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Please cite this article as:

Dhaundiyal S., Pandey S., Tyagi M., Bachheti R.K., Rai N. Biocontrol: a bibliometric analysis of microbial biocontrol research for plant disease management. Journal of Plant Protection Research. DOI: 10.24425/jppr.2026.3256

Review

Biocontrol: a bibliometric analysis of microbial biocontrol research for plant disease management

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Received: March 22, 2026

Accepted: May 11, 2026

Online Pree-Proof Publication: May 26, 2026

Responsible Editor: Aneesa Batool

DOI: 10.24425/jppr.2026.3256

Abstract

Biocontrol has enormous potential to replace chemical pest management as a sustainable alternative, especially in tackling plant diseases with microbes. This study provides a basic outline of the research impact, trend progression, and interdisciplinary relationships in biocontrol studies via a bibliometric analysis integrated with a systematic literature review.

The bibliometric technique of traversing dominant themes, emerging trends, and interdisciplinary connections has piqued the interest and attention of researchers and their collaborators worldwide; however, a definitive conclusion can be drawn only after studying the methodological similarities and differences between the papers, for which more such analyses are required. This bibliometric analysis facilitates understanding of the severity and economic detriment implicated by plant pathogens in tandem with further research work on the application of biocontrol methods. Publications from Scopus (2004–2024) were analyzed using RStudio, complemented by a PRISMA-directed systematic review of methodological frameworks to determine the severity of research on combating plant pathogens. Publication output, country contributions, authorship patterns, citation metrics, and keyword occurrences were interpreted cautiously because the final subset is relatively small and reflects database and screening choices. The present study, therefore, integrates both approaches and also revealed that India contributed the highest number of papers within the final dataset of 39 papers, and that the literature is distributed across multiple journals and publishers, propounding a disjointed yet interdisciplinary field. The authors of this research do not claim any national or technological supremacy based solely on publication counts but position their findings as an exploratory overview of a screened Scopus dataset. Emphasis on the mechanisms that vary by strain, host, pathogen, and environmental context has also been laid. In summation, a network or graphical representation can be helpful in understanding a research problem and its efficacious remedial measures, here, 'plant diseases' and 'biological control,' respectively.

Keywords: biocontrol, bibliometric, microbes, plant diseases, research impact

Introduction

Science is the catalyst for change, and journals play a vital role in promoting and sharing influential research by curating, improving, and disseminating information. Over time, the actual impact of a research paper can be measured by the inspiration it kindles in further studies. Sharing research discoveries is crucial for advancing science (Colavizza *et al*. 2021). However, in the age of data abundance and data-driven prediction and discovery, publications are evaluated based on their publication, location or citation count, aside from their actual contribution to knowledge. Citation metrics, publication-related metrics, science mapping, and network analysis are widely used to assess the scientific performance of individuals and organizations (Askarov *et al*. 2022). Limited data on plant mortality rates and lifetimes, especially in older stands, impede efforts to understand and anticipate long-term ecosystem dynamics and phytopathogen attacks. In integrated plant disease management and sustainable agroforestry, inaccurate 'data crunching' or 'information interpretation' could disconcert the efforts to solve the problem effectively (Murariu *et al.* 2025). Ensuring the availability of diverse, extensive datasets is crucial when dealing with different types of data. The growing accessibility of information from various open science initiatives, including Web of Science, Scopus, PubMed, and Google Scholar, presents new opportunities for comprehensive databases that can facilitate bibliometric analytical studies. The analysis above provides a roadmap for further research and highlights the relevant research constituencies and trends assessment, which can help save a lot of time for further studies. In any case, the use of an open science database, the precision of keywords, and the conciseness of the filters used determine how successful data interpretation is.

Deforestation and desertification have been known since ancient times. Still, there is a likelihood that the global goal to end habitat destruction and food insecurity by 2030 will not be met. There are two major goals which should be emphasized: improving conservation to protect biodiversity and mitigating climate change (Wijerathna-Yapa & Pathirana 2022). Plant diseases and infestation form a significant part of plant cover loss, damage and serious mortality They form a major setback to ensuring an adequate supply of food, fiber, and biomaterials, especially considering the need to increase global food production by at least 70% by 2050 (Savary *et al.* 2021). This pressing issue, therefore, makes it imperative to find sustainable solutions. The unambiguous and precise research gaps in these areas include the lack of open and high-quality data about plant disease mortality and phytopathogen attacks. The problem of data availability persists and its enforcement policies are inadequate. Some methodologies can be misleading or incorrect due to specious conclusions. Elimination of redundant data can be technically challenging, and the evolution of bibliometrics related to specific fields is still evolving (Donthu *et al.* 2023)

Biocontrol technique to address the universal predicament

Plant diseases can be overcome by adopting resistant cultivars and genetic engineering; however, their development and growth time (in the case of trees) requires lengthy amounts of time, and incurs noteworthy approval costs. Furthermore, while disease-resistant plant types are successful at managing many illnesses, their resistance can deteriorate after a few years of release due to various variables such as pathogen changes, recombination events, and reduced field resistance. Chemical management has been widely utilized to raise crop yields by protecting crops against pests and diseases, thereby improving crop quality and agricultural production.

However, chemical fungicides have been linked to detrimental side effects such as food contamination and biomagnification, environmental pollution, and higher food production expenses. Many pesticides are also toxic to beneficial insects and soil fungi that can make their way into the food chain. These chemicals deposit on crops and yield. Biological control is safer than harmful pesticides, as it provides a method for controlling plant diseases and pest infestations. Biological control includes the deployment of natural biocontrol agents (for example: bacteria, fungi, viruses, nematodes, parasites, etc.) or 3P's predators, parasites, and pathogens to eliminate plant pests and diseases. These biological treatments can interrupt pest life cycles, reduce pest populations, and prevent disease transmission. Biological control, by harnessing nature's power, provides a long-term, sustainable and ecologically benign solution. Microbial biocontrol involves the use of microorganisms to suppress plant pathogens through mechanisms such as antibiosis, competition for nutrients and space, mycoparasitism, induced resistance, and volatile-mediated inhibition.

Their implementation requires a detailed understanding of the target pests and diseases, as well as the interconnections between them, their natural enemies, and the host plants. It involves accurate testing and experimentation, and, before selection, monitoring their efficacy, adaptability, and management accordingly. Successful implementation of biological control can reduce dependence on chemical pesticides, reduce environmental impacts, and promote the long-term health and resilience of forest and agricultural ecosystems (Rahman *et al.* 2018). Previous studies cited in the manuscript show that taxa such as *Trichoderma*, *Bacillus*, *Pseudomonas*, *Streptomyces*, and several yeasts can combat and reduce disease incidence through multiple defense and synthesis mechanisms. This makes microbial biocontrol a scientific necessity and a practically relevant area for plant pathology, phytoprotection, and sustainable agriculture and forestry (Ntyam Mendo *et al*. 2023).

However, bibliometric analyses can only map out how the literature is distributed and discerned; they cannot by themselves establish the efficacy of field trials, consistency across varied environments, or superiority over all other plant disease-management strategies. The reliability of bibliometric interpretation depends on how reproducible the search strategies are. The more logical and transparent the screening process is, the more clearly defined the indicators are, and normalized keywords become.

This study inculcated the following objectives: description of publication trends related to biocontrol in plant disease management, identification of leading countries, authors and thematic areas within the selected microbial-biocontrol dataset and summarizing microbial agents along with their modes of action against phytopathogens.

Materials and Methods

Data collection

This study utilized the Scopus database to examine the most frequent authors in the key term ‘biocontrol,’ along with their associated organizations and countries. It also identified the most commonly cited research papers. It was explicitly acknowledged that reliance on a single database can be limiting and may affect citation clarity, country counts, and source distribution relative to multi-database studies. The present work should therefore be considered as a structured Scopus-based overview rather than a comprehensive map of the entire microbial biocontrol literature. This study employed bibliometric indicators to analyze the output and standing of this strategy for controlling pathogens and other outbreaks. It also utilized tools such as bibliographic coupling, keyword analysis, and co-authorship analysis to conduct scientometric analyses, highlighting emerging research in this field. This analysis technique examined published research to map how the field has grown and shifted, revealing new directions and connections between ideas. Furthermore, this article provided a brief analysis and literature review of numerous microbial biocontrol approaches published across different periods of journals. The Scopus database was utilized, the key- biocontrol was entered and 20 years from 2004 to 2024 were filtered. Only plant and agricultural science-related journals were accessed (Fig.1). The examination of authors who have published on this theme, their journals, associated institutions, and home nations, among others, followed. Likewise, the most frequently cited articles were identified and mapped. This research employed bibliometric measures to assess the output and reputation within plant pathology and sustainable agriculture. In addition, it used tools such as bibliographic connections, keyword analysis, and co-authorship analysis to examine growth rates and recent trends. Moreover, the research offered a time-based examination of the current state and future scope for conservationists.

