Scientometric analysis of *bacillus megaterium* in plant growth promotion: trends and agricultural applications

Análisis cientométrico de bacillus megaterium en la promoción del crecimiento vegetal: tendencias y aplicaciones agrícolas

Análise centrométrica de Bacillus megaterium na promoção do crescimento vegetal: tendências e aplicações agrícolas

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Abstract

Introduction: Bacillus megaterium is a Gram-positive bacterium with significant biotechnological potential in sustainable agriculture due to its ability to enhance plant nutrition and promote root development through specific metabolic pathways. This article is derived from the research project entitled "Scientometric Analysis of Bacillus megaterium as a Plant Growth-Promoting Bacterium for Its Application in Regenerative Agriculture."

Methodology: A scientometric review was conducted following the PRISMA 2020 protocol to characterize the current state of research on B. megaterium as a plant growth-promoting bacterium. Scientific articles were retrieved from Scopus, PubMed, and Web of Science™, applying predefined inclusion and exclusion criteria. Bibliographic metadata were analyzed using the Bibliometrix package in RStudio.

Results: A total of 18 articles published between 2010 and 2024 were analyzed. Since 2020, a sustained increase in scientific output has been observed, with a strong emphasis on indole-3-acetic acid biosynthesis, phosphate solubilization, and siderophore production. Brazil, India, and Egypt were identified as the leading contributors to scientific production. Environmental factors, production strategies, and applications in biofertilization and biocontrol were also highlighted.

Conclusion: B. megaterium exhibits key physiological mechanisms that improve plant nutrient-use efficiency and contribute to the sustainability of agricultural production systems.

Originality: This study provides an updated overview of scientific trends related to B. megaterium in agricultural contexts, identifying thematic gaps and emerging research areas.

Limitations: Although relevant trends were identified, there is still limited evidence regarding field validation and long-term ecological impacts, highlighting the need for further investigation.

Keywords: Biofertilizers, Bacterial Metabolism, Microbial Metabolic Pathways, Physiological Regulation, Bibliometric Analysis.

Resumen

Introducción: Bacillus megaterium es una bacteria Gram positiva con un alto potencial biotecnológico en la agricultura sostenible, debido a su capacidad para mejorar la nutrición vegetal y promover el desarrollo radicular mediante rutas metabólicas específicas. Este artículo es producto del proyecto de investigación titulado "Análisis cienciométrico de Bacillus megaterium como bacteria promotora del crecimiento vegetal para su aplicación en la agricultura regenerativa".

Metodología: Se realizó una revisión cienciométrica siguiendo el protocolo PRISMA 2020, enfocada en la caracterización del estado actual de la investigación sobre B. megaterium como bacteria promotora del crecimiento vegetal. Los artículos científicos fueron identificados mediante búsquedas en Scopus, PubMed y Web of Science™, aplicando criterios predefinidos de inclusión y exclusión. Los metadatos bibliográficos fueron analizados en RStudio mediante el paquete Bibliometrix.

Resultados: Se analizaron 18 artículos publicados entre 2010 y 2024. Desde 2020 se evidenció un incremento sostenido en la producción científica, con especial énfasis en la biosíntesis de ácido indol-3-acético, la solubilización de fosfatos y la producción de sideróforos. Brasil, India y Egipto fueron identificados como los principales países contribuyentes. Asimismo, se destacaron factores ambientales, estrategias de producción y aplicaciones en biofertilización y biocontrol.

Conclusiones: B. megaterium presenta mecanismos fisiológicos clave que contribuyen a mejorar la eficiencia en el aprovechamiento de nutrientes por parte de las plantas y favorecen la sostenibilidad de los sistemas agrícolas.

Originalidad: Este estudio proporciona un panorama actualizado de las tendencias científicas relacionadas con B. megaterium en contextos agrícolas, identificando vacíos temáticos y áreas emergentes de investigación.

Limitaciones: Aunque se identificaron tendencias relevantes, existe evidencia limitada sobre la validación en campo y los impactos ecológicos a largo plazo, lo que evidencia la necesidad de investigaciones adicionales.

Palabras clave: Biofertilizantes, Metabolismo Bacteriano, Rutas Metabólicas Microbianas, Regulación Fisiológica, Análisis Bibliométrico.

Resumo

Introdução: Bacillus megaterium é uma bactéria Gram-positiva com alto potencial biotecnológico na agricultura sustentável, devido à sua capacidade de melhorar a nutrição das plantas e promover o desenvolvimento radicular por meio de vias metabólicas específicas. Este artigo é produto do projeto de pesquisa intitulado "Análise cientométrica de Bacillus megaterium como bactéria promotora do crescimento vegetal para sua aplicação na agricultura regenerativa".

Metodologia: Foi realizada uma revisão cientométrica seguindo o protocolo PRISMA 2020, com foco na caracterização do estado atual da pesquisa sobre B. megaterium como bactéria promotora do crescimento vegetal. Artigos científicos foram identificados por meio de buscas no Scopus, PubMed e Web of Science™, aplicando critérios de inclusão e exclusão predefinidos. Os metadados bibliográficos foram analisados no RStudio utilizando o pacote Bibliometrix.

