



Bibliometric analysis on biopesticides and biological control in crops: trends and perspectives

Análisis bibliométrico sobre los biopesticidas y el control biológico en cultivos: tendencias y perspectivas

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Highlights

- Biopesticide and biological control research has consolidated as a mature and expanding field.
- China, the United States, India, and Brazil stand out as key contributors to global output.
- Core research fronts focus on *Trichoderma*, *Bacillus*, and *Pseudomonas fluorescens*, while standardisation and multisite validation remain major challenges.

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ABSTRACT

Introduction. The sustained increase in chemical pesticide use, reaching 3.73 million tonnes in 2023, together with the expansion of resistance in 273 weed species and 632 arthropod species, has intensified the need for safer alternatives in plant protection. **Objectives:** To characterise the scientific evolution of biopesticide and biological control research in crops, identifying temporal, geographical, and thematic patterns that inform sustainable technological adoption. **Materials and Methods.** A quantitative bibliometric mapping approach was applied to 6,906 Scopus-indexed records published between 1973 and 2025. Data were analysed using Bibliometrix and VOSviewer to estimate productivity, impact, collaboration, and thematic structure indicators. **Results.** The results revealed a consolidated community of 22,413 authors, with an average of 4.68 co-authors per article, 24.31% international collaboration, and a mean citation rate of 30.14. The most productive journals were *Biological Control* and *Biocontrol Science and Technology*, while China, the United States, and India led global contributions. Conceptual clusters focused mainly on *Trichoderma*, *Bacillus*, and *Pseudomonas fluorescens*, with 2005–2020 marking the highest-impact period. **Conclusions.** Biocontrol has become a scientific cornerstone of the global agroecological transition, although gaps remain in standardisation, multisite validation, and the inclusion of the Global South.

RESUMEN

Introducción. El aumento sostenido en el uso de pesticidas químicos, que alcanzó 3.73 millones de toneladas en 2023, junto con la expansión de la resistencia en 273 especies de malezas y 632 especies de artrópodos, ha intensificado la necesidad de alternativas más seguras para la protección vegetal. **Objetivos.** Caracterizar la evolución científica de la investigación sobre biopesticidas y control biológico en cultivos, identificando patrones temporales, geográficos y temáticos que orienten la adopción tecnológica sostenible. **Materiales y Métodos.** Se aplicó un enfoque cuantitativo de mapeo bibliométrico, basado en 6,906 registros indexados en Scopus publicados entre 1973 y 2025. Los datos se analizaron utilizando Bibliometrix y VOSviewer para estimar indicadores de productividad, impacto, colaboración y estructura temática. **Resultados.** Los resultados revelaron una comunidad consolidada de 22,413 autores, con un promedio de 4.68 coautores por artículo, 24.31% de colaboración internacional y una tasa media de citación de 30.14. Las revistas más productivas fueron *Biological Control* y *Biocontrol Science and Technology*, mientras que China, Estados Unidos e India lideraron las contribuciones globales. Los clústeres conceptuales se centraron principalmente en *Trichoderma*, *Bacillus* y *Pseudomonas fluorescens*, y el periodo 2005–2020 marcó la etapa de mayor impacto. **Conclusiones.** El biocontrol se ha convertido en una piedra angular científica de la transición agroecológica global, aunque persisten brechas en estandarización, validación multisitio e inclusión del Sur Global.



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INTRODUCTION

The pressure to protect agricultural production through sustainable approaches is now more intense than ever⁽¹⁾. The FAO estimates that up to 40% of global crop production is lost annually due to pests and plant diseases⁽²⁾. Economically, losses associated with invasive insects exceed USD 70 billion per year, while plant diseases generate costs of more than USD 220 billion, placing global food security under sustained stress and accelerating the search for management strategies compatible with both environmental and human health⁽³⁾. In parallel, global pesticide use in agriculture reached 3.73 million tonnes of active ingredient in 2023 (2.40 kg ha⁻¹ of cultivated land), and international trade in formulated products moved USD 42.8 billion in the same year. This underscores the magnitude of the challenge and the need to reduce risks without compromising effective pest control^(4,5).

Adding to this pressure is the growing spread of pesticide resistance⁽⁶⁾. The International Herbicide-Resistant Weed Database reports 273 weed species with 537 unique cases (species by mode of action) of herbicide resistance worldwide, while in arthropods the Arthropod Pesticide Resistance Database (APRD) summarises 632 resistant species to 364 compounds with 18,871 documented cases - a trend that undermines the effectiveness of schemes relying solely on chemical inputs and highlights the need for biological and integrated alternatives⁽⁷⁻⁹⁾.

In response to these limitations - and to mitigate environmental and health risks - public policies and markets have begun shifting towards safer options⁽¹⁰⁾. In Europe, the Farm to Fork strategy sets a target of reducing both the use and the risk of chemical pesticides by 50% by 2030, explicitly promoting integrated pest management (IPM) and the scaling-up of safer alternatives. This alignment between public policy and technological demand has created favourable conditions for biopesticides and biological control^(11,12).

Within this context, biopesticides - defined by the EPA as microbial pesticides, biochemical pesticides (of natural origin), and plant-incorporated protectants (PIPs) - have evolved from specialised niches to become core components of IPM and differentiated agriculture^(13,14). Concurrently, the EPA maintains an updated list of biopesticide active ingredients (microbial and biochemical), as of 17 March 2025, and reported 20 new registrations in 2023, indicating an expanding pipeline and increasing regulatory acceptance⁽¹⁵⁾. Similarly, organic agriculture - which by definition restricts synthetic inputs - covered 98.9 million hectares in 2023, with 4.3 million producers. Its share of global agricultural land stands at around 2.1%, supported by a retail market exceeding €136 billion, reflecting the growing commercial traction of more ecological plant protection approaches⁽¹⁶⁾.

This policy and regulatory framework is embedded within the 2030 Agenda: Sustainable Development Goals (SDG) 2.4 calls for resilient production systems by 2030 and promotes indicators such as 2.4.1 (the proportion of agricultural area under productive and sustainable agriculture); meanwhile, SDG 12.4 demands the environmentally sound management of chemicals throughout their life cycle to minimise adverse impacts on human health and the environment⁽¹⁷⁾. Framing the transition from synthetic inputs to biopesticides and biological control within these goals enables progress to be assessed using comparable metrics at national and

regional scales⁽¹⁸⁾.