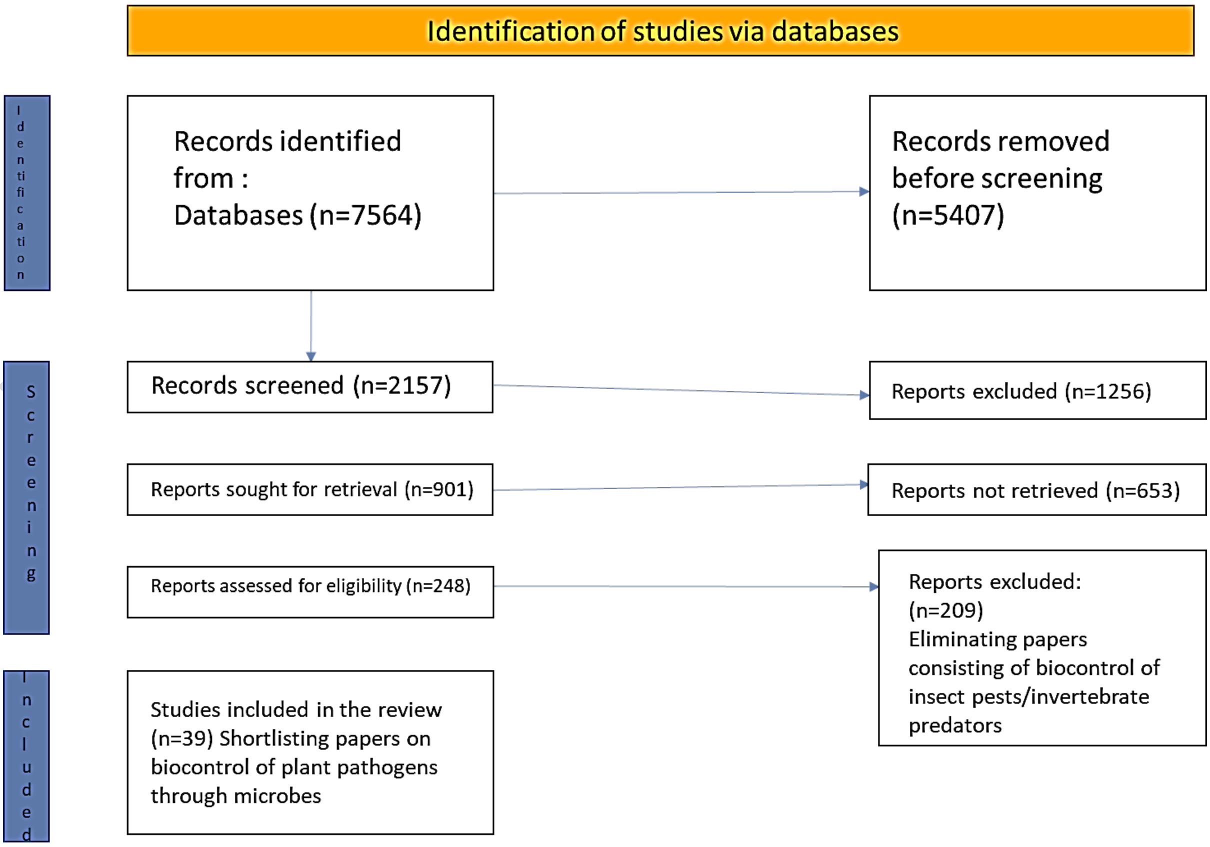

Fig. 1. Prisma flow diagram of data search and shortlisting process undertaken in this bibliometric analysis using the keyword 'biocontrol'.

Data Screening

The broad retrieval generated 7,564 records . Of these, 5,407 were excluded because they mainly addressed insect or other invertebrate pest biocontrol rather than plant disease management. The remaining 2,157 records were retained as the plant disease-related subset for further screening. A narrower microbial phytopathogen-focused screen then produced a final analytical subset of 39 records used for exhaustive microbial biocontrol-specific analyses and for the narration of representative agents and mechanisms.

During the screening process, as depicted in the Prisma flow diagram, studies were excluded if they were duplicates, irrelevant to microbial biocontrol of plant diseases niche, focused on insect or invertebrate pest biocontrol, were related to biocontrol via other organisms, or biopesticides excluding microbes, were inaccessible in full text, or did not meet the predefined eligibility criteria after full-text assessment.

By explicitly distinguishing 7,564 broad records, 2,157 plant disease-related records, and the final microbial biocontrol 39-record analytical subset, the study presented a more transparent workflow and led to lesser ambiguity around the meaning of the PRISMA-style screening process. This also accentuated the fit between the stated methodology and the measure of the conclusions. The final screened subset is therefore a more focused, exploratory interpretation of microbial biocontrol literature relevant to plant diseases.

Here is a reproducible Boolean query search on microbial biocontrol for plant diseases:

PUBYEAR > 2003 AND PUBYEAR < 2025

AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "BIOC"))

AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))

AND LANGUAGE (English)

Inclusion and exclusion criteria

Studies included were those that focused on microbial biocontrol of plant pathogens and had relevance in plant pathology, crop protection, forestry, or postharvest disease management. Studies dealing primarily with insect pest biocontrol, non-plant systems, unrelated biological interactions, duplicate or inaccessible records, or topics outside the plant disease–microbe context were excluded. There was a reduction in records, which justified topic refinement and organized eligibility assessment rather than arbitrary exclusion.

Limitations

This study has data retrieved only from Scopus and, therefore, may not cover all relevant records indexed exclusively in other databases like Web of Science, Dimensions, PubMed, or Google Scholar. Therefore, the findings from this study should be interpreted as a structured Scopus-based overview rather than an exhaustive global survey of all microbial biocontrol literature.

Results

Publication analysis

Long-term publishing patterns (for example, annual publication counts and growth rates) were identified. Analysis of publication results by geography, institution, or journal was also conducted. Different types of publications (such as articles, reviews, and conference papers) could also be classified (Fig. 2-7).

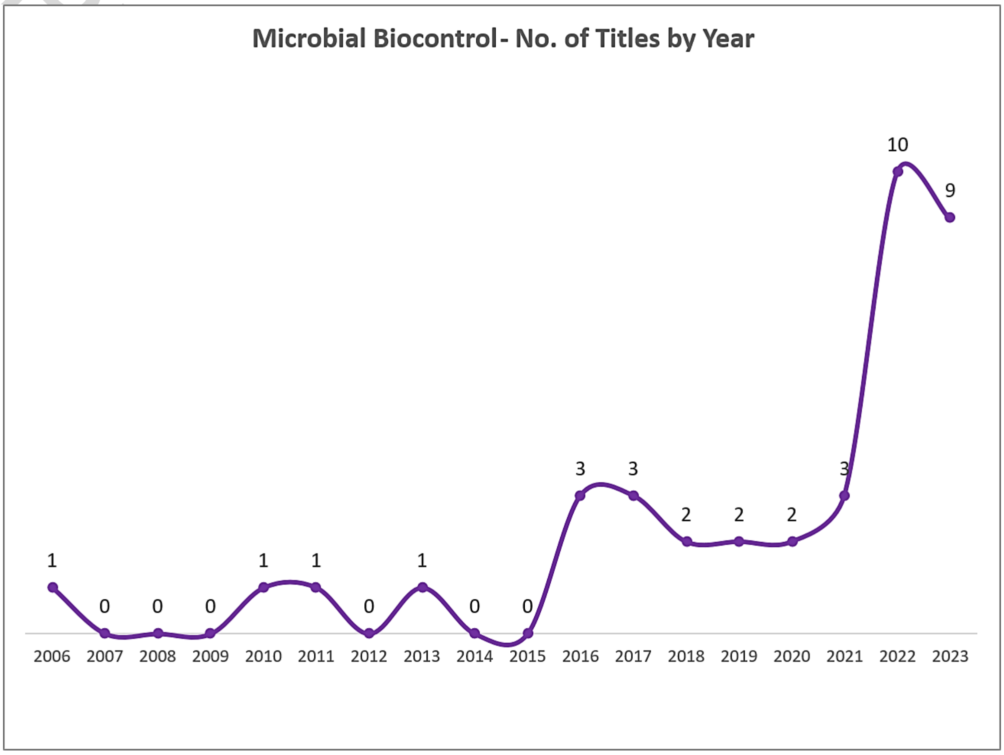

Fig. 2. Line graph depicting the number of papers written on biocontrol of plant pathogens using microorganisms.

The abrupt increase of articles from 2021- 2022, suggests a possible surge of research and study on the topic highlighting its significance in the present world. The data also may suggest growing scholarly attention within the particular niche in a highly filtered research sample. This selected literature depicts low but increasing publication activity over time, with the highest annual count observed around 2022 in the visualization of the original dataset.