Resultados: Dezoito artigos publicados entre 2010 e 2024 foram analisados. Desde 2020, observa-se um aumento sustentado na produção científica, com ênfase particular na biossíntese do ácido indol-3-acético, na solubilização de fosfato e na produção de sideróforos. Brasil, Índia e Egito foram identificados como os principais países contribuintes. Fatores ambientais, estratégias de produção e aplicações em biofertilização e biocontrole também foram destacados.

Conclusões: B. megaterium apresenta mecanismos fisiológicos essenciais que contribuem para melhorar a eficiência da absorção de nutrientes pelas plantas e promovem a sustentabilidade dos sistemas agrícolas.

Originalidade: Este estudo fornece uma visão geral atualizada das tendências científicas relacionadas a B. megaterium em contextos agrícolas, identificando lacunas temáticas e áreas emergentes de pesquisa.

Limitações: Embora tendências relevantes tenham sido identificadas, há evidências limitadas sobre a validação em campo e os impactos ecológicos a longo prazo, o que destaca a necessidade de mais pesquisas.

Palavras-chave: Biofertilizantes, Metabolismo Bacteriano, Vias Metabólicas Microbianas, Regulação Fisiológica, Análise Bibliométrica.

1. INTRODUCTION

Bacillus megaterium is a Gram-positive, aerobic, mesophilic, spore-forming bacterium belonging to the phylum Firmicutes [1]. Its name refers to its large cell size, making it one of the largest species within the genus Bacillus [2]. This microorganism has been widely studied due to both its industrial relevance and its emerging role in sustainable agriculture, where it has demonstrated significant potential as a plant growth-promoting bacterium (PGPB) [3]. Its remarkable ability to adapt to diverse ecological niches, combined with its broad metabolic potential, makes it an ideal candidate for biotechnological applications focused on biofertilization and biocontrol [4], [5].

The beneficial functions of B. megaterium in the plant rhizosphere are associated with various metabolic pathways [6] responsible for nutrient solubilization and the synthesis of bioactive compounds that stimulate plant growth [7]. Among the most relevant mechanisms is the solubilization of mineral phosphates through the production of organic acids, such as gluconic, citric, and lactic acids [8], which acidify the rhizosphere and release inorganic phosphorus that is otherwise unavailable to plants [9]. Although B. megaterium does not establish symbiotic atmospheric nitrogen fixation, it participates in the assimilation and transformation of nitrogen compounds available in the soil, including nitrates and ammonium, through enzymes involved in nitrogen metabolism. These processes include the reduction of nitrates (NO_2^-) and nitrites (NO_3^-) mediated by nitrate reductase and nitrite reductase enzymes [10]. Such functions enhance plant nutrition and contribute to greater nitrogen-use efficiency in crops [11].

Another key mechanism is the synthesis of phytohormones, particularly indole-3-acetic acid (IAA), through tryptophan-dependent pathways such as the indole-3-pyruvic acid pathway [12]. This phytohormone stimulates cell division and elongation, promoting more robust root system development and increasing the uptake of water and nutrients [13]. In addition, B. megaterium produces siderophores, which are low-molecular-weight compounds with a high affinity for ferric iron (Fe^{3+}). These molecules facilitate iron acquisition by plants in soils where this micronutrient is poorly available [14].

At the biocontrol level, B. megaterium is capable of synthesizing antimicrobial compounds, including lipopeptides such as iturin, fengycin, and surfactin, as well as hydrolytic enzymes, including chitinases, glucanases, and proteases, which degrade the cell walls of phytopathogenic fungi [15]. These activities, together with its ability to induce systemic resistance in plants, contribute to reducing disease incidence and improving crop resilience under both biotic and abiotic stress conditions [16].

Collectively, the metabolic processes exhibited by B. megaterium not only directly enhance plant growth but also promote a healthier and more functional rhizospheric environment [17]. Its application in agricultural systems represents an ecological and efficient strategy to partially or completely replace the use of chemical fertilizers and pesticides, in accordance with the principles of regenerative agriculture and environmental sustainability [18].

Despite its multiple benefits as a plant growth-promoting bacterium, the application of Bacillus megaterium in agricultural systems presents several challenges and limitations that must be considered. One of the main concerns is the variability in efficacy among strains, which may be influenced by genetic differences, soil and climatic conditions, and crop type. This variability complicates the standardization of commercial applications and may affect the consistency of agronomic outcomes. Furthermore, additional evidence is required regarding its long-term performance under complex and diverse agricultural conditions [19].

Another critical aspect involves its interaction with the native soil microbiota. Several studies have reported that the application of B. megaterium can alter the microbial composition of soil ecosystems, indirectly influencing the availability of nutrients such as phosphorus and potassium and, consequently, crop productivity [20]. These modifications may produce either beneficial or adverse effects depending on the agroecological context. Therefore, further field-based studies are needed to evaluate soil resilience and microbial health under repeated applications of this bacterium and to better understand its long-term ecological implications [21].