Evidence of risk is also compelling. In the European Union, based on samples collected in 2023, 58% of food products analysed contained no quantifiable residues, 38.3% were within legal limits, and 3.7% exceeded the Maximum Residue Limit (MRL)⁽¹⁹⁾. Although the average dietary risk remains low, these hotspots of non-compliance require continued monitoring and the gradual substitution of hazardous compounds with safer alternatives⁽²⁰⁾. At the planetary scale, 64% of global agricultural land is at risk of contamination from more than one active ingredient and 31% faces high risk, with significant overlaps in regions of high biodiversity. Moreover, existing literature links neonicotinoids with declines in bee reproduction and population persistence - a critical issue given that around 75% of food crops depend, at least partially, on animal pollination⁽²¹⁾.

Given the thematic and methodological dispersion observed in research on biopesticides and biological control in crops - ranging from the isolation and characterisation of microbial and botanical agents to field evaluation, regulation, commercial acceptance, and agronomic sustainability - bibliometric analysis emerges as an appropriate tool to synthesise the accumulated evidence^(22,23). This method enables the identification of key actors (countries, institutions, and authors), the characterisation of collaboration and co-citation networks, and the recognition of scientific and regulatory milestones, such as the approval of biopesticides by the EPA or the update of FAO and European Commission guidelines. It also helps to locate research gaps that constrain scaling-up, such as the limited standardisation of formulations, low adoption in extensive crops, and the scarce evaluation of comprehensive environmental impacts⁽²⁴⁻²⁶⁾.

The relevance of this study lies in the fact that only through panoramic vision can robust empirical foundations be established to guide integrated pest management policies, prioritise research lines, promote technological transfer, and strengthen agricultural biosecurity strategies within the framework of sustainability^(27,28).

Understanding the complexity of this field, with the aim of promoting effective interventions for crop protection and the reduction of environmental and health risks, first requires a broad reading of the theoretical and methodological development achieved over the past three decades. This overview leads to the central research question: What is the level of scientific development on biopesticides and biological control in crops, and how has it evolved over time? From this, twelve specific questions are derived: i) How has the scientific production on biopesticides and biological control in agricultural crops evolved over time?, ii) What types of documents predominate, and what is their relative weight in the period analysed?, iii) Which thematic areas are most associated within Scopus, and how are they distributed?, iv) Which institutions and countries lead scientific production, and what is their relative contribution?, v) Who are the most influential authors, and how are their trajectories and collaborations characterised?, vi) To what extent does author productivity follow Lotka's Law, and what does this reveal about the concentration of scientific leadership?, vii) Which journals account for the largest dissemination of research on biopesticides and biological control?, viii) How is the core of journals organised according to Bradford's Law and its diffusion zones?, ix) What is the level of international collaboration among countries and institutions?, x) What does Reference Publication Year Spectroscopy

(RPYS) reveal about the historical roots and the years of highest impact?, xi) Which seminal publications, methods, or regulatory frameworks explain the citation peaks detected in the RPYS?, xii) What are the trends and emerging lines guiding the future research agenda according to keyword dynamics and the thematic map?

Based on these questions, the general objective is formulated as follows: to describe and quantitatively analyse the evolution of research on biopesticides and biological control in agricultural crops, identifying temporal, geographical, and thematic patterns, collaboration networks, and influential sources, in order to strengthen decision-making and technological adoption for sustainable plant protection.

MATERIALS AND METHODS

To characterize the scientific evolution of biopesticides and biological control in agricultural crops, bibliometric mapping was applied as a quantitative method grounded in mathematical and statistical modelling, aimed at analyzing scientific production and patterns of scholarly communication in this field. This approach enables the synthesis of trends, the identification of influential authors, institutions, and countries, and the detection of research gaps and emerging lines, thereby providing a panoramic view of the domain ‘biopesticides, biological control, and agricultural crops’. Implementation followed the stages proposed by Luna-Morales et al.⁽²⁹⁾: (i) formulation of the general and specific research questions; (ii) selection of the reference database; (iii) construction of a reproducible search equation; and (iv) statistical analysis and visualization of the retrieved metadata.

The study adopts a quantitative, exploratory–descriptive approach with a non-experimental, longitudinal, and retrospective design. The analytical strategy focused on tracing and interpreting the evolution of the scientific literature on biopesticides and biological control from the earliest records to 2025, in order to reconstruct its historical trajectory, identify inflection points, and assess the degree of thematic consolidation^(30,31).

Based on the research question, the following canonical search equation was developed by selecting key terms most relevant to the field: TITLE (“biopesticid*” OR “biological control” OR biocontrol) AND TITLE-ABS-KEY (crop* OR agricultur* OR horticultur* OR “plant protection” OR “plant disease*” OR phytopathog* OR phytosanitar* OR postharvest OR “field trial*” OR greenhouse OR “weed* control” OR “seed treat*” OR cultivation OR farming OR “plant health” OR “integrated pest management” OR ipm) AND TITLE-ABS-KEY (“microbial pesticide*” OR “biocontrol agent*” OR “entomopathogenic fung*” OR “entomopathogenic vir*” OR “entomopathogenic bacter*” OR “entomopathogenic nematod*” OR “Bacillus thuringiensis” OR trichoderma OR beauveria OR metarhizium OR “Pseudomonas fluorescens” OR baculovir* OR nucleopolyhedrovir* OR granulovir* OR steinernema OR heterorhabditis OR “botanical pesticide*” OR “plant extract*” OR “plant-derived pesticid*” OR “essential oil*” OR azadirachtin OR neem OR thymol OR carvacrol OR eugenol OR citronella) AND NOT TITLE-ABS-KEY (malaria OR dengue OR zika OR chikungunya OR “public health” OR “human health” OR “clinical trial” OR veterinary OR “urban pest” OR mosquito OR “vector-borne”).

The search was executed on 20 September 2025, without restrictions on language or time period, to ensure comprehensive field retrieval. Scopus was used as the information source owing to its multidisciplinary coverage, refined subject filters, and high-quality metadata, which enable analyses of authors, affiliations, countries, journals, and collaboration networks. This single-source design was selected to maximize metadata consistency and reproducibility across the full bibliometric workflow. The equation was designed to exclude studies related to public health, veterinary science, or medical entomology, with the aim of concentrating the analysis on agriculture and plant protection.

Within this framework, the 6,906 records retrieved were exported in Comma Separated Values (CSV) format for statistical processing and visualization. A manual thematic screening was performed to remove non-pertinent records, thereby ensuring corpus specificity and reducing the ‘noise’ associated with publications on urban pests or human health. Data were organized and cleaned in spreadsheets (Microsoft Excel) to facilitate interpretation⁽³²⁾.

The bibliometric analysis was conducted using Bibliometrix 5.1.1 (2025) within the R environment and VOSviewer 1.6.20 (2023). Bibliometrix enabled the calculation of productivity indicators (authors, countries, journals), impact measures (citations, and the h-, g-, and m-indices), and scientific collaboration (co-authorships and institutions), in addition to applying classical bibliometric models such as Lotka’s Law (author productivity) and Bradford’s Law (journal cores)⁽³³⁾. VOSviewer, developed by Leiden University, was employed to generate networks of keyword co-occurrence, co-authorship, and bibliographic coupling, with density visualization and normalization by association strength^(34,35).

