closely, representing 34% of the publications, highlighting the region's significant contribution to applied studies involving plant growth-promoting bacteria. Europe represented 18% of the included articles, while Africa accounted for 9% of the publications. North America showed the lowest relative frequency, with only 2% of the included studies.

The distribution of the selected articles by country revealed a strong concentration of scientific output in a limited number of locations (Figure 3B). Brazil stood out as the country with the highest number of publications, totaling 19 articles. In Asia, China and India were strongly represented, with 12 and five articles, respectively. In Europe, the studies are distributed across different countries, with higher frequency in Germany, France, and Greece, whereas in Africa, a concentration was observed in South Africa and Egypt. North America showed low representation, with only Mexico having an article included. These results suggest that, despite the global distribution of the studies—based on the article inclusion criteria—scientific output over the last ten years remains concentrated in a few countries.

Figure 3 - Geographic distribution of selected articles: (A) proportion of studies by continent, and (B) number of publications by country



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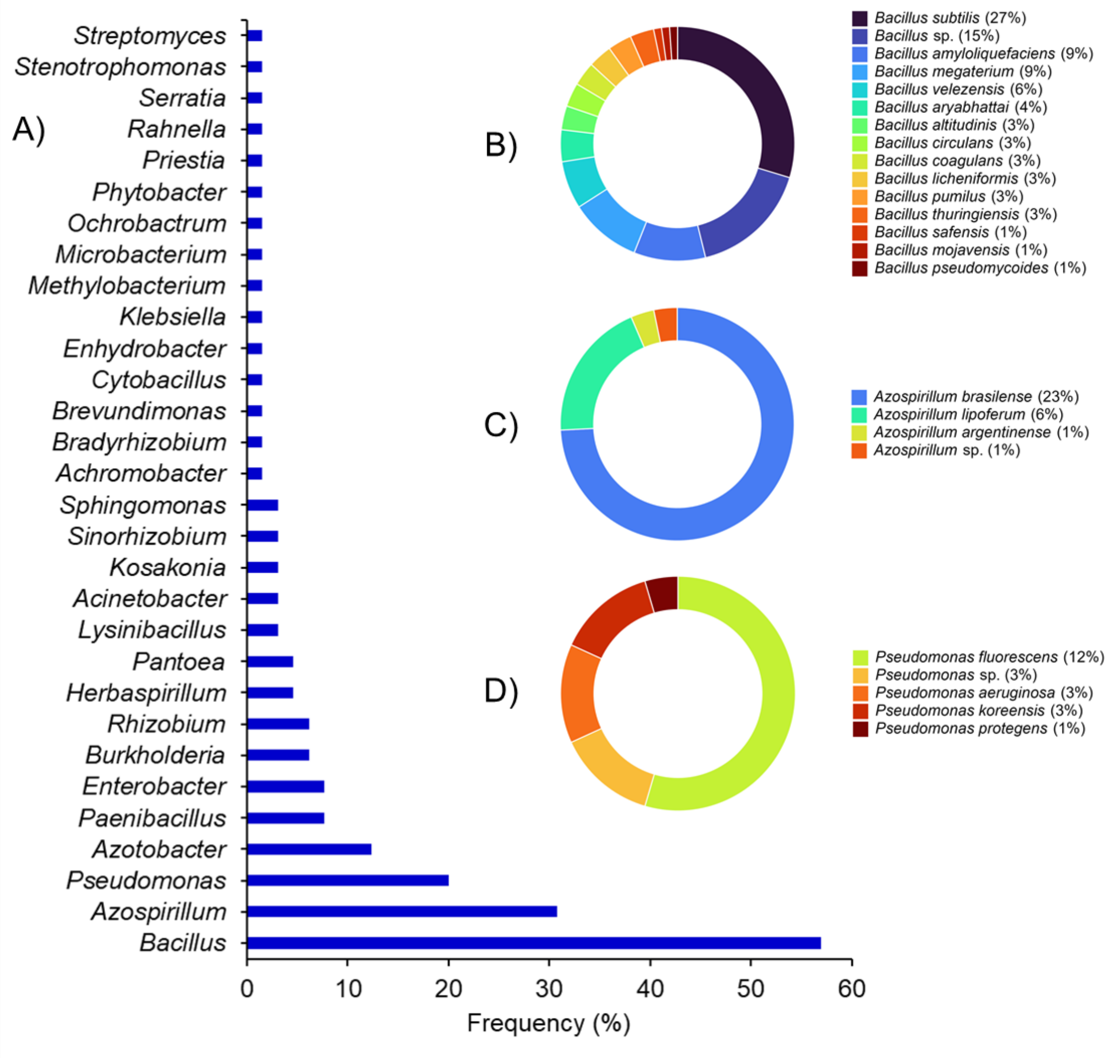
The distribution of PGPB identified in the selected articles revealed a predominance of a few genera, with a strong emphasis on *Bacillus*, *Azospirillum*, and *Pseudomonas*, which accounted for the highest frequencies across the studies (Figure 4A). Other genera were identified with lower representation.