2. MATERIALS AND METHODS

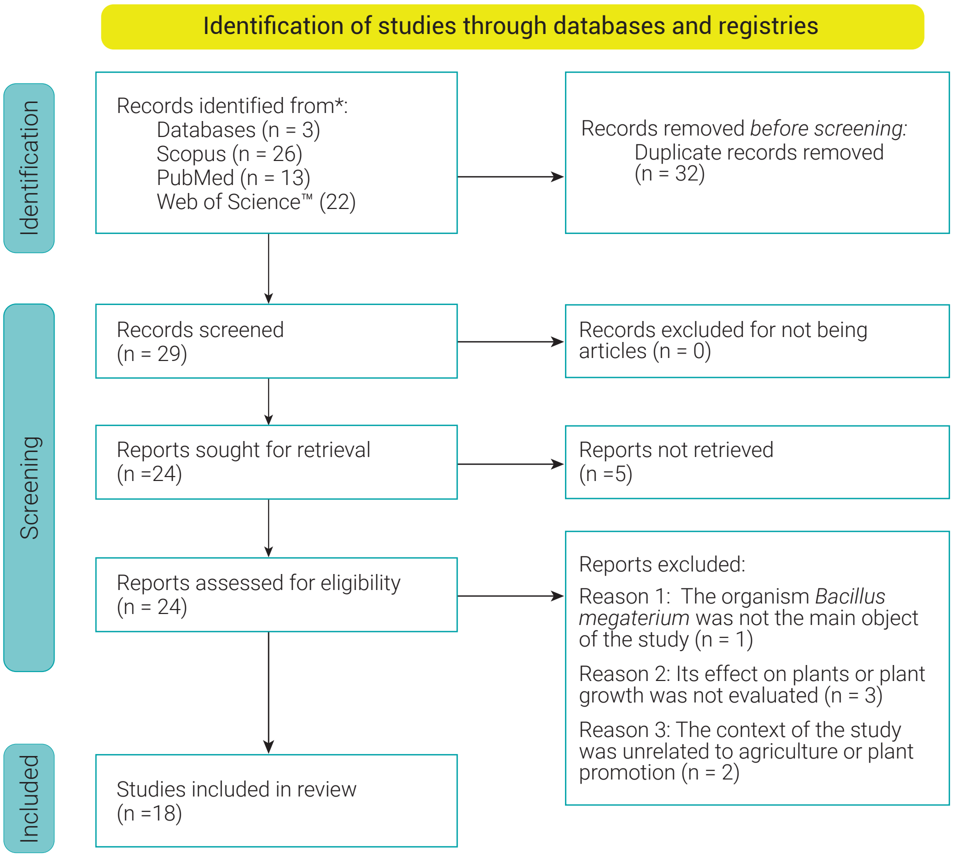

Figure 1. Prism diagram of the systematic review process and reference selection.
Source: own work

This review was conducted using a scientometric approach, following the guidelines established in the PRISMA 2020 protocol [22]. The objective was to identify, analyze, and synthesize scientific articles focused on the study of Bacillus megaterium as a plant growth-promoting bacterium, with particular emphasis on its biochemical pathways, physiological mechanisms, and applications in sustainable agriculture.

2.1 Search Strategy

The literature search was conducted in March 2025 using three high-impact scientific databases: Scopus, PubMed, and Web of Science™. The following search equation was applied:

(“Bacillus megaterium” AND “plant growth promoter”)

No restrictions regarding publication year or language were applied, ensuring a broad and inclusive search strategy. The initial search retrieved 61 records: 26 from Scopus, 13 from PubMed, and 22 from Web of Science™.

2.2 Inclusion and Exclusion Criteria

The following criteria were established for article selection:

Inclusion criteria:

- Original research articles or systematic reviews.
- Studies that directly or indirectly evaluated the effects of B. megaterium on plant growth.
- Studies describing physiological and biochemical mechanisms or agricultural applications.

Exclusion criteria:

- Studies in which B. megaterium was not the primary microorganism under investigation.
- Studies that did not evaluate its effects on plants or did not address metabolic processes.
- Studies outside the agricultural context (e.g., exclusively ecological, clinical, or industrial studies).
- Articles that were not available in full text.

During the initial screening process, 32 duplicate records were removed, leaving 29 articles for full-text assessment. Of these, five articles could not be retrieved because of access restrictions. After applying the inclusion and exclusion criteria, a final set of 18 articles was selected for analysis.

2.3 Data Processing and Analysis

Bibliographic metadata, including authorship, publication year, country of affiliation, keywords, citations, and publication sources, were exported in BibTeX and CSV formats and subsequently processed using the Bibliometrix package in RStudio.