In addition, the Reference Publication Year Spectroscopy (RPYS) model was applied to identify the field’s historical roots and to detect citation peaks that mark scientific milestones. The combination of these methods enabled the mapping of the intellectual structure, thematic evolution, and collaboration networks surrounding biopesticides and biological control, providing an integrated reading of the status and prospects of scientific knowledge on sustainable plant protection.

Data Availability

The dataset supporting the findings of this study has been deposited in Mendeley Data and is publicly accessible in: Hoyos-Alayo, Walter Manuel (2025), “Bibliometric analysis on biopesticides and biological control in crops: trends and perspectives”, Mendeley Data, V1, doi: <https://doi.org/10.17632/3k3gh2pw65.1>

RESULTS

As shown in (**Figure 1**), the general bibliometric indicators of the analyzed corpus and summarise the scale and maturity of the scientific field on biopesticides and biological control in crops. The period 1973–2025 comprises 6,906 documents drawn from 1,063 sources and authored by 22,413 researchers, evidencing a broad and consolidated scholarly community. Although the apparent annual growth rate is stable (0%), collaborative density is high, with an average of 4.68 co-authors per article and 24.31% international co-authorship, reflecting

the field's global and interdisciplinary nature. The mean document age (9.3 years) and the average of 30.14 citations per publication indicate continuous output and sustained citation. Likewise, a base of 23,995 keywords and more than 41,000 references highlights the domain's conceptual and methodological diversity. Taken together, these values depict a mature, collaborative, and highly visible scientific area whose recent expansion aligns with the transition towards sustainable plant protection models.



Figure 1. Overview of the Scopus dataset on biopesticides and biological control in crops.

As shown in (Figure 2), the temporal evolution of scientific output on biopesticides and biological control in crops between 1973 and 2025, evidencing an exponential growth pattern from 2000 onwards. Following an initial period of sparse production, the curve steepens from 2010 and peaks in 2024 with 607 publications, reflecting the field's consolidation and its rising prominence on the global scientific agenda. This increase coincides with the expansion of sustainable agricultural policies, the strengthening of integrated pest management, and the surge of bioproducts in international markets. The slight dip observed in 2025 results from the provisional closure of the observation window and does not indicate a genuine downturn. Overall, the trajectory confirms an expanding scientific dynamic driven by the convergence of biotechnological innovation, environmental regulation, and demand for sustainable agricultural systems.

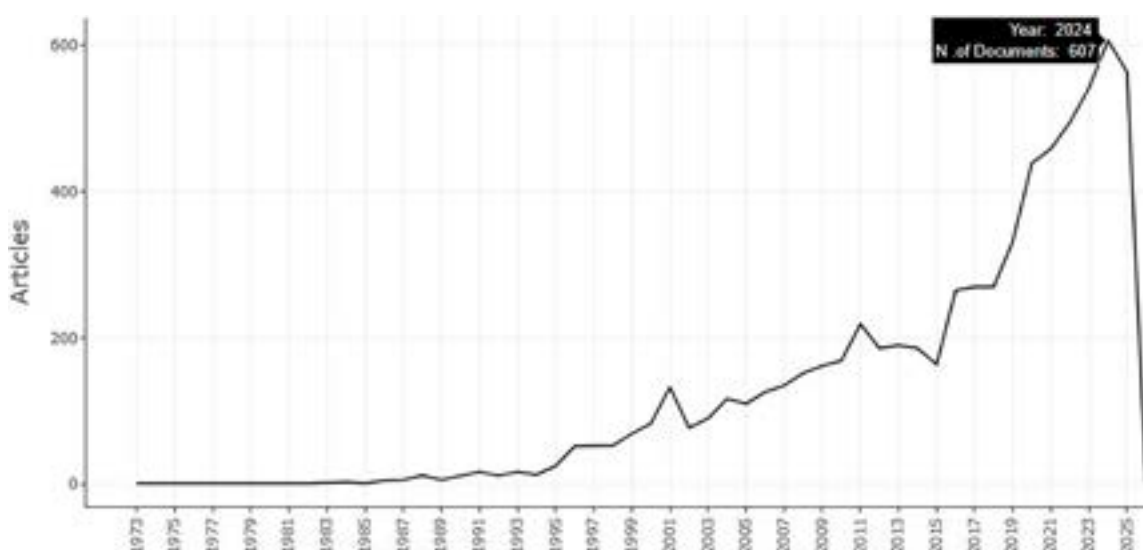


Figure 2. Annual scientific production on biopesticides and biological control in crops.

(Figure 3) identifies the most productive authors in the study of biopesticides and biological control in crops, highlighting the consolidation of an international academic core with strong European leadership. Neus Teixidó tops the ranking with 37 publications, followed by Josep Usall⁽³⁵⁾ and Michael Wisniewski⁽³²⁾, evidencing close collaboration among institutions specialising in plant pathology and postharvest science. Other key figures, such as Genève Défago, Samir Droby, and Maria Lodovica Gullino, further reinforce the linkage between basic research and technological application in microbial and botanical biocontrol. The group's relatively even distribution indicates a cohesive scientific community that sustains knowledge generation and facilitates transfer into sustainable agricultural practice. This authorial core constitutes the field's intellectual backbone and shapes current trends in biological innovation applied to pest management.

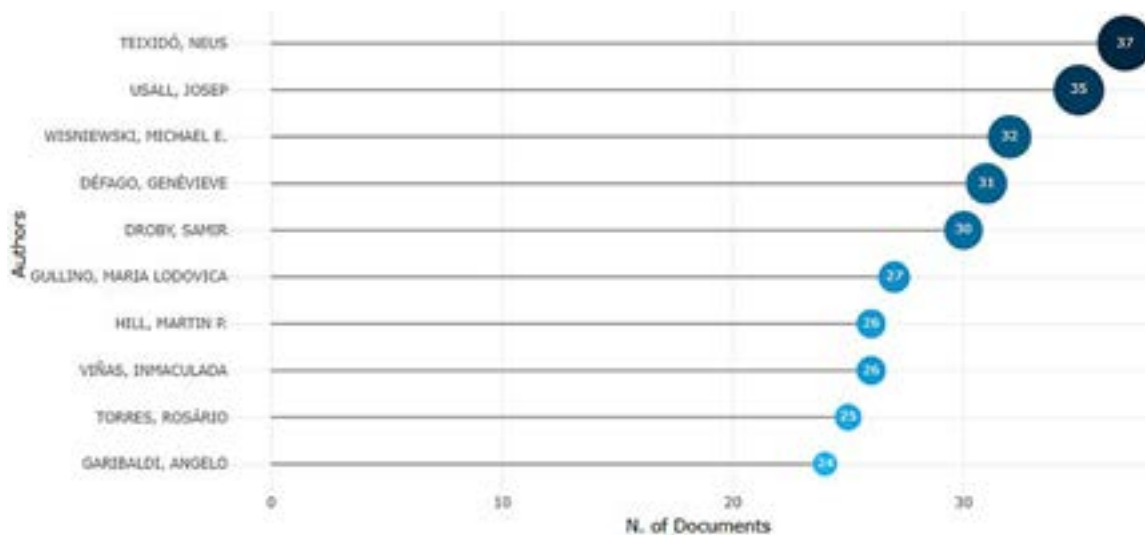


Figure 3. Leading authors by number of publications.

