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REVIEW

Soil health multifunctionality of biological products in agriculture: overview and research perspectives

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Summary
Globally, the use of biological products, including biological control agents, biofertilizers, and bioinoculants, has increased significantly as a strategy to reduce dependence on synthetic inputs and promote sustainable agriculture. However, its effects on soil health are still poorly explored. Therefore, this study aimed to analyse the multifunctionality of biological products in agriculture, focusing on soil health, using a systematic review and bibliometric analysis approach. This analysis involves summarizing their mechanisms of action, categories, and impacts. Parameters such as the number of publications per year, the most cited articles, the frequency of keywords and international scientific collaboration networks between countries were analysed. The results showed an expansion in the number of publications on biological products and biological products over the years, with a significant growth in recent years, with emphasis on Brazil and Russia. The most frequent keywords include 'biological products', 'biological product', 'soil', 'fungi', 'bacteria', and 'biological control', and the most cited articles address topics such as the use of *Azospirillum sp.* in agriculture, the combined application of biological products to control soil diseases, and the inoculation of seeds with *Bacillus subtilis*. Although few studies have directly evaluated soil health, the results indicate that biological products are related to improvements in soil health, which stimulate the microbiota and promote greater productivity, thereby positively impacting the physical and chemical properties, highlighting the importance of an integrated approach for soil health.

Keywords: Soil quality; bioinputs; biological functionality; agricultural sustainability

Introduction

The multifunctionality of biological products refers to their capacity to influence multiple dimensions of agricultural and environmental system, such as nutrient cycling, pathogen suppression, and soil structure improvement (Gindri *et al.*, 2020). Under Brazilian legislation (Decree 11,940/2024), which establishes the National Bioinput Program, biological product can be defined as 'the product, process or technology of plant, animal or microbial origin, intended for use in the production, storage and processing of agricultural products, in aquatic production systems or planted forests, which positively interfere with the growth, development and response mechanism of animals, plants, microorganisms and derived substances and which interact with physical, chemical and biological products and processes' (Brasil, 2020).

This definition ranges from products with a low level of added technology, such as organic fertilizers based on manure and vegetable compost, to vaccines, probiotics, and plant protection products, whether they are produced on a local or industrial scale using cutting-edge technology. Biological products are often used in the context of reducing the use of products of synthetic or mineral origin (Farrell, *et al.,* 2016; Goulet, 2021). Thus, a more specific definition may be that of Aubert et al. (2018): 'A biological input is a living organism or element of biological origin, as opposed to elements of chemical, synthetic or mineral origin, introduced into an agricultural plot to help optimize production'. Even more simply, they can be defined on the basis of their functions, i.e. as products of biological origin that aim to promote soil fertility, biological activity, and plant growth (Farrell *et al.,* 2016). In this respect, biological products can be divided into three major product groups: biological control, bio-fertilizers, and bio-inoculants (Goulet, 2021).

Biological control inputs aim to control a population of organisms harmful to crops, such as the use of *Trichoderma* spp. to suppress phytopathogenic fungi. Biofertilizers are designed to improve soil fertility, for instance, by promoting nutrient cycling. Bioinoculants, such as strains of *Rhizobium spp*., support plant development, often through biological nitrogen fixation or the production of organic compounds that alleviate environmental stress (Brasil, 2020; Florencio *et al.,* 2022; Goulet, 2021).

There is specific legislation for different categories of products, including soil conditioners. According to the Secretariat of Agricultural Defense Normative Instruction 35/2006, soil conditioners are defined as inputs that improve the physical, physicochemical, or biological properties of the soil. Biological conditioners, in turn, are subdivided into activators and replenishers. According to Maeda (2021), these may also include by-products from fertilizer manufacturing, such as agricultural gypsum. In this study, the focus is on biofertilizers and biostimulants. Although some biological conditioners may conceptually overlap with these biological products, they are distinguished here by their main function rather than by their legal classification.

Depending on their primary mode of action, biostimulants may also be considered biological products, as they enhance plant growth and stress tolerance without directly supplying nutrients (Yakhin *et al.,* 2017). Therefore, in the context of this study, biostimulants are included within the broader category of biological products. What follows is an overview of the rule of biological products in Brazilian agriculture and their contribution to promoting soil multifunctionality.