The scientometric analysis included the following components:

- Identification of the most productive and influential authors in the field.
- Evaluation of annual scientific production.
- Analysis of annual thematic trends.
- Assessment of scientific production by country.
- Generation of a word cloud (WordCloud) to visualize the relative frequency of the most relevant terms.
- Conceptual analysis of the biochemical processes described in the selected articles, with emphasis on metabolic pathways, microbial physiology, and environmental factors influencing the activity of Bacillus megaterium.

Additionally, a critical and systematic review of the 18 selected articles was conducted, synthesizing information related to microbial physiology, metabolic pathways (such as indole-3-acetic acid biosynthesis), environmental factors, production strategies, and biotechnological perspectives.

3. RESULTS

3.1 Annual Scientific Production

Figure 2 illustrates the annual evolution of scientific publications related to Bacillus megaterium as a plant growth-promoting bacterium during the period from 2010 to 2024. During the first half of the analyzed period (2010–2018), scientific production was limited and intermittent, with one or no publications per year, reflecting the emerging nature of this research area.

From 2019 onward, an increasing trend in scientific production can be observed, characterized by a sustained growth in the number of publications. This increase became more pronounced after 2020, reaching a peak in 2023 with six publications, representing approximately 33% of the total articles included in this review. Although a slight decrease was observed in 2024, scientific output remained active with at least one publication, indicating continued interest in this field.

As highlighted by [23], this trend reflects the consolidation of B. megaterium as a relevant biotechnological agent in agriculture, driven by its ability to participate in key processes such as indole-3-acetic acid (IAA) synthesis, mineral nutrient solubilization, and antimicrobial compound production. These characteristics contribute to improved plant nutritional efficiency and promote the sustainability of agricultural production systems.

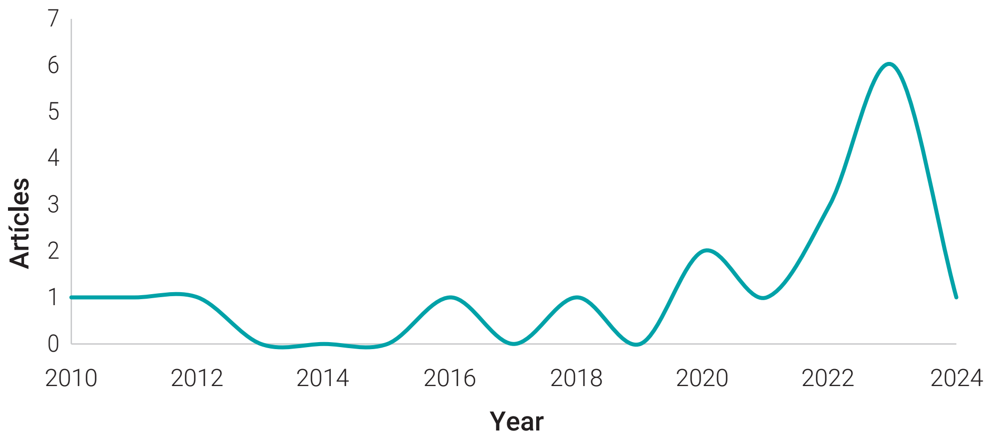

Figure 2. Annual scientific production.
Source: own work

3.2 Annual Trending Topics

Figure 3 presents the most relevant emerging topics in research on Bacillus megaterium as a plant growth-promoting bacterium during the period analyzed (2015–2024). The term "Bacillus megaterium" has appeared consistently throughout the last decade, confirming its central role in agricultural biotechnology and its growing recognition as a multifunctional microorganism.

The emergence of terms such as "indole-3-acetic acid" (IAA) and "ammonia" reflects an increasing research focus on microbial metabolic traits that directly influence plant physiology. The sustained presence of IAA highlights the importance of auxin biosynthesis through tryptophan-dependent pathways, which play a fundamental role in promoting root elongation, cell division, and lateral root development. Likewise, the occurrence of the term "ammonia" indicates growing interest in the ammonification potential of B. megaterium, a characteristic that enhances nitrogen availability in the rhizosphere and contributes to sustainable nutrient management in agricultural systems.

Interestingly, the inclusion of "16S rRNA" as a trending topic in recent years indicates a shift toward molecular-level investigations. This trend suggests that researchers are increasingly employing phylogenetic and genomic tools to characterize novel strains, identify functional genes, and determine their ecological niches. Such molecular approaches not only improve taxonomic resolution but also facilitate the identification of genes associated with biofertilization, stress tolerance, and plant–microbe interactions.

Furthermore, the analysis of thematic trends reveals a transition from descriptive studies—primarily focused on strain isolation and preliminary bioassays—to more integrative and mechanistic investigations. This evolution is aligned with global efforts aimed at developing more efficient, reliable, and environmentally safe biofertilizers tailored to specific crops and soil conditions.

Overall, these emerging topics reflect the progressive consolidation of Bacillus megaterium as a key microorganism in sustainable agriculture and highlight the increasing integration of physiological, biochemical, and molecular approaches to better understand and optimize its agricultural applications.