(Figure 4) depicts the distribution of author productivity according to Lotka's Law, showing a high concentration of researchers with low publication frequency and a small core of highly productive authors. Approximately 80% of authors contribute a single article, whereas only a minimal fraction exceeds ten publications, reflecting the characteristic pyramidal structure of consolidated scientific fields. The empirical curve closely fits the theoretical model, indicating a pattern of maturity and progressive specialisation in which a few groups lead knowledge generation and set the main research directions. This behaviour confirms the presence of stable academic leadership and collaborative networks that sustain the scientific expansion of biopesticides and biological control in crops.

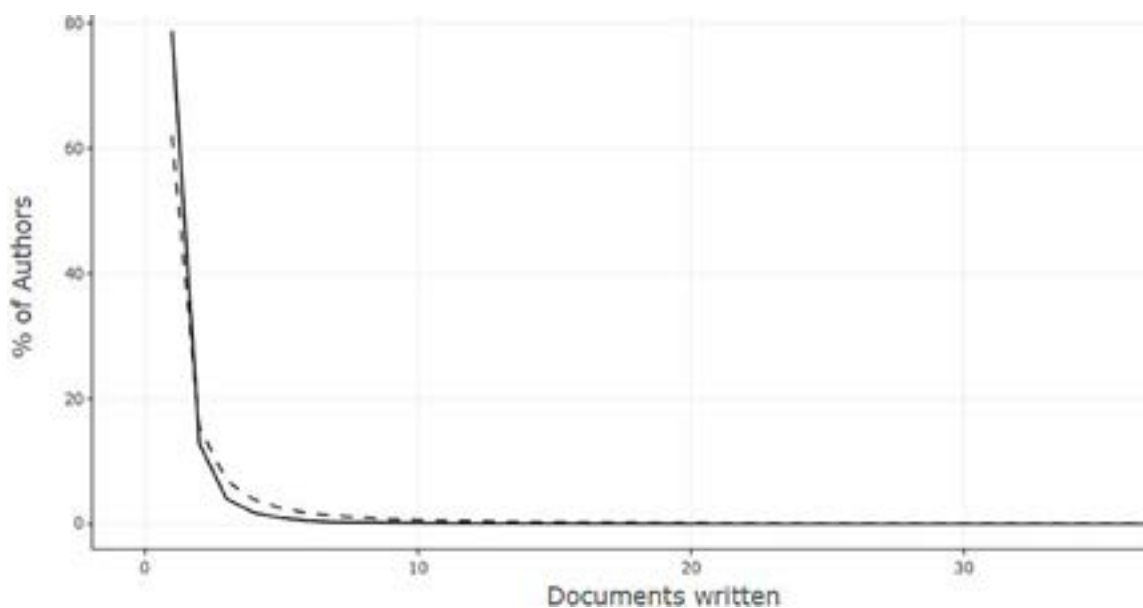


Figure 4. Lotka's law distribution of author productivity.

(Figure 5) presents the most productive journals in the field of biopesticides and biological control in crops, evidencing a thematic concentration in high-impact specialist outlets. *Biological Control* leads with 363 publications, followed by *Biocontrol Science and Technology* (344) and *BioControl* (289), forming the core vehicles for dissemination in this area. Complementary journals such as *Crop Protection*, *Frontiers in Microbiology*, and *Pest Management Science* extend the scope towards integrated pest management, applied microbiology, and agricultural sustainability. This pattern reflects the consolidation of a robust editorial ecosystem that links basic research, technological development, and field application, thereby ensuring global visibility and the transfer of knowledge towards a more sustainable and biotechnologically advanced agriculture.

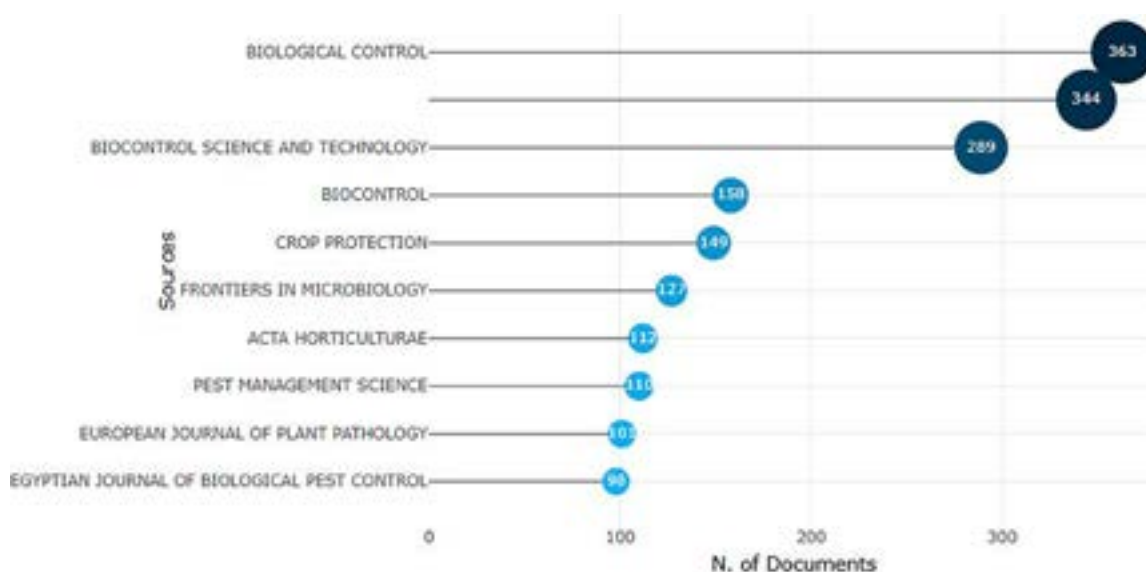


Figure 5. Leading journals by number of publications.