At the species level, it was observed that, within the genus *Bacillus*, *Bacillus subtilis* was the most frequently reported species, accounting for 27% of the studies, followed by *Bacillus* sp. (15%), *B. megatherium* and *B. amyloliquefaciens* (both at 9%), while the remaining species showed individual frequencies below 6% (Figure 4B). For the genus *Azospirillum*, a strong concentration of *Azospirillum brasilense* was observed, accounting for 23% of occurrences, with lower representation of *A. lipoferum* (6%) and *A. argentinense* (1%) (Figure 4C).

Regarding the genus *Pseudomonas*, *Pseudomonas fluorescens* was the most frequently used species, accounting for 12% of the studies, followed by *P. koreensis*, *Pseudomonas* sp., and *P. aeruginosa* (each at 3%), while *P. protegens* showed a lower relative frequency (Figure 4D).

Figure 4 - Genera and species of plant growth-promoting bacteria (PGPB) used in maize. A) Frequency of genera identified in the selected articles (n= 65); B) Frequency of *Bacillus* species; C) Frequency of *Azospirillum* species; D) Frequency of *Pseudomonas* species



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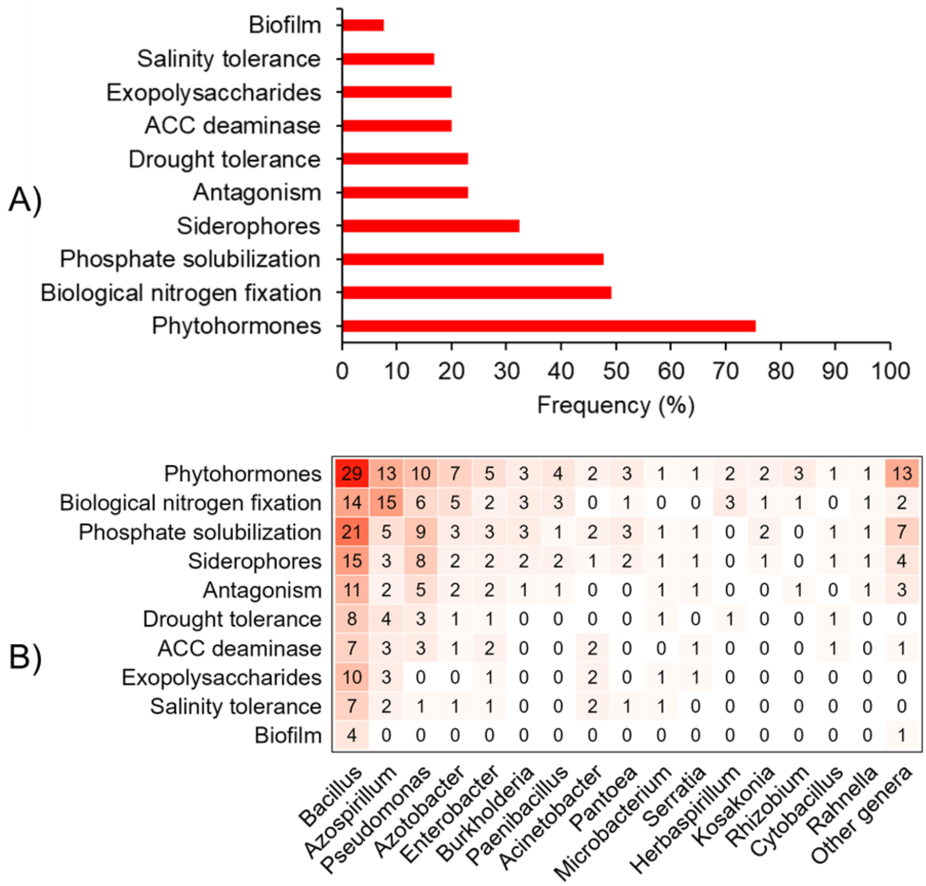
The functional characteristics related to plant growth promotion exhibited by the bacteria occur at varying frequencies. Phytohormone production was a predominant trait, occurring in 75% of the articles, followed by biological nitrogen fixation and phosphate solubilization, both observed in practically half of the selected studies (Figure 5A). Siderophore production was observed with a frequency of 32%, whereas antagonism, drought tolerance, ACC deaminase activity, exopolysaccharide production, and salinity tolerance were reported between 17% and 20% of the articles. Biofilm production was the least frequently reported characteristic.