Overview of biological products in Brazilian agriculture

South America is a leader in the use and regulation of biological products in agriculture (Goulet, 2021). Brazil is one of the largest consumers and producers of biological products in the world, using them in almost 30% of the area planted with crops in the country, estimated at 85.7 Mha (Samora, 2023). Sugarcane, soybeans, cotton, and coffee stand out in terms of the use of some biological products, accounting for around 75% of the total consumption of biocontrol products. (Goulet, 2021).

A study carried out in 2023 projected that approximately USD 3,091 billion would be invested in the Brazilian biological product market by 2030 (1USD $\sim$ 5,5 BRL used for conversion), with a growth rate of 23% between the years 2022 and 2023 (Embrapa, 2023). Between 2000 and 2020, in Brazil, microbial biocontrol agents predominated, accounting for an average of 60% of the new biological products registered, increasing significantly to 80% in 2020, with more than half of the products registered being bioinsecticides. Sales of biocontrol products increased by 15% between 2018 and 2019. As a result, the total market for chemical and biological crop protection products in Brazil reached 11.6 billion US dollars, compared to 10.3 billion three years earlier (Goulet, 2021). Organic fertilizers had a revenue of more than USD 309,1 million in 2022; although the sales are small compared to the mineral fertilizer market, biocontrol products are growing significantly year on year (Abisolo, 2023).

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Table 1. Categories and quantities of agricultural products registered in the AGROFIT and SIPEAGRO systems, with emphasis on biological products in agriculture related to soil health

Database	Category	Quantity
AGROFIT*	Acaricide	229
	Bactericidal	28
	Pheromones	48
	Fungicide	738
	Insecticide	755
	Nematicide	36
	Total	1,834
SIPEAGRO**	Biofertilizer	9
	Organic Fertilizer	11,602
	Inoculant	521
	Plants Substrate	620
	Total	12,752

*AGROFIT = Plant Protection Agrochemicals System; **SIPEAGRO = Integrated System for Agricultural Products and Establishments.

To date, the number of biological products registered for commercial use in Brazil has gone from one in 2005 to 482 in February 2023 (Bettiol and Medeiros, 2023). The biopesticides registered in the country mainly target nematodes, corn leafhoppers (*Dalbulus maidis*), caterpillars, and the brown soybean bug (*Euschistus heros*), which reflects the diversity of products currently used. In addition to the market value, the number of biological products registered with the Ministry of Agriculture is constantly growing, as is the number of companies producing them and the number of organisms available (Vidal and Dias, 2023). The expansion in the number of registrations of agricultural biological products may reflect the proven impact on improving crop productivity, as, for example, observed in studies with *Azospirillum spp*, where research has shown that the inoculation of *Azospirillum spp*. can significantly increase agricultural productivity. Hungria et al. (2010) reported a 26% yield gain in corn associated with *A. brasilense*, due to nitrogen fixation and better absorption of nutrients such as phosphorus and potassium. In July 2023, there were 529 products registered in AGROFIT (the Plant Protection Agrochemicals System) and 12,752 in SIPEAGRO (the Integrated System for Agricultural Products and Establishments). The categories of these products are detailed in Table 1.

The evolution of the market and the number of biological product registrations show the diversity of biological product applications and the evolution of research in the area, as well as the growing interest in this technology (Mamani de Marchese and Filippone, 2018; Vidal and Dias, 2023). As challenges related to the production and use of biological products are overcome, such as storage, quality control, application technology, and the acculturation of producers to this technology over agrochemicals, the adoption of biological products tends to grow (Guimarães *et al.*, 2019; Parra, 2014, 2023). Therefore, biological products will be increasingly present in agricultural production systems, and it is important to assess their effects on soil health.

The importance of biological products in maintaining soil health

Soil health can be defined as the ongoing capacity of soil to function within ecosystem boundaries to support plant, animal, and human life (Lehmann *et al.*, 2020). This concept evolved from the broader idea of soil health, aiming to encompass the entirety of soil functions within the context of ecosystem health, rather than focusing solely on agricultural production (Lehmann *et al.*, 2020).

One of the key pillars of soil health lies in the functioning of its biological component, where various groups of microorganisms play essential roles. These include bacteria, fungi, protozoa, nematodes, arthropods, algae, and actinomycetes. These microorganisms perform a range of vital functions that contribute to soil health and fertility, such as decomposing organic matter, cycling nutrients, biologically fixing nitrogen, solubilizing phosphorus, suppressing pathogens, promoting

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plant growth, and improving soil structure. In this context, biological products have the potential to enhance the biological component of the soil while posing a lower risk of negative environmental impacts (Maitra *et al.*, 2021).