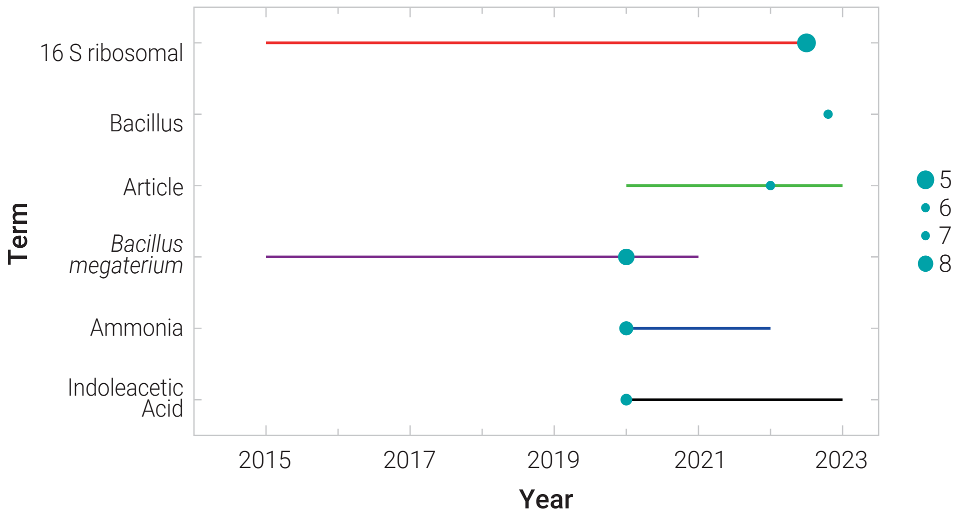

Figure 3. Annual Trending Topics.
Source: own work

The trending topics suggest that this research field is undergoing a process of maturation, evolving from predominantly empirical applications toward more precise, knowledge-based biotechnological strategies. This deeper understanding of the functional roles of B. megaterium is essential for unlocking its full potential in sustainable agriculture and facilitating the large-scale implementation of its applications under real field conditions.

These findings indicate that current research is focused not only on the isolation and practical application of B. megaterium, but also on the detailed understanding of its metabolic mechanisms of action. Such advances open new opportunities for optimizing its use in sustainable agricultural practices and for developing more efficient and targeted biofertilization strategies.

3.3 Scientific Production by Country

Figure 4 illustrates the geographical distribution of author affiliations associated with research on Bacillus megaterium as a plant growth-promoting bacterium. The reported frequency corresponds to the number of times a country appears in the affiliations of authors across the articles included in the analysis.

Brazil emerged as the country with the highest number of author affiliations, followed by India, Egypt, the United States, and Pakistan. This distribution reflects the growing global interest in the agricultural applications of B. megaterium, particularly among developing countries seeking sustainable alternatives for agricultural production.

The strong representation of these regions may be associated with the search for low-cost and effective biological solutions aimed at reducing dependence on chemical fertilizers and improving agricultural productivity. Most studies focus on mechanisms such as indole-3-acetic acid (IAA) biosynthesis, phosphate solubilization, and siderophore production, all of which contribute to enhanced plant growth and development under challenging environmental conditions.

Furthermore, the geographical distribution of scientific production demonstrates that research on B. megaterium has become increasingly relevant in countries facing agricultural sustainability challenges, where the adoption of microbial-based technologies represents a promising strategy for improving crop performance while reducing environmental impacts.

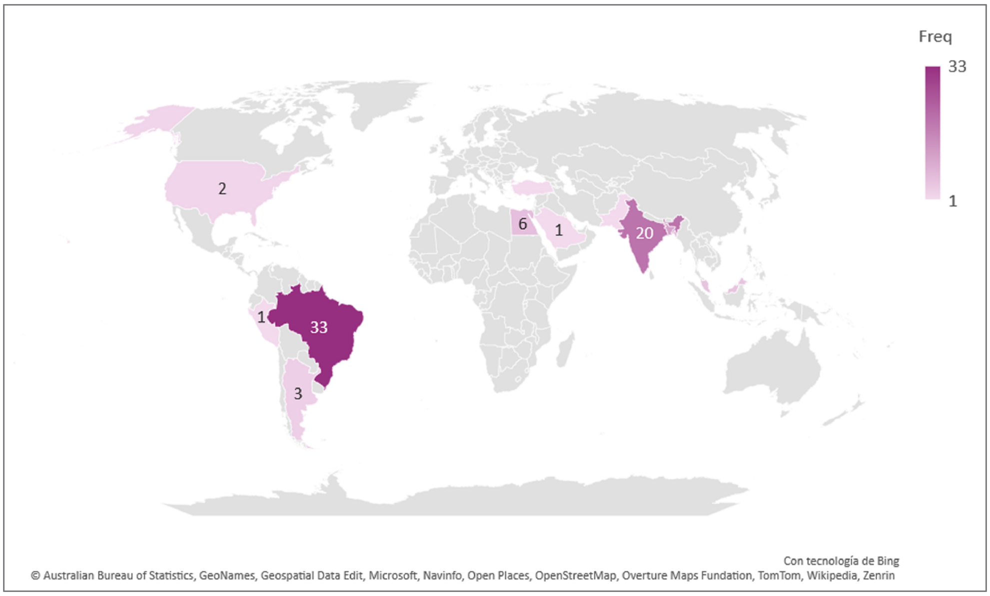

Figure 4. Geographical distribution of author affiliations in studies on Bacillus megaterium as a plant growth promoter.