The distribution of functional characteristics among the bacterial genera revealed a predominance of the genus *Bacillus*, which exhibited the most diverse functional profile compared to the other genera, testing positive for all the reported characteristics. Next, the genera *Azospirillum*, *Pseudomonas*, and *Azotobacter* stood out, although with a smaller number of articles. The other genera were represented in few studies (Figure 5B).

Figure 5 - Functional traits of plant growth-promoting bacteria. A) Relative frequency (%) of studies reporting each characteristic. B) Distribution of selected articles among different bacterial genera. Functional traits and bacterial genera were not mutually exclusive (n = 65)



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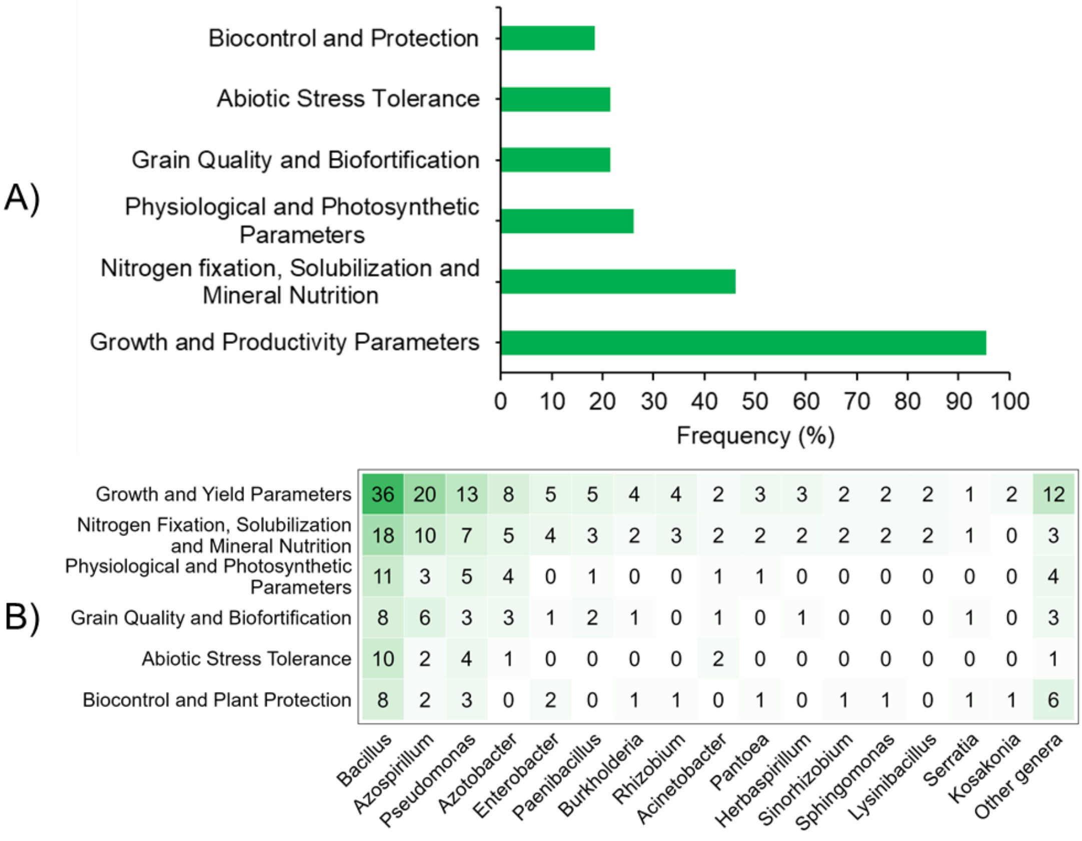
Regarding the categories of biostimulation and protection conferred by the bacteria in the selected articles (Figure 6A), a predominance of effects focused on growth and productivity parameters (95%) was observed, followed by nitrogen fixation, solubilization, and mineral nutrition (46%). Studies related to physiological and photosynthetic parameters, quality and grain biofortification, and abiotic stress tolerance showed an intermediate frequency, in the range of 22% to 26%. On the other hand, biocontrol and protection were less investigated (18%).