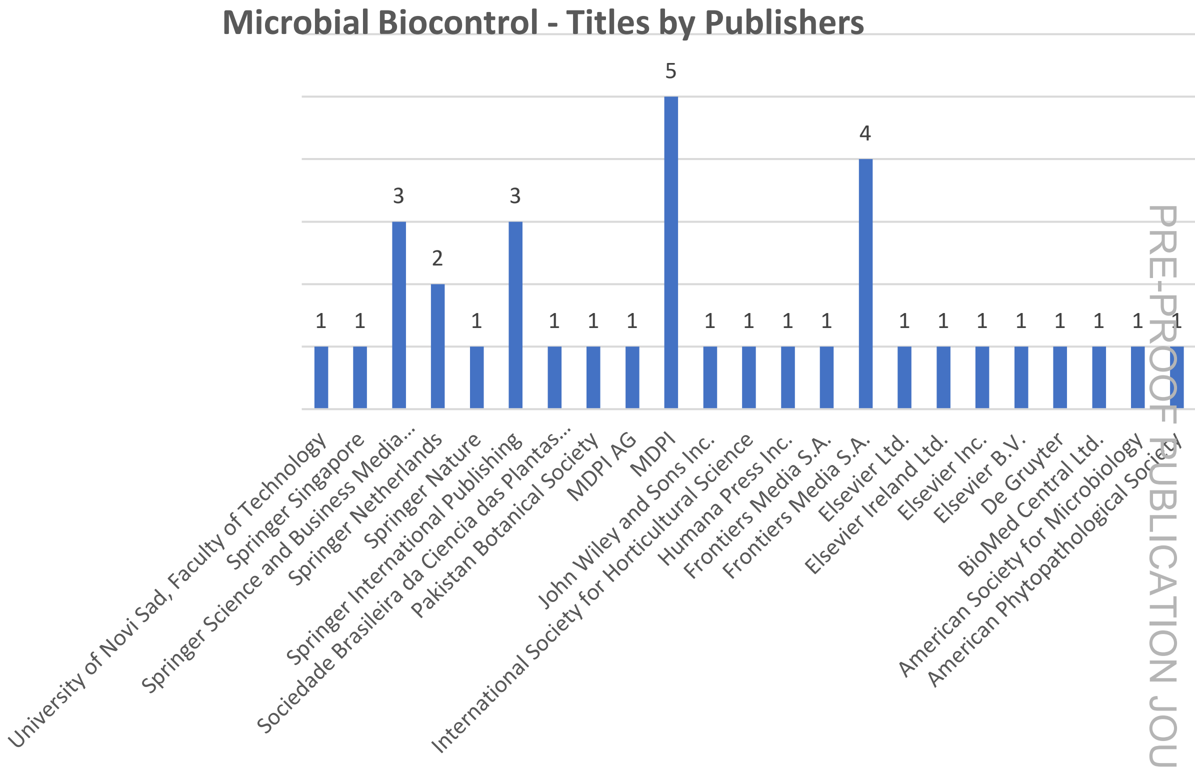

Fig. 3. Number of papers across various publications.

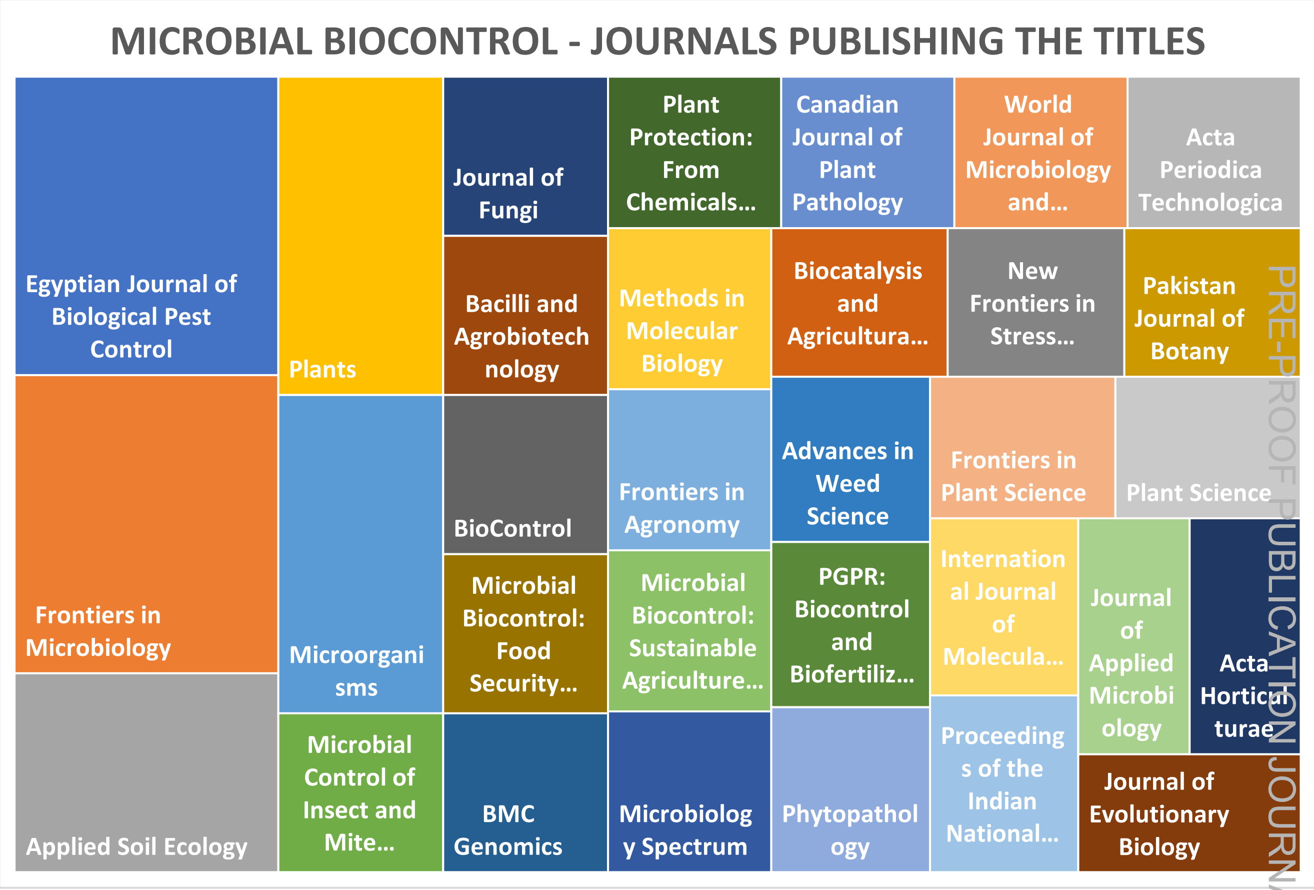

Fig. 4. The boxes with bigger sizes refer to a greater number of papers published in this realm.

Many outlets contribute only one publication to each journal. In bibliometric terms, this dispersion is suggestive of fragmentation of the literature, but it may also indicate that this field is interdisciplinary rather than consolidated within a few journals. It deals with only microbial biocontrol research, spanning multiple domains, including plant pathology, microbiology, food science, postharvest biology, and sustainable agriculture. Therefore, the field appears interdisciplinary rather than consolidated within a small number of specialist journals.

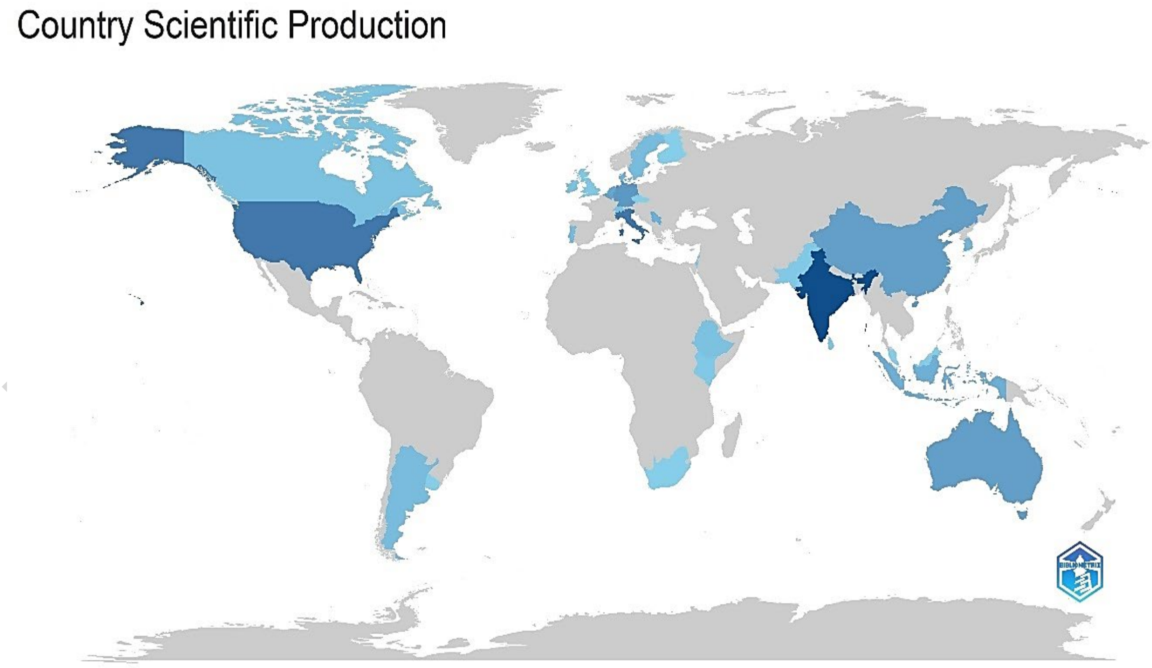

Fig. 5. Country-wise scientific literature production: India producing the maximum number of papers