3.4 Co-occurrence network map

Figure 5 shows the keyword co-occurrence map generated with VOSviewer, based on the articles selected for this review. It visualizes the most frequent terms associated with *Bacillus megaterium* in the context of plant growth promotion, as well as their thematic connections. The node size represents the relative frequency of the term, while the thickness of the lines indicates the intensity of co-occurrence.

The central node, "*Bacillus megaterium*", is closely linked to key concepts such as "plant growth", "plant growth-promoting bacterium", "indole-3-acetic acid", "ammonia", and "siderophore". These terms show that recent research has focused mainly on the metabolic pathways that promote plant growth, with the biosynthesis of auxins, such as indoleacetic acid (IAA), being one of the most recurrent. Likewise, the mention of "ammonia" and "hydrogen cyanide" suggests interest in compounds associated with nutrition and biocontrol.

The presence of other terms such as "plant height", "seedling", "fresh weight" y "chlorophyll" It indicates that studies have consistently evaluated agronomic parameters to quantify the effect of bacterial inoculation. Terms such as "16S RNA", "genetics", and "controlled study" also reflect the integration of molecular tools and robust experimental designs.

Overall, the map confirms that the physiological and biochemical processes of *B. megaterium* such as the production of phytohormones, nutrient solubilization and defense mechanisms constitute the central axes of its application as a biotechnological agent in sustainable agriculture.

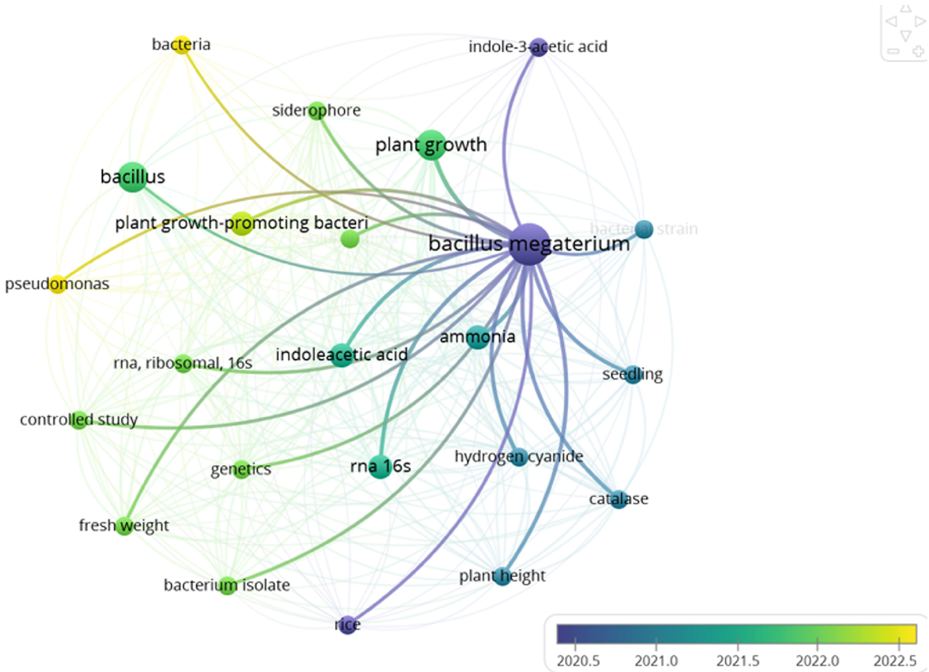

Figure 5. co-occurrence network map generated from the most frequent terms in the articles analyzed on *Bacillus megaterium* as a plant growth promoter.
Source: own work

3.5 Analysis of the Microbial Biochemical Processes of Bacillus megaterium

Regarding the microbial biochemical processes associated with Bacillus megaterium in the context of plant growth promotion, the most relevant metabolic pathways, environmental factors, physiological mechanisms, and biotechnological applications linked to this bacterium were identified.

The analysis revealed that the most extensively studied metabolic pathway is the biosynthesis of indole-3-acetic acid (IAA) from tryptophan, particularly through the indole-3-pyruvic acid (IPyA) pathway, which is considered a key mechanism for promoting root growth in a wide range of plant species [24].

3.5.1 Microbial Metabolism

The principal biochemical processes of Bacillus megaterium involved in plant growth promotion are described below.

• Production of Indole-3-Acetic Acid (IAA)

B. megaterium produces IAA, a key auxin involved in stimulating root cell elongation, primarily through the tryptophan-dependent indole-3-pyruvic acid (IPyA) pathway. In this process, tryptophan serves as the principal precursor and is initially converted into indole-3-pyruvic acid by the action of aminotransferase enzymes. Subsequently, a decarboxylase converts this intermediate into indole-3-acetaldehyde, which is finally oxidized to IAA by oxidase enzymes [25].