The distribution of publications according to the bacterial genera studied highlighted a strong concentration of research involving the genera *Bacillus*, *Azospirillum*, and *Pseudomonas*, which accounted for the highest number of publications across all biostimulation and protection categories (Figure 6B). In contrast, several bacterial genera such as *Microbacterium*, *Rahnella*, *Streptomyces*, *Phytobacter*, *Enhydrobacter*, and *Ochrobactrum* appeared infrequently in the literature, generally limited to only one or two biostimulation categories; this highlights possible knowledge gaps regarding their potential as plant growth-promoting bacteria.

Figure 6 - Frequency of response categories and distribution of bacterial genera in the analyzed articles. (A) Relative frequency (%) of articles classified into each response category. (B) Number of articles per response category and bacterial genus. Categories and bacterial genera were not mutually exclusive (n = 65)



	Bacillus	Azospirillum	Pseudomonas	Azotobacter	Enterobacter	Paenibacillus	Burkholderia	Rhizobium	Acinetobacter	Pantoea	Herbaspirillum	Sinorhizobium	Sphingomonas	Lysinibacillus	Serratia	Kosakonia	Other genera
Growth and Yield Parameters	36	20	13	8	5	5	4	4	2	3	3	2	2	2	1	2	12
Nitrogen Fixation, Solubilization and Mineral Nutrition	18	10	7	5	4	3	2	3	2	2	2	2	2	2	1	0	3
Physiological and Photosynthetic Parameters	11	3	5	4	0	1	0	0	1	1	0	0	0	0	0	0	4
Grain Quality and Biofortification	8	6	3	3	1	2	1	0	1	0	1	0	0	0	1	0	3
Abiotic Stress Tolerance	10	2	4	1	0	0	0	0	2	0	0	0	0	0	0	0	1
Biocontrol and Plant Protection	8	2	3	0	2	0	1	1	0	1	0	1	1	0	1	1	6

Source: Prepared by the authors.

DISCUSSION

Modern agriculture has been shaping itself around environmentally friendly practices that seek to improve productivity without negatively impacting the environment (Şimşek, 2025). The use of PGPB as bioinoculants has generated significant results, since these microorganisms can contribute positively to the reduction of chemical fertilizers while promoting sustainable development (Silva *et al.*, 2022; Maciel-Rodríguez *et al.*, 2025).

The increase in publications from 2020 onwards reflects shifts in the global landscape, driven by the need to adopt more sustainable practices and the chemical fertilizer crisis in the international market (Assefa *et al.*, 2025). Brazil's leading role is a reflection of the National Bioinputs Program, which is coordinated by the Ministry of Agriculture and Livestock, and aims to expand and strengthen the country's bioinputs sector (Vidal *et al.*, 2021).

The genera *Bacillus*, *Azospirillum*, and *Pseudomonas* together accounted for more than 50% of the strains used in the studies. The genus *Bacillus* belongs to the group of endospore-forming Gram-positive bacteria, which confers it a certain degree of resistance to extreme heat, ultraviolet radiation, desiccation, and nutrient scarcity (Shrestha *et al.*, 2025); it can be naturally found in soil (Hellany *et al.*, 2024), in the rhizosphere (Sun *et al.*, 2025), and also as an endophyte in various plants (Semwal *et al.*, 2023). Among the 16 *Bacillus* species identified in the selected studies, *B. subtilis* was the most frequent. When applied to maize, bacterial strains of this species promoted an increase in biomass (Aquino *et al.*, 2022), higher total solids and crude protein (Efthimiadou *et al.*, 2020), and increased grain protein and fiber content (Katsenios *et al.*, 2022), in addition to increasing shoot dry weight and grain yield, and improving plant biochemical attributes (chlorophyll a, b, and total, carotenoids, total soluble sugars, and amino acids) when combined with nano-zinc oxide (Jalal *et al.*, 2023).