(Figure 6) illustrates the application of Bradford's Law, depicting the dispersion of articles by publishing journal and revealing a classic core-periphery pattern. The source core—led by *Biological Control*, *Biocontrol*

Science and Technology, and *BioControl*—concentrates the bulk of scientific output, constituting the central axis of scholarly communication in biopesticides and biological control. Progressing towards the outer zones, the number of articles per source declines sharply, evidencing thematic diversification and the field's interdisciplinary expansion into journals of microbiology, phytopathology, and integrated pest management. This structure confirms the domain's maturity and consolidation, wherein a small set of specialist journals functions as the principal platform for global dissemination and scientific reference.

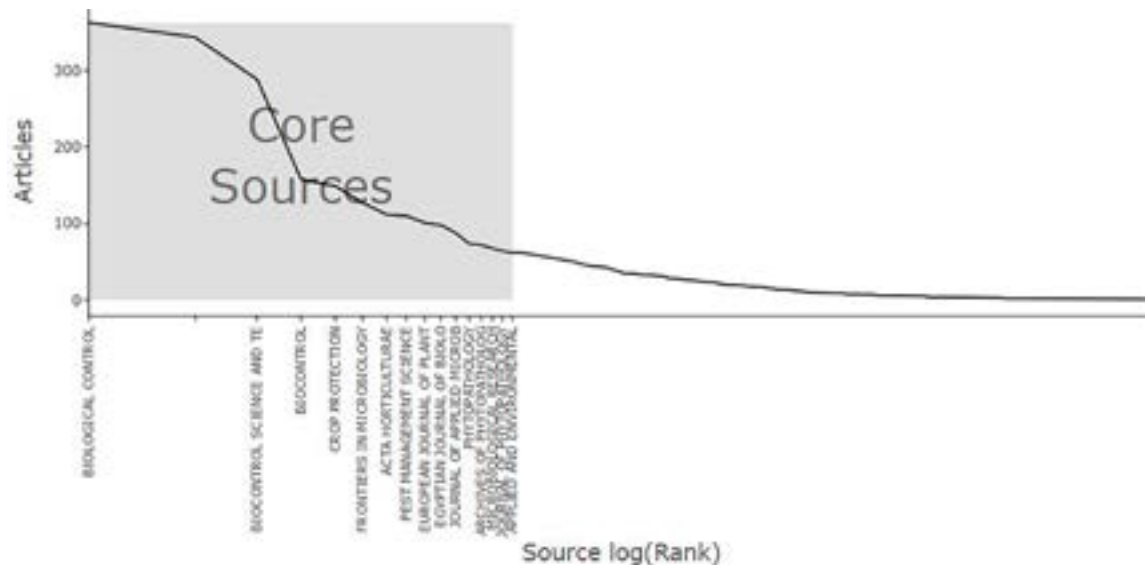


Figure 6. Bradford's law distribution of core.

(**Figure 7**) highlights the institutions with the highest scientific output on biopesticides and biological control in crops, revealing pronounced Asian leadership in knowledge generation. The Chinese Academy of Agricultural Sciences leads with 328 publications, followed by Tamil Nadu Agricultural University (326) and Nanjing Agricultural University (321), reflecting the strong research momentum in China and India on sustainable agriculture and applied biotechnology. Institutions such as the Institute of Plant Protection, the ICAR–Indian Agricultural Research Institute, and Huazhong Agricultural University reinforce this pattern, noted for their specialisation in plant pathology, agricultural entomology, and the management of biocontrol agents. In Europe, the Institut de Recerca i Tecnologia Agroalimentàries (IRTA) and Sveriges lantbruksuniversitet (SLU) exemplify the convergence of applied research with sustainable production systems. Overall, the landscape confirms a geographically structured field dominated by highly collaborative Asian and European hubs that are shaping the scientific and technological frontier of agricultural biocontrol worldwide.

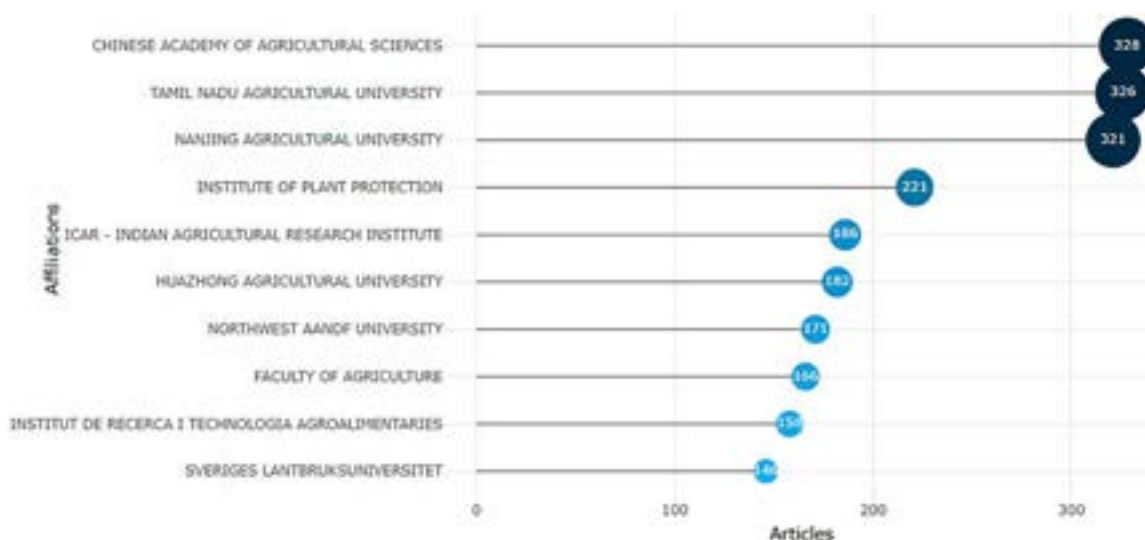


Figure 7. Most productive institutional affiliations in biopesticides and biological control research.

(Figure 8) presents the global distribution of scientific output by country and shows a clear Asian–North American hegemony in research on biopesticides and biological control in crops. China, the United States, and India lead the ranking with close to one thousand publications each, concentrating most of the knowledge produced worldwide and reflecting their capacity to invest in agri-biotechnological research. Within Europe, Italy and Spain stand out for their roles in developing commercial formulations and sustainable agriculture policies, while Brazil emerges as the Latin American reference point with significant contributions to microbial biocontrol. Countries such as Canada, Egypt, the United Kingdom, and Australia complement the global network through lines oriented towards innovation and climate adaptation. Taken together, the map depicts a highly internationalised scientific field. This country-level distribution is consistent with the international co-authorship observed in the corpus (24.31%) (Figure 1), and indicates that cross-country collaboration accompanies the expansion of biocontrol research as a strategic pillar of sustainable agriculture.