IAA production is regulated by several factors, including the concentration of exogenous tryptophan, the carbon source available in the medium (preferably sucrose), and pH conditions, with an optimum value of approximately 7.0. This phytohormone enhances root hair formation and improves the uptake of water and nutrients by plants [26].

• Phosphate and Mineral Solubilization

Phosphate solubilization occurs through the secretion of organic acids, including gluconic, citric, and lactic acids, which reduce the pH of the rhizosphere and dissolve insoluble phosphate compounds such as $Ca_3(PO_4)_2$. A key enzyme involved in this process is glucose dehydrogenase (GDH), which catalyzes the oxidation of glucose into gluconic acid [27].

This mechanism also facilitates the solubilization of other essential minerals, including zinc (Zn) and potassium (K). The availability of glucose and the acidity of the surrounding medium are important factors influencing the efficiency of this process.

• Siderophore Production

B. megaterium produces catecholate- and hydroxamate-type siderophores, such as desferri-bacillibactin, which are capable of chelating Fe^{3+} under conditions of low iron availability in the soil [28]. These compounds are synthesized by non-ribosomal peptide synthetase (NRPS) systems encoded by dhb-like genes [29].

Siderophore production increases under iron-deficient conditions and is regulated by the ferric uptake regulator (Fur) system, which represses the expression of siderophore biosynthesis genes when sufficient iron is available [30].

• Synthesis of Antimicrobial Compounds

B. megaterium synthesizes lipopeptides such as iturin, fengycin, and surfactin, which disrupt the cellular membranes of pathogenic fungi and bacteria. These bioactive molecules are produced by multigene NRPS enzyme complexes and are typically activated under conditions of biotic stress or microbial competition [31].

• Production of Selenium Nanoparticles (Se^0)

Certain strains of B. megaterium are capable of reducing selenite (SeO_3^{2-}) to elemental selenium (Se^0) through extracellular mechanisms mediated by nitrate reductase and redox-active compounds present in the cell supernatant. This process leads to the formation of selenium nanoparticles with antimicrobial properties and potential applications in biofortification [32].

• Antioxidant Activity and ACC Deaminase Production

The production of antioxidant enzymes, including catalase and peroxidase, together with ACC deaminase, contributes to plant tolerance against oxidative stress and reduces ethylene accumulation under stress conditions. ACC deaminase catalyzes the degradation of 1-aminocyclopropane-1-carboxylic acid (ACC), the direct precursor of ethylene, thereby promoting plant growth under adverse conditions such as drought and salinity stress [33].

3.5.2 Factors Affecting Biochemical Processes

The metabolic efficiency of B. megaterium is influenced by several environmental and nutritional factors:

- Soil pH: Optimal activity is generally observed between pH 6.5 and 7.5, although some strains can tolerate pH values as low as 4.0 [34].
- Tryptophan Availability: The presence of tryptophan significantly enhances IAA biosynthesis and promotes phytohormone production [35].
- Carbon and Nitrogen Sources: Sucrose and yeast extract have been identified as optimal substrates for stimulating the production of secondary metabolites and growth-promoting compounds [36].
- Environmental Conditions: The bacterium exhibits tolerance to temperatures ranging from 28 to 37 °C and moderate salinity levels of approximately 2–3% NaCl [37].

- Inoculation Method: Seed inoculation has demonstrated greater effectiveness than direct soil application, resulting in improved colonization efficiency and plant growth responses [38].

3.5.3 Production Methods and Operational Conditions

The production of IAA by Bacillus megaterium has been optimized under laboratory conditions through the use of enriched culture media and specific precursors. The principal precursor is tryptophan, which is typically added to the culture medium at concentrations ranging from 500 to 600 µg/mL [39].

Carbon sources such as sucrose and starch, together with nitrogen sources such as yeast extract, have been identified as optimal substrates for maximizing IAA biosynthesis. The pH of the medium also plays a significant role, with optimal production occurring between pH 6.5 and 7.5. Once fermentation is completed, IAA can be quantified using the Salkowski reagent and, for greater analytical accuracy, by chromatographic techniques such as High-Performance Liquid Chromatography (HPLC) or Thin-Layer Chromatography (TLC) [40].

3.5.4 Biotechnological Perspectives

The application of Bacillus megaterium is projected as a strategic tool for several biotechnological purposes, including:

- Reduction in the use of chemical fertilizers in agricultural systems [17].
- Biofortification of crops with essential micronutrients [41].
- Bioremediation of soils contaminated with heavy metals, including arsenic, mercury, and cadmium [42].
- Development of sustainable biofertilizers and biological control agents [43].

The integration of B. megaterium into regenerative agriculture and bioeconomy programs represents one of the most promising avenues for the future of agricultural biotechnology.