With growing concerns about environmental sustainability, biological products have gained attention due to their multifunctional and relevance across various agricultural functions. However, it remains essential to deepen our understanding of the diversity, roles, and specific contributions of these biological products to soil health, a fundamental element of sustainable productivity. Therefore, a comprehensive and thorough analysis of the topic is necessary to provide relevant, well-supported information that can guide the effective adoption and use of biological products in agriculture. This study proposed that biological products contribute to soil health by performing multiple functions. We investigated whether they improve soil fertility, increase biological activity, and aid plant growth. The study involved a comprehensive literature review on the role of biological products in agriculture, emphasizing their importance for soil health. This study aimed to compile and analyse the main mechanisms proposed in the literature through which biological products act to improve soil health, considering their different categories: biological control, bio-fertilizers, and bio-inoculants.

Material and methods

The study employed a structured literature review, which synthesizes the results of individual studies in a structured and descriptive manner, without emphasizing statistical significance (Galvão and Ricarte, 2019). Although no formal protocol (e.g., Preferred Reporting Items for Systematic Reviews and Meta-Analyses – PRISMA) was registered, we adopted several of its key principles, such as clear inclusion/exclusion criteria, filtering by subject areas and document types, and structured reporting of selection steps. The PRISMA methodology is acknowledged as a valuable reference for improving transparency and reproducibility in future reviews (Page *et al.*, 2021). The literature search involved a combination of search terms across all databases on the Scopus® platform (https://www.scopus.com/). The search was conducted using the 'Search documents' field, with queries across 'All fields'. The advanced search utilized the following terms/keywords: ('biological products' AND soil*) OR ('biological product' AND soil*) OR (bioinput* AND soil*). The search covered articles from 1996 to 2023. The term 'soil' was used exclusively in the database to focus on the impact of these inputs on soil health.

A total of 560 documents were identified and screened to ensure they aligned with the scope of this review. The first filter, 'Subject areas', narrowed the results to relevant fields, including Agricultural and Biological Sciences, Environmental Sciences, Molecular Biology, Genetics and Biochemistry, Immunology and Microbiology, and Planetary and Earth Sciences. The second filter, 'Document type', restricted the search to articles, reviews, books, and book chapters.

At the end of the search, 362 articles were obtained and used to understand the subject and prepare the review. However, some articles were unrelated to the topic of interest. Therefore, we excluded keywords that did not align with the scope of the review, such as 'drug effect', 'drug isolation', 'drug structure', 'unclassified drug', 'polymerase chain reaction', 'oil', 'bone', 'article', 'human/humans', 'review/reviews', and 'procedures'. Journals that were not relevant to the study context were also excluded, leaving journals from the following areas: 'Agricultural and Biological Sciences', 'Environmental Science', 'Earth and Planetary Sciences', and 'Biochemistry, Genetics, and Molecular Biology'. This refinement resulted in 203 documents after individually screening them for any mention of the relationship between biological products and soil health; 85 documents were selected for further analysis. (Figure 1).

All gathered literature was synthesized and analysed to highlight the importance of the subject and to provide insights into the multifunctionality of biological products and their relevance to