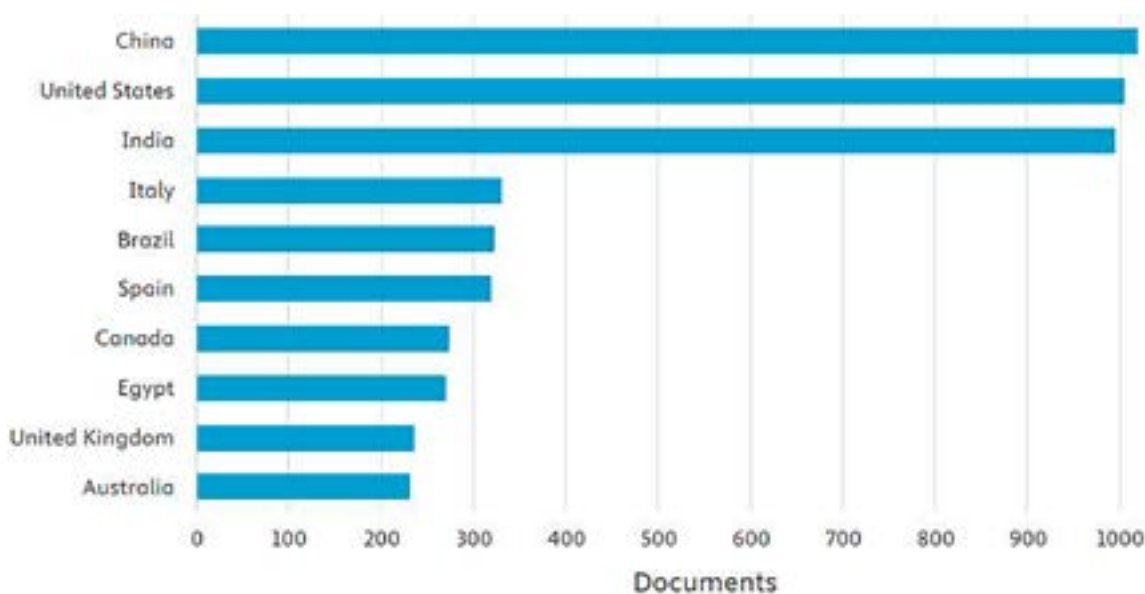


Figure 8. Country-level scientific production in biopesticides and biological control research.

(Figure 9) displays the temporal evolution of the most frequent terms in the literature on biopesticides and biological control, revealing a marked conceptual intensification over the past two decades. The term “biological control” leads with 2,767 cumulative occurrences by 2025, followed by “biocontrol” and “biocontrol agent”, confirming the centrality of these approaches on the global scientific agenda. From 2000 onwards, a sustained acceleration is evident, driven by the expansion of integrated pest management and the valorisation of microorganisms as control agents. Associated terms such as “fungi”, “plant diseases”, and “biological pest control” reflect thematic diversification towards ecological interactions, field efficacy, and applications across varied agricultural systems. This pattern evidences the maturity of a consolidating field in which biotechnology and sustainability converge to redefine plant protection in the context of climate change and global food security.

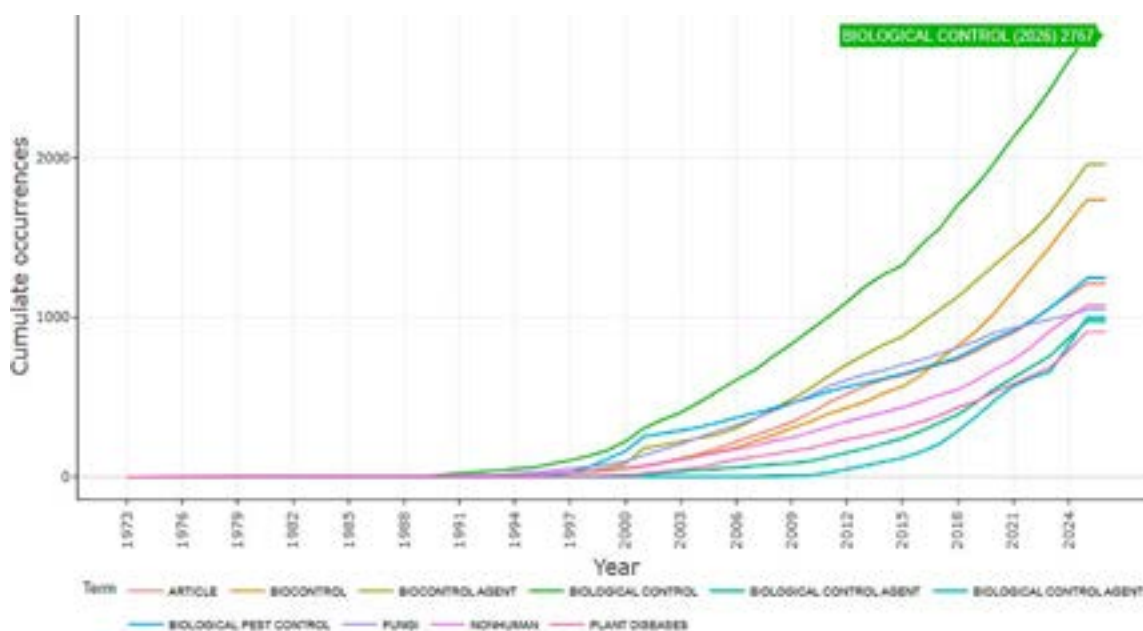


Figure 9. Temporal evolution of key research terms.

(Figure 10) shows the thematic distribution of publications on biopesticides and biological control, evidencing the field’s multidisciplinary character. Forty-six per cent of documents fall within Agricultural and Biological Sciences, confirming the domain’s agroecological and production-oriented roots. This is followed by Biochemistry, Genetics and Molecular Biology (13.1%) and Immunology and Microbiology (12.7%), reflecting growing interest in the genetic and functional characterisation of microorganisms with biocontrol potential. Environmental Science (10.3%) and Medicine (5.8%) broaden the perspective towards ecological impacts and biosafety. To a lesser extent, disciplines such as Engineering, Chemical Engineering, and Multidisciplinary Science indicate the incorporation of technological and modelling approaches. Overall, this profile reveals a convergence across agricultural, biological, and environmental sciences that strengthens the scientific foundations of biocontrol and supports its integration into sustainable agricultural systems worldwide.

(**Figure 12**) presents Reference Publication Year Spectroscopy (RPYS), which identifies the periods of greatest influence in building knowledge on biopesticides and biological control in crops. The curve shows a sustained rise in citations from the mid-1980s, with a pronounced upswing from 1995 that peaks between 2005 and 2020—the period during which conceptual frameworks for integrated pest management were consolidated and biopesticide regulation by international agencies was strengthened. This pattern reflects the maturation of a theoretical and experimental corpus integrating applied microbiology, agricultural ecology, and biotechnology. Recent declines do not indicate a loss of relevance but rather the normalisation of citation patterns in the most recent literature. Overall, the trend confirms the consolidation of a robust scientific foundation, underpinned by historical contributions that support the contemporary expansion of biocontrol as an essential strategy for agricultural sustainability.