4. DISCUSSION

The scientometric analysis conducted on Bacillus megaterium as a plant growth-promoting bacterium reveals a growing trend in scientific production over the last decade, particularly since 2020. It is important to note that the limited number of articles retrieved (n = 18) reflects the current state of scientific production specifically focused on Bacillus megaterium and its role in plant growth promotion. Although this number may restrict the generalization of some scientometric trends, it also highlights that this is an emerging field with considerable potential, representing an opportunity for future studies with broader bibliographic coverage.

This increase in scientific production can be attributed to the growing interest in sustainable agricultural strategies and to the biotechnological potential of this bacterium to improve plant nutrition and enhance resilience under abiotic stress conditions [44]. The identification of recurrent keywords, including indole-3-acetic acid (IAA), phosphate solubilization, siderophores, and biofertilizers, confirms that microbial biochemical processes constitute the core focus of current research on B. megaterium [35], [45]–[47].

Consistent with these findings, the analyzed studies highlight IAA biosynthesis through tryptophan-dependent pathways as the principal metabolic process of interest, together with mechanisms associated with the solubilization of essential nutrients such as phosphorus (P), potassium (K), and zinc (Zn), as well as the production of antimicrobial metabolites.

The thematic mapping and keyword co-occurrence analysis revealed three major research clusters. The first cluster grouped terms such as indole-3-acetic acid, phosphate solubilization, and siderophores, reflecting a strong research focus on the biochemical mechanisms underlying plant growth promotion. The second cluster included terms such as 16S rRNA, genomic analysis, and stress tolerance, indicating a growing interest in the molecular characterization of B. megaterium strains. The third cluster was associated with terms such as biofertilizer, soil remediation, and crop productivity, suggesting an applied research line oriented toward the development of sustainable agricultural technologies.

These clusters highlight the multidimensional nature of this research field and demonstrate its evolution from predominantly descriptive studies toward mechanistic investigations and application-oriented approaches.

Despite the growth in scientific production, the author collaboration network still exhibits a fragmented structure, with limited consolidation of stable research groups. Although a co-authorship network map was not included in this study, the bibliometric analysis revealed a low degree of interconnectivity among authors, with most publications appearing as isolated contributions or within small, disconnected clusters. This pattern reinforces the observation of a dispersed authorship structure and highlights the need to promote international and interdisciplinary collaborations to consolidate research agendas and increase the scientific impact of future studies. Furthermore, these findings suggest an opportunity to establish international research networks aimed at standardizing methodologies and conducting large-scale field trials, considering that most current studies remain restricted to controlled laboratory or greenhouse conditions.

Recent advances have included the integration of B. megaterium into microbial consortia, combining it with other plant growth-promoting bacteria such as Bacillus subtilis and Lysinibacillus sp., with the objective of improving fertilizer use efficiency and controlling emerging diseases such as rice pod spot [48]. Similarly, the application of omics-based approaches has revealed the presence of genes associated with heavy metal resistance and selenium nanoparticle production, opening new perspectives for biofortification and bioremediation strategies [49].

The emergence of the term “16S rRNA” in recent years indicates a significant methodological transition in this field, moving beyond applied agronomic studies toward the genetic and molecular characterization of bacterial strains. This approach enables a more precise understanding of the functional mechanisms of B. megaterium and enhances the selection of strains possessing specific traits adapted to agricultural requirements [50].

Despite these advances, there remains a lack of field validation studies and longitudinal research evaluating the long-term effects of B. megaterium on soil microbiomes, as well as the ecological risks associated with the release of non-native or genetically modified strains. In addition, although its role in improving nutrient assimilation is widely recognized, its competitive interactions with native soil microorganisms remain insufficiently understood [51].

Future research should focus on the development of biofertilizers specifically formulated for diverse soil types and climatic conditions, while exploring their integration into regenerative agricultural systems. Furthermore, greater attention should be given to understanding the molecular mechanisms regulating the expression of critical metabolic pathways under environmental stress conditions. The bioprospecting of novel strains from extreme environments and the application of gene-editing technologies also represent promising directions for advancing this field of research.

5. CONCLUSIONS

This scientometric review demonstrates the growing scientific interest in Bacillus megaterium as a plant growth-promoting bacterium, particularly since 2020. The studies analyzed consistently highlight key biochemical mechanisms, including indole-3-acetic acid biosynthesis, phosphate solubilization, and siderophore production. These microbial processes enhance nutrient availability, stimulate root development, and increase plant resilience to stress conditions, supporting the potential of B. megaterium as both a biofertilizer and a biological control agent.

However, important research gaps remain regarding field validation, strain standardization, and the assessment of long-term impacts on soil microbial communities. To consolidate the sustainable application of B. megaterium in agricultural systems, future studies should focus on evaluating its molecular mechanisms under real production conditions, developing specific bioformulations adapted to different agroecological contexts, and incorporating omics-based tools for strain optimization and characterization.

Additionally, strengthening international collaborative research networks will be essential to accelerate knowledge generation, improve methodological standardization, and promote the effective biotechnological exploitation of this promising microorganism within sustainable and regenerative agriculture systems.

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