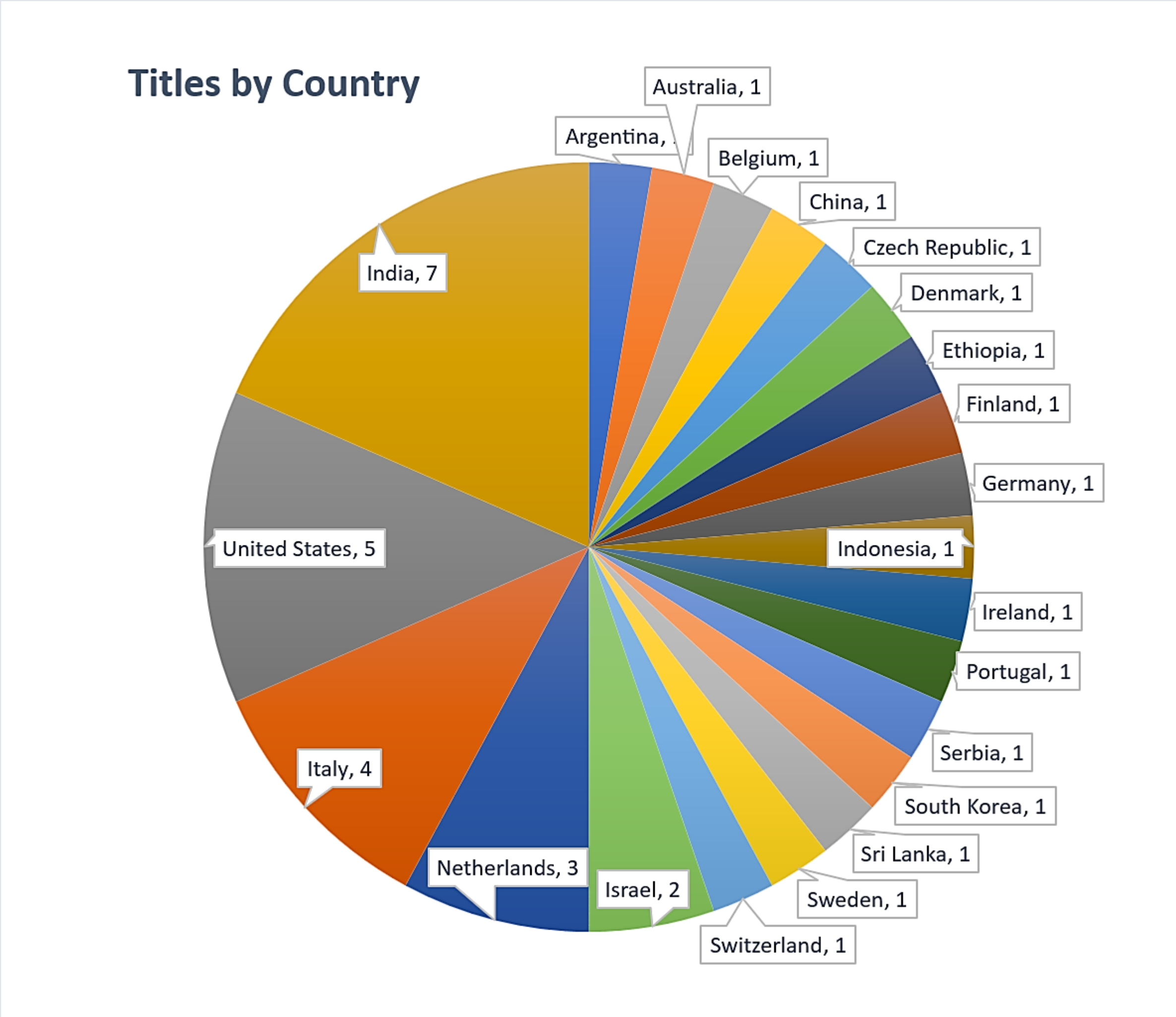

Fig. 6. Country-wise count of published papers

It can therefore be interpreted that India occupied the top position in the visualizations provided by the dataset, while the remaining data along country distribution was comparatively smaller and spread across multiple countries. This geographic pattern may reflect both research priorities on a regional scale and indexing boundaries of the selected database.

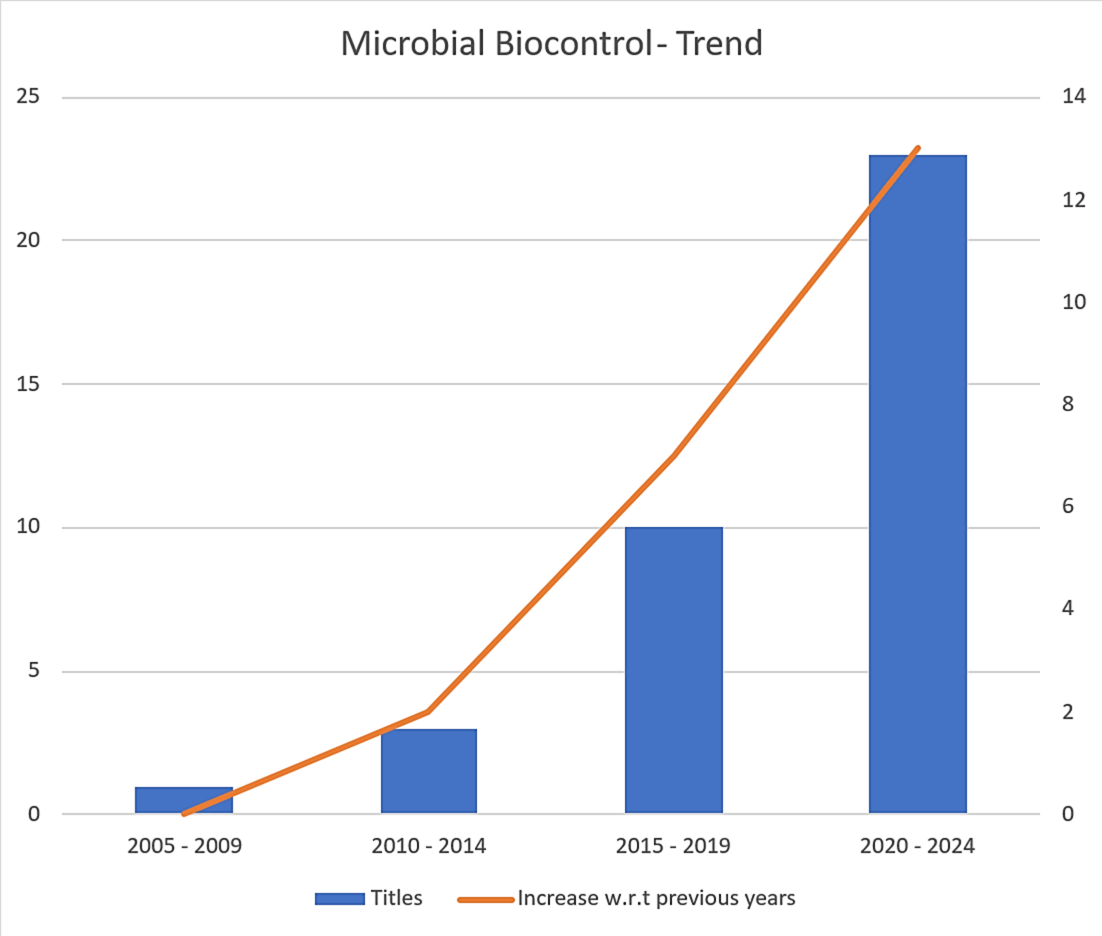

Fig. 7. Increasing popularity trend based on every four years, as shown in the graph

Citation analysis

The bibliometric analysis was performed using the *R* statistical computing environment (R Core Team 2024), available at https://www.r-project.org/, and the "bibliometrix" package.

A few tools and analysis techniques are listed hereunder: Calculating citation metrics such as total citations, citations per paper, and h-index.

Local citations are defined here as citations received within the retrieved study dataset, and global citations as citations recorded in the source database. It is used to identify and rank influential authors within specific networks, such as co-authorship networks or citation networks. This incorporation of neighboring authors gives a refined view of an author's impact within a localized context (Fig. 8-9) (Norris *et al.* 2010). The *h*-

index, in normal terms, can be defined as the maximum value of h such that the given author/journal has published at least h papers that have each been cited at least h times (Hirsch 2006).

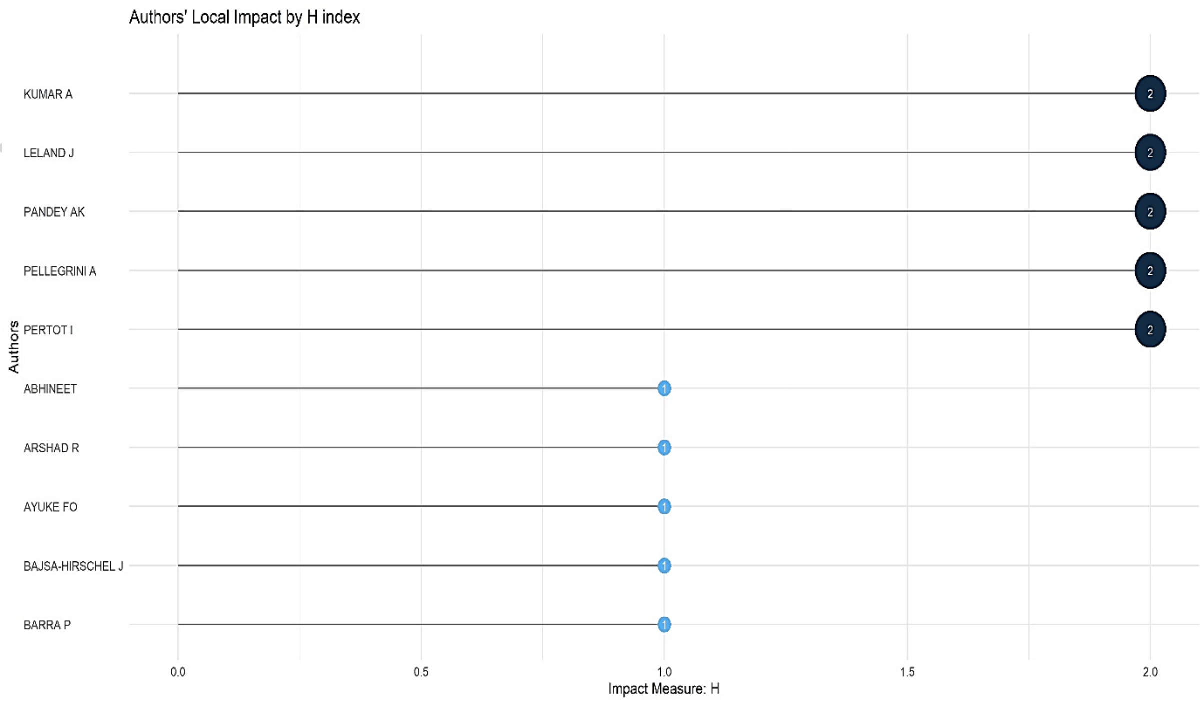

Fig. 8. H index measuring local impact.