The genus *Azospirillum* comprises Gram-negative bacteria found in soils (Shirokov *et al.*, 2025), the rhizosphere (Kamble *et al.*, 2025), plant roots, and aquatic environments (Xu *et al.*, 2023). These bacteria are capable of fixing nitrogen naturally with the aid of the nitrogenase enzyme, and are also able to produce phytohormones (auxins, cytokinins, and gibberellins) that stimulate plant growth (Giri *et al.*, 2025). Among the four species identified in the analyzed studies, *A. brasilense* was the most frequent. It promoted an increase in plant height (Dartora *et al.*, 2016), improved grain yield and nitrogen uptake (Martins *et al.*, 2017), contributed to reducing the use of nitrogen fertilizers (Oliveira *et al.*, 2017), and enhanced phosphorus uptake in maize (Pereira *et al.*, 2020).

The genus *Pseudomonas* comprises Gram-negative, non-spore-forming, straight rod-shaped bacteria. They can be found in soil and water, as well as associated with plants (Rojo-Bezares *et al.*, 2024; Ahmed *et al.*, 2025; Stancu, 2025). They exhibit metabolic versatility, utilizing a wide variety of organic compounds as carbon and energy sources, and are also applied in bioremediation processes (Medić & Karadžić, 2022). The species *P. fluorescens* was the most frequent. Strains of this species promoted several improvements in maize, such as increased zinc accumulation in the shoot and grains, higher grain albumin concentration when associated with nano-zinc oxide (Jalal *et al.*, 2023), and increased chlorophyll a and soluble sugar content under drought stress (Khaledi *et al.*, 2025).

Among the functional traits evaluated in the articles, phytohormone production, biological nitrogen fixation, phosphate solubilization, and siderophore production were the most frequent. The high frequency of studies assessing phytohormone production explains why over 90% of the articles focused on growth and yield parameters. Phytohormones produced by bacteria can vigorously stimulate root system development (Deng *et al.*, 2022), increasing the root surface area in contact with the soil (Oliveira-Paiva *et al.*, 2025), which translates into a higher capacity for water and nutrient uptake (Abrar *et al.*, 2025).

Biological nitrogen fixation and phosphate solubilization are traits of utmost importance for these bacteria, since they can assist in reducing fertilizer losses to the environment (Karmakar *et al.*, 2025), thereby enhancing fertilizer use efficiency by plants, as observed in the studies by Galindo *et al.* (2024) and Oliveira-Paiva *et al.* (2024).

The siderophores produced by these bacteria can also benefit plants through biofortification and the uptake of iron and zinc, which may increase the concentrations of these nutrients in the grains (Ahmad *et al.*, 2023), in addition to playing a role in pathogen control (Ghazy & El-Nahrawy, 2021). Although these mechanisms were the most frequent, studies reporting drought and salinity tolerance, as well as the production of EPS and the ACC deaminase enzyme, indicate potential research trends for the coming years.

Given the exacerbation of climate change, the application of these bacteria may transition from a role exclusively focused on growth promotion and biofertilization to encompassing climate resilience concepts (Sherzad, Nawakht, and Sherzad, 2025). These include mechanisms such as the modulation of ethylene levels in stress-exposed plants via ACC deaminase (Abrar *et al.*, 2025), as well as the formation of biofilms and exopolysaccharides, which can aid in water retention (Khaledi *et al.*, 2025). Although these functional traits were reported at a lower frequency than the main ones, their presence indicates that bacteria harboring these traits may be crucial for sustaining maize growth and yield. Consequently, they can help mitigate the damage induced by abiotic stresses in areas facing extreme drought and degraded soils.

CONCLUSION

This systematic review demonstrated that field studies using PGPB in maize cultivation have expanded significantly since 2020, being mostly concentrated in Asia and South America, with China and Brazil taking the lead. The genera *Bacillus*, *Azospirillum*, and *Pseudomonas* predominated in the reviewed literature, with *B. subtilis*, *A. brasilense*, and *P. fluorescens* as the most explored species. Phytohormone production, biological nitrogen fixation, and phosphate solubilization were the most frequently reported growth-promoting mechanisms. Growth and yield parameters were the dominant biostimulation categories, while biocontrol, crop protection, and abiotic stress tolerance were less frequent, highlighting critical gaps. Therefore, we conclude that there is a strategic need to diversify the bacterial genera studied to further research on the crop's yield stability and nutritional value amidst global climate challenges.

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