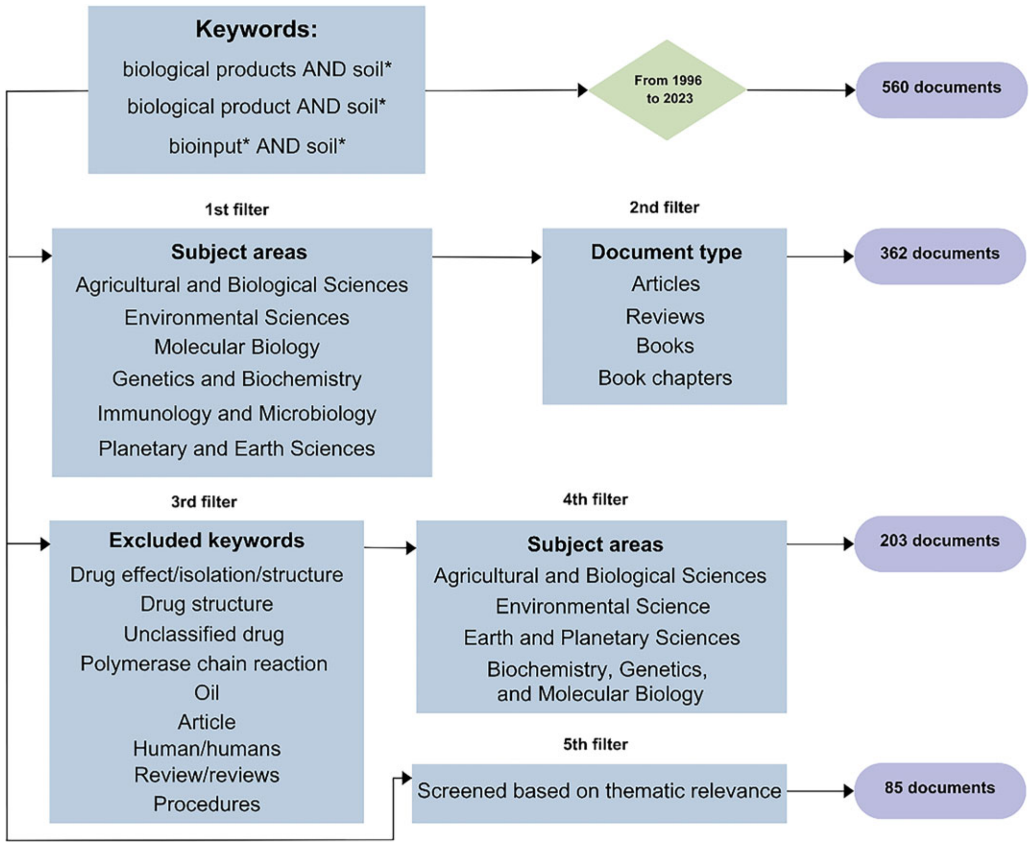

Figure 1. Systematic filtering process for biological products in agriculture publications.

soil health. The files were downloaded in Comma-Separated Values format and analysed using the 'Analyse search results' function on the Scopus® platform. The data were then exported to Microsoft Office Excel (version 2021) and VOSviewer software (version 1.6.17) (Van Eck and Waltman, 2010), available at https://www.vosviewer.com/.

Several parameters were analysed in this process, including: (i) Number of Publications per Year: The number of publications was recorded and organized by year to identify trends and variations over time; (ii) Most Cited Articles: The most cited articles within the dataset were identified to highlight influential and relevant works in the field; (iii) Keyword Frequency: An analysis was conducted on the frequency of keywords used in the articles, highlighting the most commonly found terms and providing an overview of the main themes and areas of interest; and (iv) International Scientific Collaboration Network: Co-authorship analysis was used to identify scientific collaborations between countries, mapping the connections and partnerships established in the production of knowledge on the subject.

VOSviewer generates maps in three stages: calculation of the similarity matrix, mapping, and adjustments (translation, rotation, and reflection), as described by Van Eck and Waltman (2010). In this study, maps were developed to illustrate connections between keywords and countries in scientific research, highlighting coloured groupings that represent stronger collaboration networks. Rectangles on the maps represent the terms, with their size proportional to their frequency of occurrence. The data obtained with VOSviewer provide insight into the current state of a field of study. This analysis identifies broad areas, gaps, and key points requiring further

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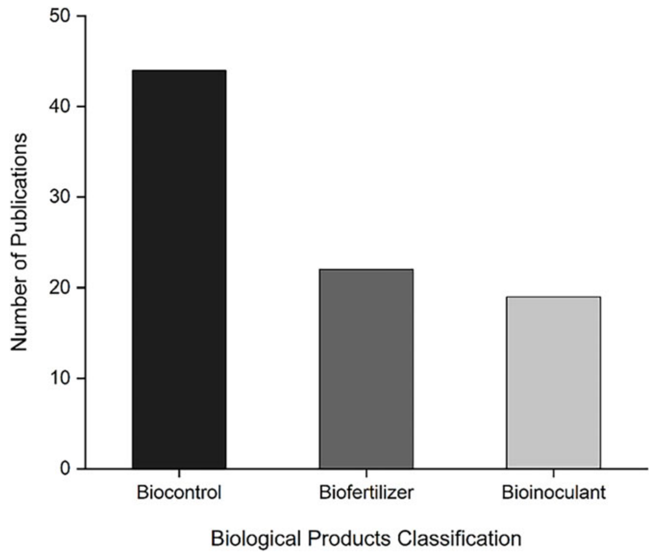

Figure 2. Number of publications according to biological products classification: biocontrol products, biofertilizers, and bioinoculants.

attention, aiding in the understanding of the evolution of scientific knowledge. This approach offers a comprehensive view for researchers and professionals interested in advancing their fields, and is a valuable tool, as highlighted by Van Eck and Waltman (2010).