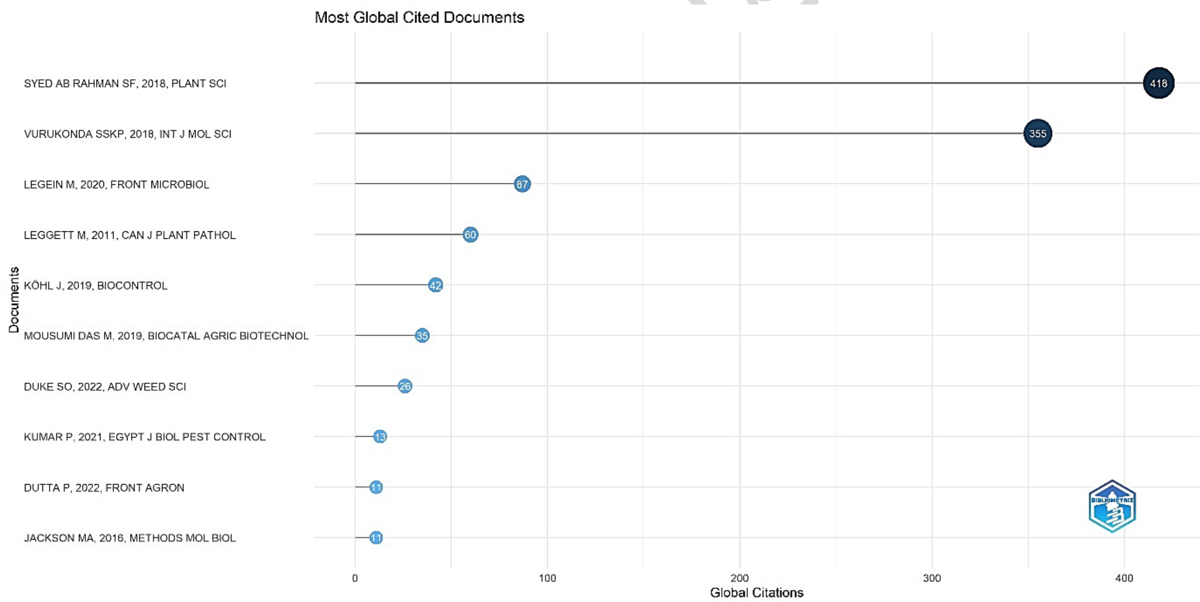

Fig. 9. Global impact measured author-wise

Discernment and prioritization of prominent authors within particular networks, including those of co-authorship and citation, is also provided within this software. Such influence from adjacent authors gives rise to an approach that yields a more intricate understanding of an author's effect in both local and global settings (Norris *et al*. 2010). Local citations refer to the number of times a paper is cited within a specific dataset or context. These are results of limited sets of academic publications usually accessed from a particular database or collection. Global citations use indexed publications in expanded databases such as Scopus, Web of Science, or Google Scholar to cite a document. Here, Syed AB Rehman SF 2018 made the maximum global contribution (418) to the theme "biocontrol of plant diseases through microbes" (Fig. 10). It also identified highly cited contributions, including the widely referenced 2018 review on emerging microbial biocontrol strategies.

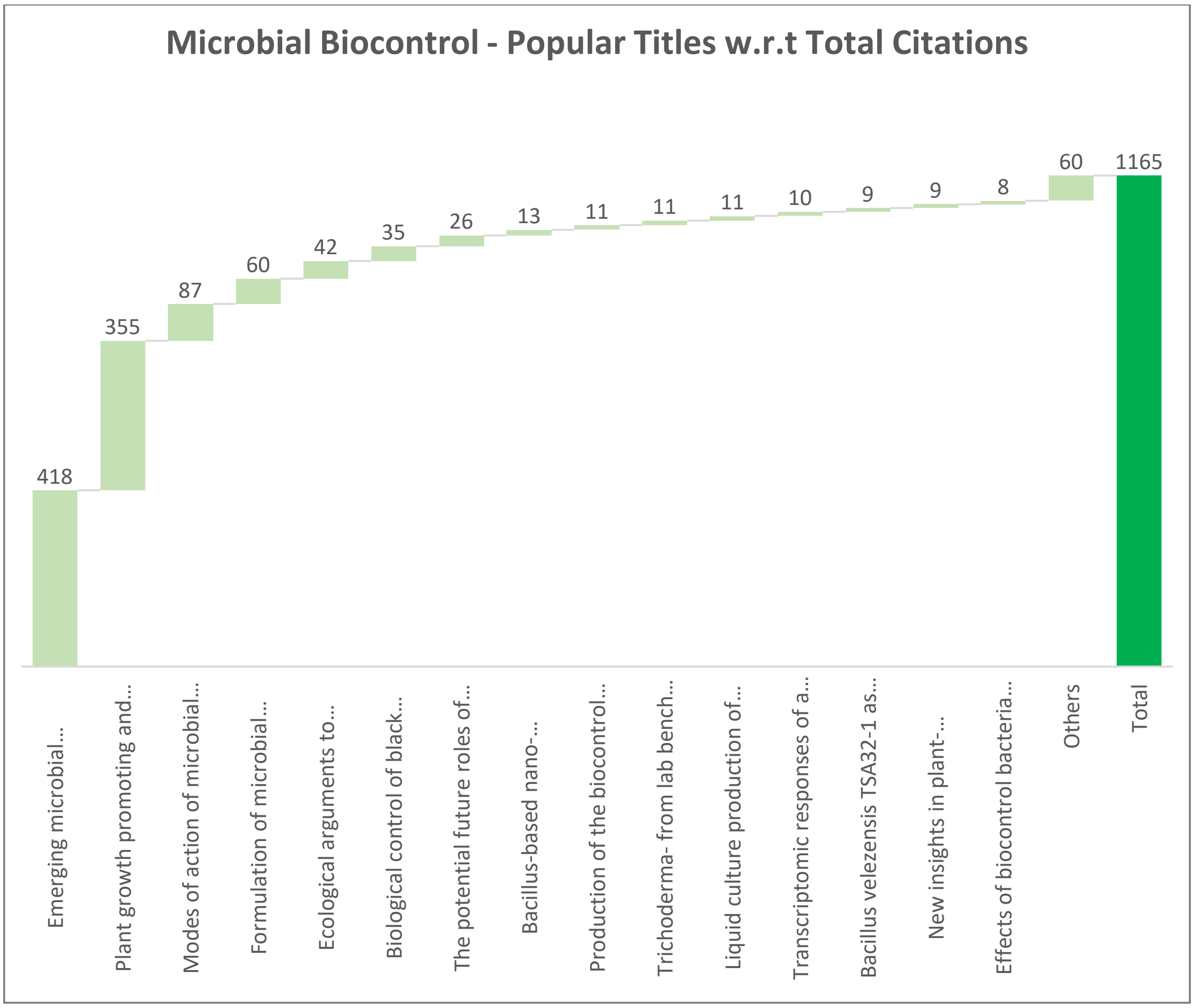

Fig. 10. Waterfall chart of the most popular papers concerning their citations

Author analysis

The author analysis includes

- Identifying prolific authors and their publication output.
- Analyzing author collaboration networks to identify key collaborators and research communities.

The author's collaboration extent can be measured using the formula: 1- (Total publications/No. of contributing authors). The value always lies between 0 and 1 and is termed the collaboration coefficient. In this case, it measures 0.75, indicating substantial multi-author contribution in the field (this metric is treated as a descriptive authorship indicator rather than a definitive methodological claim) (Chou 2024) (Fig. 11, 12).