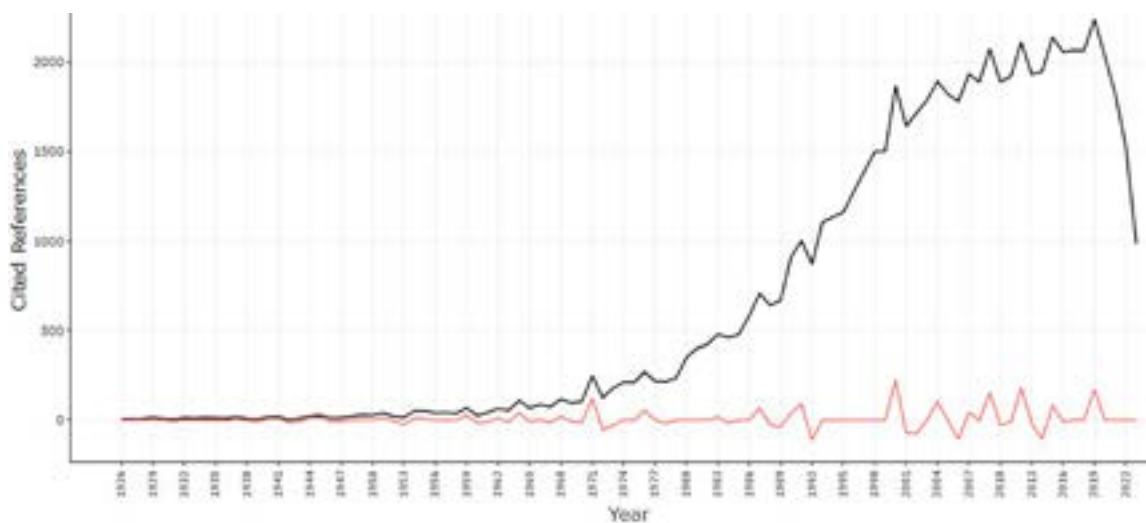


Figure 12. Reference publication year spectroscopy in biopesticides and biological control research.

(**Figure 13**) presents the thematic map, which synthesizes the field’s conceptual organization alongside its degree of development and importance. In the upper-right quadrant lie the motor themes - most notably “biocontrol”, “article”, and “nonhuman” - indicating high centrality and density, that is, structural relevance and the capacity to articulate other research lines. In the lower zone, the terms “biological control”, “biocontrol agent”, and “biological pest control” are consolidate as basic themes that constitute the domain’s foundational core and underpin the theoretical and methodological evolution of biocontrol. By contrast, “animals” and “weed control” appear as marginal or declining themes, associated with more specific approaches that are less connected to the central lines of inquiry. Overall, the map confirms a mature scientific structure organized around a dominant axis of microbial and botanical biocontrol, with growing integration across ecological, molecular, and applied perspectives.

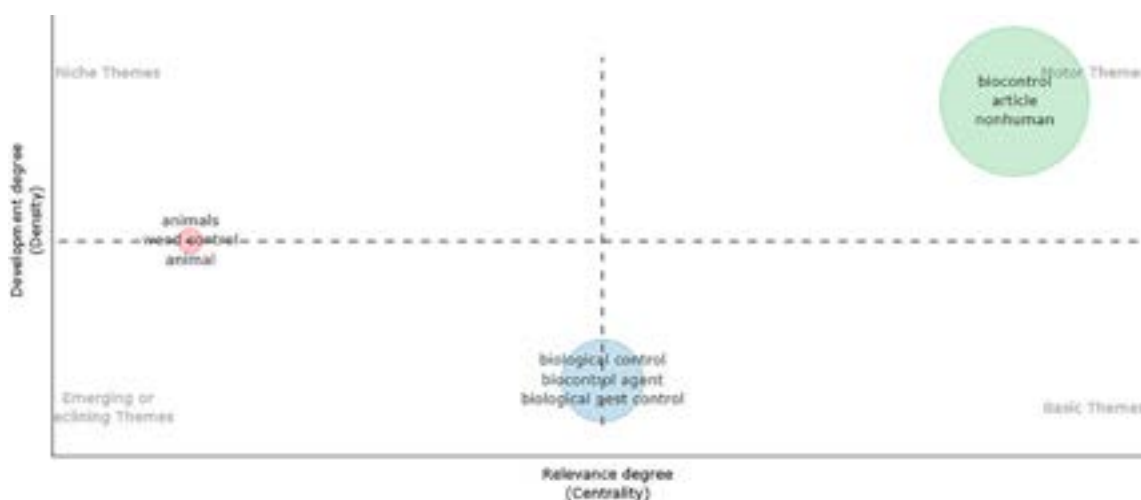


Figure 13. Thematic map of research topics in biopesticides and biological control.

DISCUSSION

As shown in (Figure 1), the synthetic indicators reveal a mature, globally interconnected field with a sustained growth rate, capable of integrating biotechnological innovations within stringent regulatory frameworks⁽²⁷⁾. The high collaborative density and robust citation profile confirm a cohesive scientific community oriented towards solving real-world challenges in sustainable agriculture⁽³⁶⁾. This consolidation - typical of disciplines transitioning towards technological innovation - demonstrates that research on biopesticides and biological control has become a cornerstone of plant health management, underpinned by solid scientific evidence and tangible economic prospects^(37,38).

According to (Figure 2), temporal evolution exhibits an exponential expansion from 2000, associated with policies to reduce chemical pesticide use, regulatory incentives driven by international bodies, and the development of platforms for discovery and scaling of microbial strains^(4,9). The inflection observed in the past decade coincides with the strengthening of biosafety frameworks and bioinput certifications, suggesting a shift from exploratory research towards the consolidation of a regulated biotechnological market^(39,40). In this scenario, the standardization of efficacy and traceability criteria will be decisive in translating scientific production into commercial and environmental impact⁽⁴¹⁾.

As detailed in (Figures 3-4), the authorship structure reflects the typical hierarchy of specialized fields, with a highly productive core and a broad periphery of emerging contributors. This pattern - often termed the Matthew effect - concentrates visibility and resources within established teams while simultaneously setting methodological standards that strengthen reproducibility⁽⁴²⁾. A key future challenge is to democratize authorship through inclusive research networks and South-South cooperation that integrate capacities for applied biotechnology and validation under tropical conditions, where biodiversity offers still underexploited comparative advantages^(43,44). These processes could enhance the participation of Latin American institutions in international networks such as the Global Soil Biodiversity Initiative or the FAO Biocontrol Hub⁽⁴⁵⁾.