The articles were classified according to the type of biological product used: biocontrol product, biofertilizer, or bioinoculant (Figure 2), based on categories defined in legislation and literature. This classification considers the function of each biological product in comparison to related chemical products. Soil health indicators were evaluated, and the effects observed from the application of the biological products were discussed.

Results

Number of publications per year

According to the 203 documents identified before content refinement, there has been a significant growth in publications on biological products over the years, particularly from 2018 onwards (Figure 3). In the last 10 years, from 2014 to 2023, there were a total of 100 publications, representing a period of significant progress in the field, with an average of 10 publications per year. Furthermore, in the last 5 years, from 2019 to 2023, there were 76 publications, reflecting a substantial growth in scientific output in this specific area.

Considering the 85 documents identified after thorough screening on the effects of biological products on soil health, the results reveal a steady rise in publications on biological products and biological products over the years, with a marked rise in recent years, particularly from 2018 onwards (Figure 3). In the last 10 years (2013–2022), a total of 74 articles were published, accounting for approximately 87% of all registered publications. In the last 5 years (2018–2022), 50 articles were published, representing around 59% of the total. This high concentration of recent publications highlights the growing interest and research activity in this area during the most recent period. The increased number of publications in the last years is also aligned with the exponential growth of soil health papers in the last decade in Brazil, as recently reported by Cherubin et al. (2025).

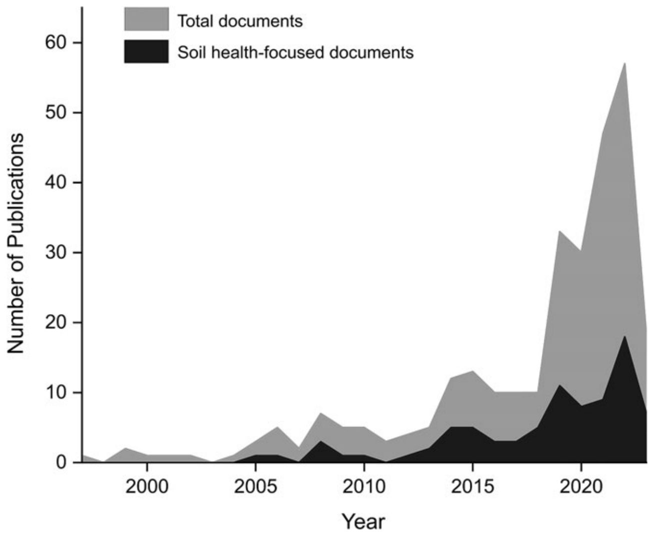

Figure 3. Number of publications over time on biological products: total documents (203) versus soil health-focused studies (85).

The results show a diverse geographical distribution of scientific production on biological products that influence soil health. Brazil and Russia stand out, with Brazil leading the list with 16 documents, followed by Russia with 14. Other countries also contribute significantly to the field, including India (9 documents), China (4), Spain (4), the United States (4), and Italy (4).

Among the articles listed, '*Azospirillum sp*. in current agriculture: From the laboratory to the field' has the highest number of citations so far, with a total of 184 (Table 2). This study was published by Cassán and Diaz-Zorita (2016) in the journal Soil Biology and Biochemistry, and received an average of 26.29 citations per year. The first three articles on the list are about specific organisms. The document selection prioritized scholarly impact, with relevance determined by citation count. Highly cited articles can reflect the methodological or theoretical usefulness of a study, making it central to scientific progress (Bornmann and Daniel, 2008), representing fundamental advances or widely recognized syntheses in a field, influencing subsequent research (Garfield, 2006).