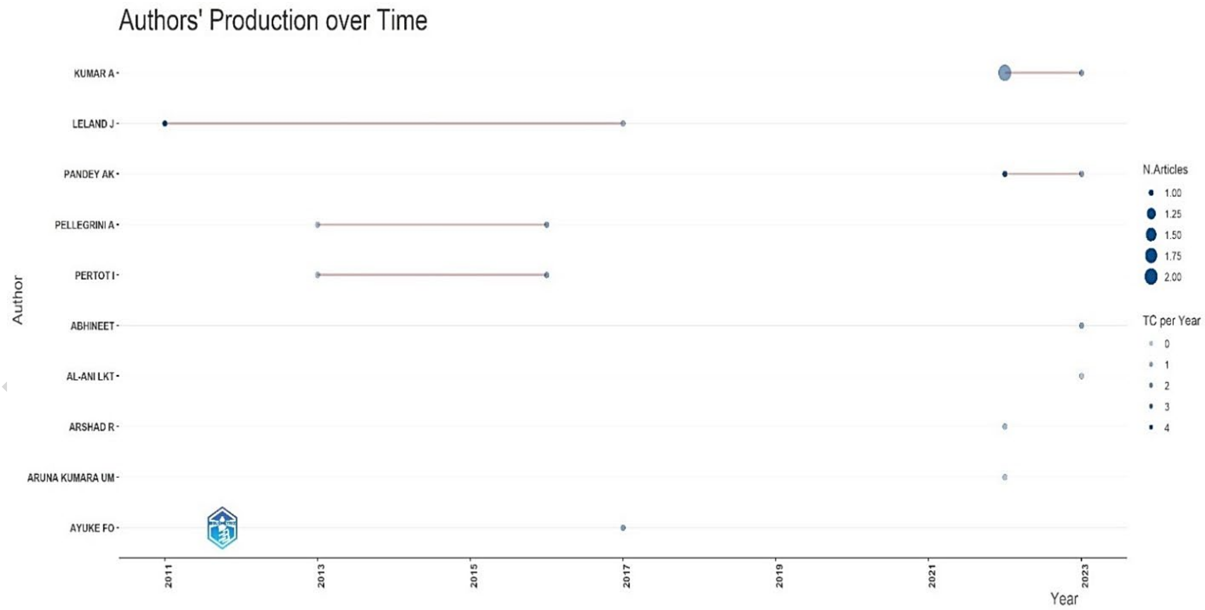

Fig. 11. Number of publications authored by an individual across different time intervals.

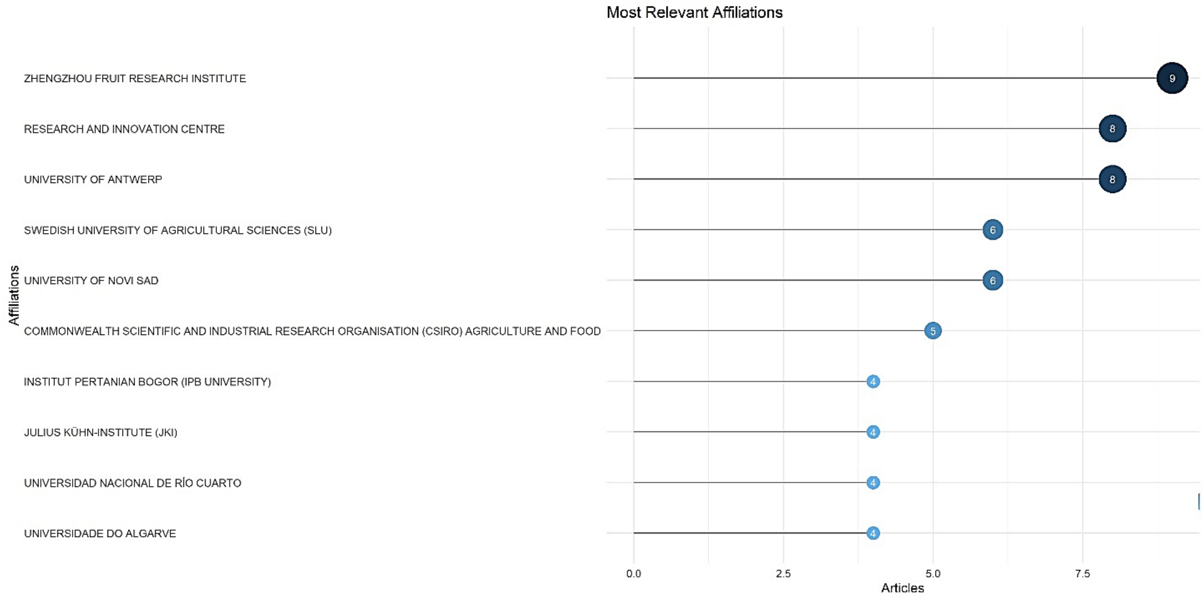

Fig. 12. Most relevant author collaborations along with the number of articles published. This is aimed at analyzing institutional collaboration networks to identify partnerships and research networks.

Essentially, Lotka's law highlights the uneven distribution of scientific productivity among authors. It implies that a few prolific authors contribute significantly more than the majority of authors who produce only a small number of papers. Lotka's law sheds light on the disparity in scholarly output and provides a framework for understanding author productivity in scientific research (Nattar 2019). As can be observed in the above graph, the dotted line represents the pattern suggested by Lotka's Law, where more than 75% of the authors tend to write one paper, less than 25% write at least two papers, and less than 5% of authors write two papers.

Similarly, based on the papers analyzed in Biocontrol Through Microbes**,** the solid line follows the same trajectory as Lotka's Law suggests (Fig. 13). This uneven productivity distribution is a feature of many scientific domains and supports the view that microbial biocontrol research includes a limited number of repeat contributors encased by a broader peripheral community.

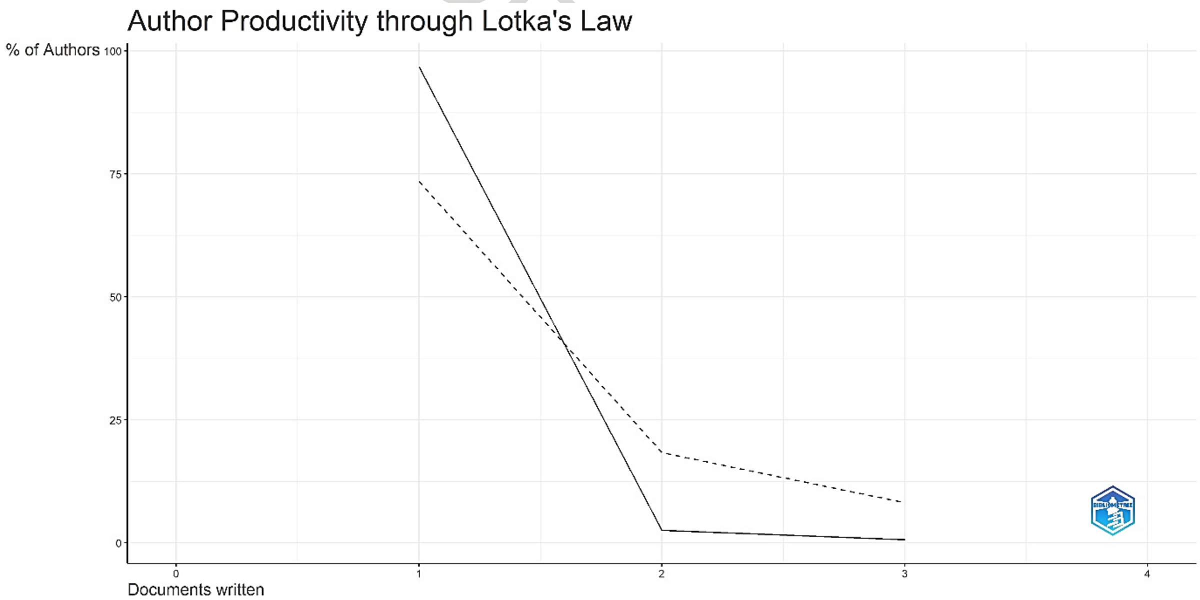

Fig. 13. Lotka's law states that the number of authors who write x contributions (such as research papers) in a given period is a fraction of the number of authors who write a single contribution.

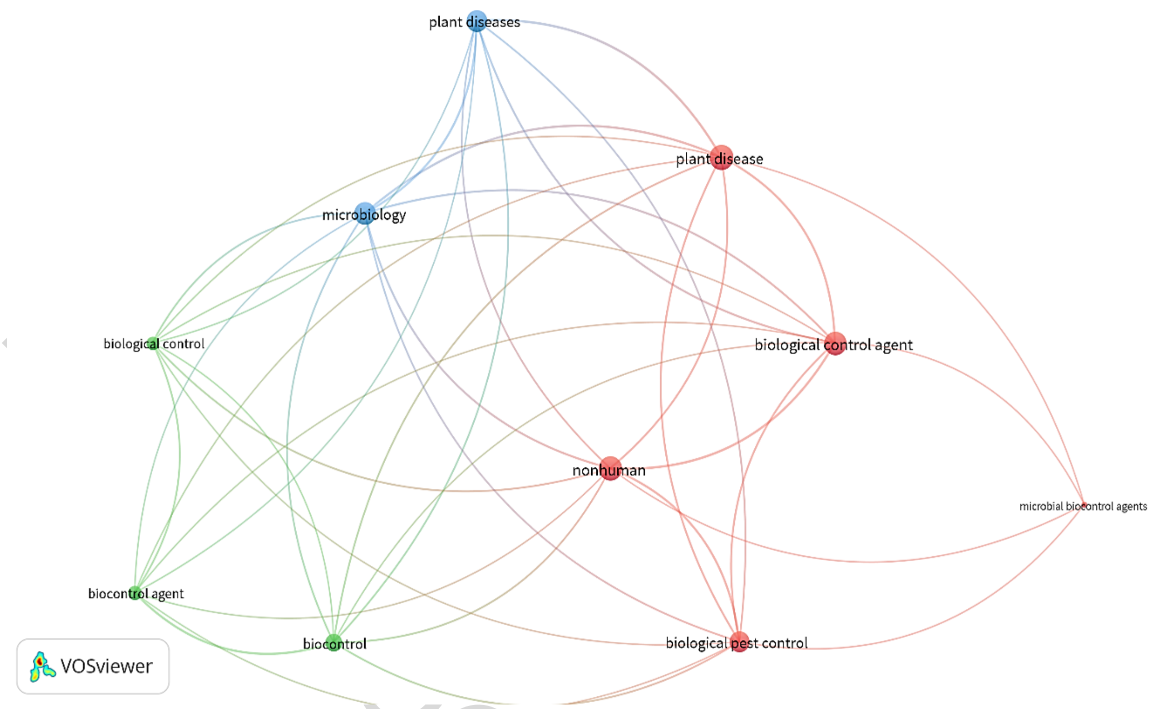

Fig. 14. The most relevant 10 keywords and their interconnections.