As shown in (**Figures 5-6**), the editorial ecosystem is concentrated in highly cited specialist journals, ensuring technical rigour but constraining interdisciplinary visibility. This thematic bias helps explain why the transfer of results into agricultural policy or the circular economy remains incipient⁽⁸⁾. Overcoming this limitation requires cross-diffusion in boundary-spanning journals dedicated to sustainability and the bioeconomy, where findings on efficacy and safety can be discussed holistically alongside economic and social performance indicators⁽⁴⁶⁻⁴⁸⁾.

As evidenced in (**Figures 7-8**), leadership from Asia, Europe, and North America forms a consolidated innovation triangle that combines critical research mass, stable regulatory frameworks, and strong public-private investment^(11,49). However, the under-representation of megadiverse regions in the Global South - despite their potential as sources of native strains - constitutes a strategic gap⁽³⁷⁾. Strengthening Latin American and African nodes would diversify the genetic base of biocontrol agents and contextualize technologies for semi-arid and tropical agroecosystems, thereby contributing to biotechnological sovereignty and epistemic equity^(41,50,51). This would also bolster regional food security and reduce technological dependency.

As shown by Figures 9 and 10, semantic evolution reflects a process of conceptual maturation in which the lexicon shifts from generalist framings to terminologies that describe functional interactions, specific microorganisms, and rhizosphere processes⁽⁵²⁾. This shift denotes an epistemic transition from descriptive microbiology to the ecological engineering of systems, wherein biological control is conceived as an emergent function of microbial trophic networks⁽⁵³⁾. Consequently, there is a need for holistic metrics that integrate agronomic efficacy, ecological stability, and socio-economic compatibility, aligned with SDGs 1, 2, 12, and 15 as well as FAO resilience targets ^(54,55).

As seen in (**Figure 11**), the co-occurrence map positions biocontrol at the epicentre of a multidisciplinary network linking phytopathology, applied microbiology, and agronomy. The strength of clusters centred on *Trichoderma*, *Bacillus*, *Pseudomonas*, and entomopathogenic fungi confirms the existence of validated technologies, while also revealing the challenge of achieving consistency in formulations and persistence under field conditions^(56,57). Integrating omics studies with metabolic modelling and multisite validation will help bridge the gap between experimental efficacy and real agronomic performance, accelerating the transition towards stable, reproducible, and predictive bioproducts^(58,59).

According to (**Figure 12**), reference publication year spectroscopy traces a genealogy consistent with key milestones in the field's institutionalization, including the creation of biopesticide regulations, the adoption of Good Agricultural Practices (GAP) frameworks, and the consolidation of integrated pest management (IPM) programmes⁽⁶⁰⁾. This trajectory shows progressive scientific and regulatory professionalization underpinning the domain's current maturity. Future advances will depend on integrating predictive modelling, artificial intelligence, and life cycle assessment (LCA) as tools for the intelligent management of biocontrol⁽⁶¹⁾.

As organized in (**Figure 13**), the thematic map synthesizes a research ecosystem in which motor themes - centred on soil microbiology, formulation, and agronomic efficacy - are complemented by emerging fronts in circular bioeconomy, climate-smart crop protection, and resistance management⁽⁶²⁾. This configuration

suggests that the field's future will depend not only on technical innovations but also on its capacity to embed itself within sustainable production systems that align profitability, resilience, and ecological restoration^(63,64). Such thematic convergence anticipates a phase of structural maturity in which technological advances and agricultural transition policies reinforce one another.

From the convergence displayed across (**Figures 1–6 and 9–13**), three routes for technological and policy scaling emerge. First, the international standardization of inoculant quality and traceability to enable transparent global markets⁽⁶⁵⁾. Second, the creation of open repositories for multisite trials and interoperable metadata to permit comparative meta-analyses⁽⁶⁶⁾. Third, the integration of biocontrol into IPM packages through economic incentives, eco-labelling, and green certifications⁽⁶⁷⁾. These routes could accelerate the transition towards agriculture free from synthetic pesticides and contribute to the commitments of the Kunming - Montreal Global Biodiversity Framework.

In the realm of scientific cooperation, as suggested by (**Figures 7–11**), North-South and South-South alliances represent a strategic opportunity to balance capacities in research, production, and validation of bioproducts. Combining industrial biofabrication infrastructure in the North with biological diversity in the South can give rise to fairer and more effective public–private consortia, provided that equitable data governance, shared intellectual property, and technology-transfer mechanisms geared towards sustainability and food sovereignty are guaranteed⁽⁶⁸⁾.

Finally, as synthesized in (**Figures 2, 9, 11-13**), the field has moved beyond experimental validation and is advancing towards standardization and responsible scaling. The question is no longer whether biocontrol works, but how to optimize its performance under diverse edaphoclimatic contexts and production models^(55,69). Meeting this challenge entails closing gaps between laboratory and field, regulation and adoption, and technological maturity and economic sustainability. Only then can scientific potential translate into replicable solutions that align agricultural productivity, food security, and global ecosystem resilience.

CONCLUSIONS

The mapping of 6,906 publications confirms that research on biopesticides and biological control in crops is a mature and expanding field, particularly since 2000, with a peak in 2024. Its growth, international collaboration, document types, and subject-area distribution reflect an increasingly interdisciplinary trajectory.

The field shows a concentrated editorial and authorship structure, led by core sources such as *Biological Control*, *Biocontrol Science and Technology*, and *BioControl*, and follows Lotka's Law in author productivity. Scientific production is mainly driven by China, the United States, and India, with Brazil standing out in Latin America, while international co-authorship reaches 24.31%.

Conceptually, the field is organized around microbial and botanical biocontrol, with recurrent research fronts involving *Trichoderma*, *Bacillus*, *Pseudomonas fluorescens*, and entomopathogenic fungi. The most influential cited literature is concentrated between 2005 and 2020, a period associated with the consolidation of IPM and

biopesticide regulatory frameworks.

Despite this consolidation, challenges remain in formulation standardization, multisite validation, and broader inclusion of the Global South. Future progress will depend on international quality and traceability standards for inoculants, interoperable open repositories, and the integration of biocontrol into certified IPM packages. Overall, biocontrol is emerging as a key pillar of the agroecological transition, with direct contributions to SDGs 2 and 12.

ETHICAL CONSIDERATIONS

This bibliometric study used only secondary bibliographic metadata retrieved from Scopus. It did not involve human participants, animal subjects, personal or sensitive data, or direct intervention. Accordingly, ethical approval and informed consent were not required.

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The author declares no conflict of interest.

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