The most trending terms after assessment were non-human, plant disease, biocontrol agent, and biological pest control. Based on keyword analysis, it was emphasized that generic or database-generated terms should be separated from biologically informative author keywords before conducting final thematic interpretation.

Discussion

Keywords are very important when searching open scientific repositories for materials, as they should reflect the subject matter or area under study. Keywords should therefore be specific and limit the searches to only the most relevant documents. Generalized terms may not work well, since they yield too many unnecessary search results, making it difficult to identify significant trends. Further narrowed-down filters would be concise and available (Fig. 15).

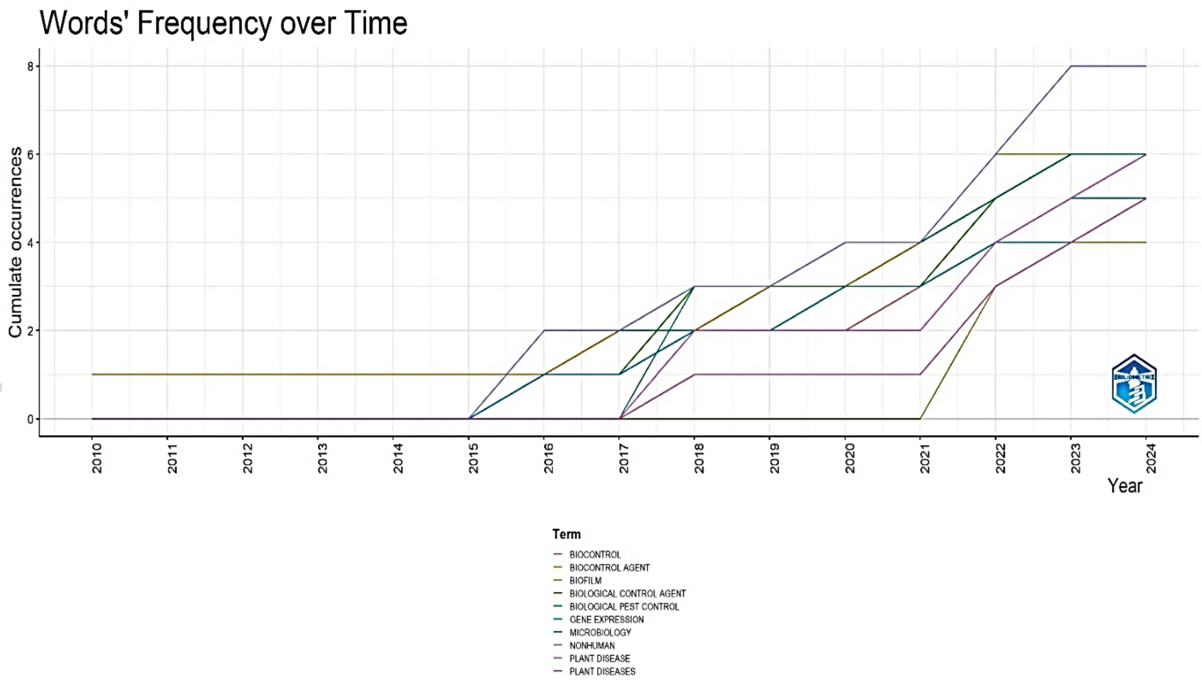

Fig. 15. The most trending terms after assessment were plant disease, biocontrol agent, and biological pest control. Only after the removal of irrelevant indexing terms, like "non-human", can final biological conclusions be drawn.

It is encouraging to see a shift away from limited evaluation measures, such as publication records. What is now necessary is careful consideration and collaboration to ensure that the alternatives prove more effective.

Research impact assessment

It provides a visual roadmap of scholarly themes, enabling a deeper understanding of research landscapes and facilitating informed choices in academic endeavors (Parlina *et al.* 2020). These two-dimensional plots explore the proximity of clusters to understand thematic similarities or differences.

Motor themes indicate high centrality and density, and emerging or declining themes indicate low centrality and density (Fig. 16).

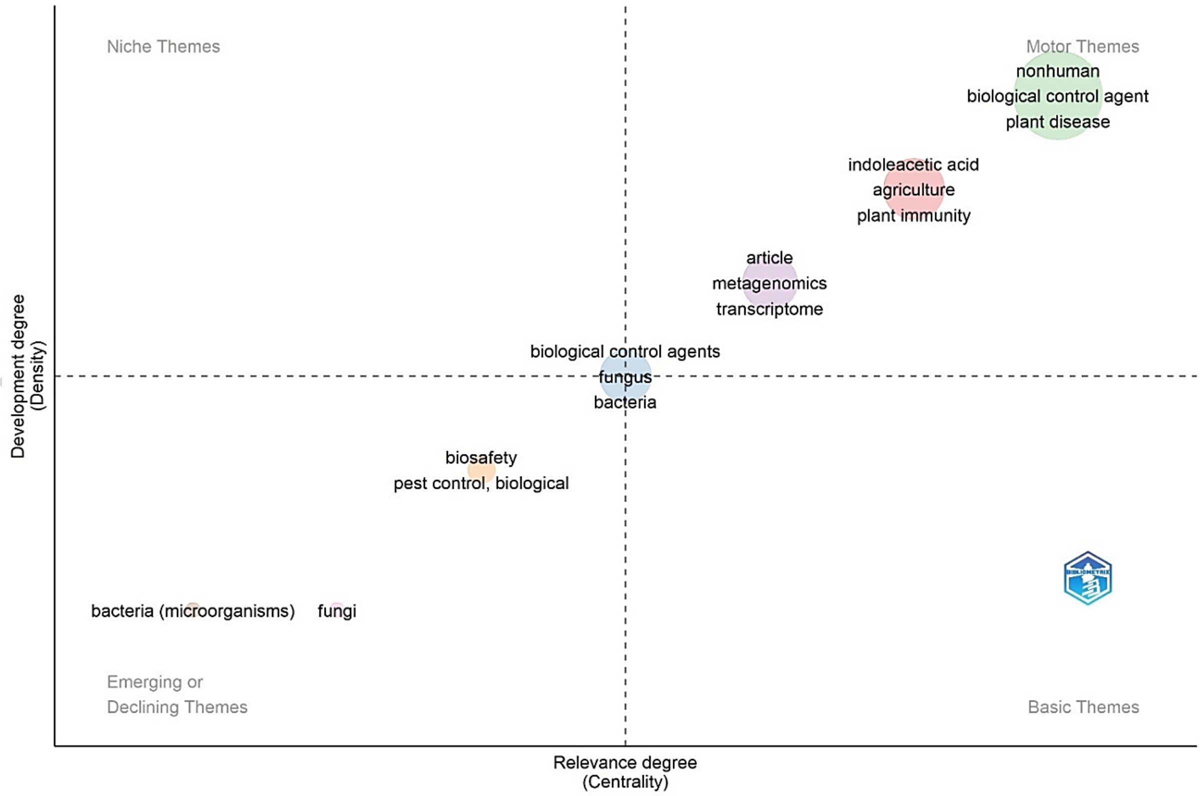

Fig. 16. A thematic map in bibliometric analysis

These thematic maps can be best interpreted as exploratory tools that help in positioning microbial biocontrol within broader plant-health and sustainable agroforestry addressal rather than as definitive predictors of future research trajectories.

Multiple commercial PGPR-based biopesticides targeting a broad spectrum of phytopathogens (fungi such as *Fusarium, Rhizoctonia, Sclerotium*, and *Pythium*; bacteria; nematodes; viruses) are available. In India itself, there is a variety of commercial multi-strain consortia (*Pseudomonas, Bacillus, Trichoderma*) for integrated pest management in crops like vegetables, pulses, and cereals. For forest trees and other plants, there is a paucity of commercialized biopesticides and biofungicides, making this a relevant and significant field to be explored and researched (Tadesse *et al*. 2025). Expounding on the key broad-spectrum commercial biofungicide formulations, there are *Pseudomonas fluorescens*-based PGPR fungicide (MagicGro (Organicabiotech)), PGPR consortium (*Bacillus subtilis* + *Pseudomonas*)-BS-Pro (Mangalam Agro Tech), *Pseudomonas* + *Bacillus* + *Trichoderma* (2×10^8 CFU/ml), *Pseudomonas*-based biofungicide- Pseudo Care (Bannari Biofertilizers), amongst others.

Filters make it possible to specify criteria such as publication date, author, journal, or research subjects of particular interest. In this way, a focused scrutiny is conducted on the attributes of the data that best describe the significance of the research topic or the focus of analysis. This method saves time while ensuring that data interpretation and trend derivation are targeted and relevant to one's research goals.

There was an attempt to demonstrate the disparity in scholarly output and a framework for understanding author productivity in scientific research on microbial biocontrol measures. Moreover, this analysis highlights the importance of evaluating research impact beyond traditional measures like publication records. An illustration of the use of bibliometric analysis and thematic mapping to provide a visual roadmap of scholarly themes and facilitate trend assessment is provided. The main goal was to improve conservation efforts in order to protect biodiversity. Issues like deforestation and food insecurity were brought to light. The importance of preventing and managing plant diseases and infestations to ensure a stable food supply via making information accessible from various sources can enhance research coherence and provide a roadmap for future studies. Based on the above metrics and research outcomes, and growing popularity among researchers, the environmental sustainability, economic feasibility, efficacy, consistency, and overall supremacy over biopesticides and biofungicides, the future potential and necessity of research and application of biocontrol measures need no more explanation. However, a precautionary measure for readers would be not to over-rely on citation metrics. This analysis also does not exclude non-traditional forms of scholarly output. A few concrete examples of the research conducted and case studies illustrating the effectiveness of the microbial biocontrol agents are cited in **Table 1.**

Table 1. Summary of some biocontrol agents and their modes of action against plant and crop diseases

Biocontrol Agent	**Mode of Action**	**Reference**

Trichoderma spp.	Competition and Mycoparasitism**:** *Trichoderma* species compete with pathogenic fungi for nutrients and space. They also produce antifungal compounds that inhibit the growth of pathogens**.** **-** Induced Systemic Resistance (ISR)**:** Trichoderma primes the plant's immune system, making it more resistant to diseases.	(Bastakoti *et al.* 2017)
Bacillus subtilis	Antibiosis**:** *Bacillus subtilis* produces antimicrobial compounds that directly suppress pathogen growth**.** Lipopeptide and hydrolytic enzymes production, biofilm-associated colonization. **-** Induced Systemic Resistance (ISR)**:** Similar to Trichoderma, it enhances the plant's defense mechanisms.	(Caulier *et al.* 2019)
Pseudomonas fluorescens	- Antibiosis: *Pseudomonas fluorescens* secretes antifungal compounds like henazine-1-carboxylic Acid (PCA), 2,4-Diacetylphloroglucinol (DAPG), pyrrolnitrin, and Hydrogen Cyanide (HCN**)** that inhibit pathogenic bacteria and fungi. **-** Iron Competition: Mostly produces siderophores to outcompete pathogens.	(Höfte, M. 2021)
Streptomyces spp.	Antibiosis, extracellular metabolite production and Induced Systemic Resistance (ISR)	(Zhou D *et al.* 2022)

Streptomyces malaysiensis	Hyperparasitism: It infects and suppresses the banana wilt pathogen (caused by *Fusarium oxysporum*).	(Zhang *et al.* 2022)
Penicillium spp.	- Antagonism: *Penicillium* species produce antifungal metabolites that inhibit pathogen growth.	(El-Sayed *et al.* 2023)
Bacillus cereus	- Antibiosis**:** *Bacillus cereus* secretes antimicrobial compounds like chitinases, proteases, cellulase, and β-glucanases that directly suppress pathogenic bacteria and fungi.	(Farina *et al.* 2024)
Bacillus amyloliquefaciens	- Antibiosis*: Bacillus amyloliquefaciens* produces antimicrobial compounds that suppress pathogenic bacteria and fungi	(Zhou Q *et al.* 2020)
Stenotrophomonas maltophilia	- Antagonism**:** *Stenotrophomonas maltophilia* produces antimicrobial compounds that inhibit plant pathogens.	(Sharma *et al.* 2024)
Xanthomonas spp.	Induced Systemic Resistance (ISR)**:** *Xanthomonas* species enhance the plant's defense mechanisms.	(Marin *et al.* 2019)
Pichia membranifaciens and Wickerhamomyces anomalus	Antagonistic Capability**:** Alginate biofilms containing either *W. anomalus* ***or*** *P. membranifaciens* also limited the incidence of fungal decay caused by *B. cinerea*	(Błaszczyk *et al.* 2022)
Saccharomyces cerevisiae	Antifungal Compounds, Nutrient Competition, Pathogen Germination Inhibition, Killer Activity, Production of Hydrolytic Enzymes.	(Lopes *et al.* 2015)

Lactobacillus plantarum	The strain exhibited excellent antifungal activity against *B. cinerea* through mechanisms such as parasitism, antibiosis, and competition.	(Chen *et al.* 2022)
Pseudomonas synxantha	It was discovered that the production of an antifungal compound inhibited the growth and development of both *Monilinia fructicola* and *Monilinia fructigena*. It also induced systemic resistance in stone fruits, making them more resistant to fungal pathogens.	(Aiello *et al.* 2019)
Rhodotorula minuta	The isolated antifungal protein strongly inhibited *Colletotrichum gloeosporioides* and is a candidate biocontrol agent.	(Ahima *et al.* 2019)
Stenotrophomonas Rhizophila	The antagonistic yeasts and bacteria produced various secondary metabolites, which include enzymes and antimicrobial agents. These also enhanced the suppression of fungal growth. Moreover, the biocontrol agents elicited systemic resistance in mango plants, enhancing their intrinsic mechanisms to counteract anthracnose infection.	(Hernandez *et al.* 2017)
Lactobacillus acidophilus	The growth of pathogenic fungi is inhibited through competition for nutrients and space. However, *Lactobacillus* species produce antimicrobial compounds, including organic acids and bacteriocins, which enhance their biocontrol activity.	(Fenta *et al.* 2021)

Bacillus velezensis	*Bacillus velezensis* produces several antifungal compounds, including cyclic lipopeptides and volatile organic compounds. Their mechanisms of action include disrupting the *Aspergillus flavus* cell membrane and inhibiting its enzymatic functions, leading to growth and reproductive inhibition.	(Li *et al.* 2022)
Clavispora lusitaniae	VOCs have distinct mechanisms. These can inhibit pathogen growth and development by preventing their cellular actions. In addition, these VOCs can induce systemic resistance in host plants, ultimately enhancing their protection against pathogenic attacks. Due to this dual mechanism of action, *Clavispora lusitaniae* can be considered a candidate for biocontrol to safeguard citrus fruits from diseases that may develop after harvest.	(Pereyra *et al.* 2022)

Note: The effectiveness of these biocontrol agents can vary based on environmental conditions, target pathogens, and crop types.

The table avoids unsupportive details and uses an approach that is more appropriate for a manuscript that combines descriptive literature with an overview rather than experimental validation.

Microbial biocontrol research has undergone steady expansion, increasingly drawing attention to the sustainable alternatives to chemical pesticides and fungicides. Thematic maps display a transition from basic toward integrated methods that connect biocontrol with plant health, climate resilience, and food security. Incorporating bibliometric trends with systematic review findings showcases quantitative patterns (publication and citation trends, core themes, influential authors) that should be compared with qualitative measures of efficacy and outcomes. However, the efficacy has not been shown in this review. The significance of biocontrol lies in its capacity to suppress plant diseases and minimize chemical use, protect beneficial organisms, and mitigate environmental concerns, thereby directly contributing to long-term resilience to biotic and abiotic stresses and to agroforestry stability.

The findings demonstrated in this article support the view that microbial biocontrol is an expanding but methodologically heterogeneous research area. The article focuses on a subset of 39 articles rather than a conventional large-scale bibliometric analysis, which by relying on a much narrower, topic-refined subset. This dispersion also means that conclusions about journal prominence remain dataset-specific. Bibliometric analysis aids in addressing this challenge by examining publication output, citation scores, collaboration networks, and keyword inter-relationships. A systematic literature review helps interpret the detailed biological significance of representative studies. The present study, therefore, integrates both approaches and also revealed that India contributed the highest number of papers within the final dataset of 39 papers. Furthermore, the literature is distributed across multiple journals and publishers, propounding a disjointed yet interdisciplinary field.

This bibliometric study emphasized that future versions of microbial biocontrol should include the exact Boolean search query, search date, subject-area restrictions, language filters, document types, metadata to be exported, and keyword-cleaning pathway. Without these elements, bibliometric interpretation remains less reproducible than desirable.

The research gaps in this arena include large-scale field evaluations across diverse ecosystems and an insufficient understanding of contextual performance in terms of soil health and climate change. There is also a paucity of integrated socio-economic factors, including biocontrol, cost–benefit analysis, regulatory practices, and risk perception among stakeholders. Priority must be given to multi-ecological zones, seasons, and locations, as well as to future research directions and multi-location, multi-season trials. Also, multiomics studies on microbial traits, plant and soil processes, and signaling pathways are necessary. Advancements in bibliometric studies would complement these efforts by emphasizing unexplored flora, regions, and pathogens, and by identifying connected research networks, which help foster collaboration and investment.

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