Table 3 shows the six most relevant Brazilian biological product articles, focusing on their application in sustainable agriculture. The studies range from the use of phosphorus-solubilizing microorganisms to the application of humic substances combined with growth-promoting bacteria. The works by Silva et al. stand out with 46 and 35 citations, reflecting the significant impact of these technologies on improving soil health and reducing the use of chemical inputs. The most recent articles, by Rocha et al. (2024) and Afridi et al. (2024), point to new trends in bioprocesses and biological control. Although these studies have not yet been cited, they can influence future research. The variation in the number of citations reflects the time of publication and the relevance of the topics; however, collectively, they all contribute to the transition towards more sustainable agricultural practices.

Figure 4 illustrates the co-occurrence network of keywords found in the selected publications, grouped by thematic clusters represented by different colours. The blue cluster, centred around 'biological products', 'soil', 'chemistry', 'microbiology', and 'bacteria', suggests a strong association with studies focused on the chemical and microbiological aspects of soil amendments. The green cluster, which includes terms like 'bacteria (microorganisms)', '*rhizobacterium*', '*rhizobiales*', and 'inoculation', is more closely related to plant-microbe interactions and nitrogen-fixing bioinoculants. The red cluster, with keywords such as 'biocontrol agent', '*Fusarium*', and

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Table 2. Top 10 most cited scientific articles related to biological products in agriculture and soil health

Title	Authors	Journal	Cited by	Year	Citations by year
Azospirillum sp. in current agriculture: From the laboratory to the field	Cassán and Diaz-Zorita	Soil Biology and Biochemistry	184	2016	26.3
Combined application of the biological product LS213with *Bacillus, Pseudomonas* or *Chryseobacterium* for growth promotion and biological control of soil-borne diseases in pepper and tomato	Domenech *et al.*	BioControl	114	2006	6.7
Seed inoculation with *Bacillus subtilis*, formulated with oyster meal and growth of corn, soybean and cotton	Araujo	Ciência e Agrotecnologia	44	2008	2.9
Sustainable soil management is more than what and how crops are grown	Kassam *et al.*	Advances in Soil Science	42	2013	4.2
Assessment of fertilizer potential of the struvite produced from the treatment of methanogenic landfill leachate using low-cost reagents	Siciliano	Environmental Science and Pollution Research	34	2016	4.9
Antagonistic potential of native strain *Streptomyces aurantiogriseus* VSMGT1014 against sheath blight of rice disease	Harikrishnan *et al.*	World Journal of Microbiology and Biotechnology	34	2014	3.8
Agrowaste bioconversion and microbial fortification have prospects for soil health, crop productivity, and eco-enterprising	Singh *et al.*	International Journal of Recycling of Organic Waste in Agriculture	26	2019	6.5
Wood chips and compost improve soil quality and increase growth of *Acer rubrum* and *Betula nigra* in compacted urban soil	Scharenbroch and Watson	Arboriculture & Urban Forestry	18	2014	2.0
Evaluation of chemical and biological seed treatments to control charcoal rot of soybean	Reznikov *et al.*	Journal of General Plant Pathology	18	2016	2.6
Technologies for the selection, culture and metabolic profiling of unique rhizosphere microorganisms for natural product discovery	Gurusinghe *et al.*	Molecules	11	2019	2.8

Table 3. Brazilian scientific articles on biological products in agriculture and soil health published in international journals

Title	Authors	Journal	Citations	Year
Phosphorus-solubilizing microorganisms: a key to sustainable agriculture	Silva *et al.*	Agriculture (Switzerland)	46	2023
The potential use of actinomycetes as microbial inoculants and biopesticides in agriculture	Silva *et al.*	Frontiers in Soil Science	35	2022
Humic substances in combination with plant growth-promoting bacteria as an alternative for sustainable agriculture	Silva *et al.*	Frontiers in Microbiology	32	2021
Burkholderia vietnamiensis G4 as a biological agent in bioremediation processes of polycyclic aromatic hydrocarbons in sludge farms	Cauduro *et al.*	Environmental Monitoring and Assessment	4	2023
Agricultural bioinputs obtained by solid-state fermentation: from production in biorefineries to sustainable agriculture	Rocha *et al.*	Sustainability (Switzerland)	1	2024
Long-term benefit contribution of chemical and biological nematicide in coffee nematode management in soil microbial diversity and crop yield perspectives	Afridi *et al.*	Microbiological Research	0	2024

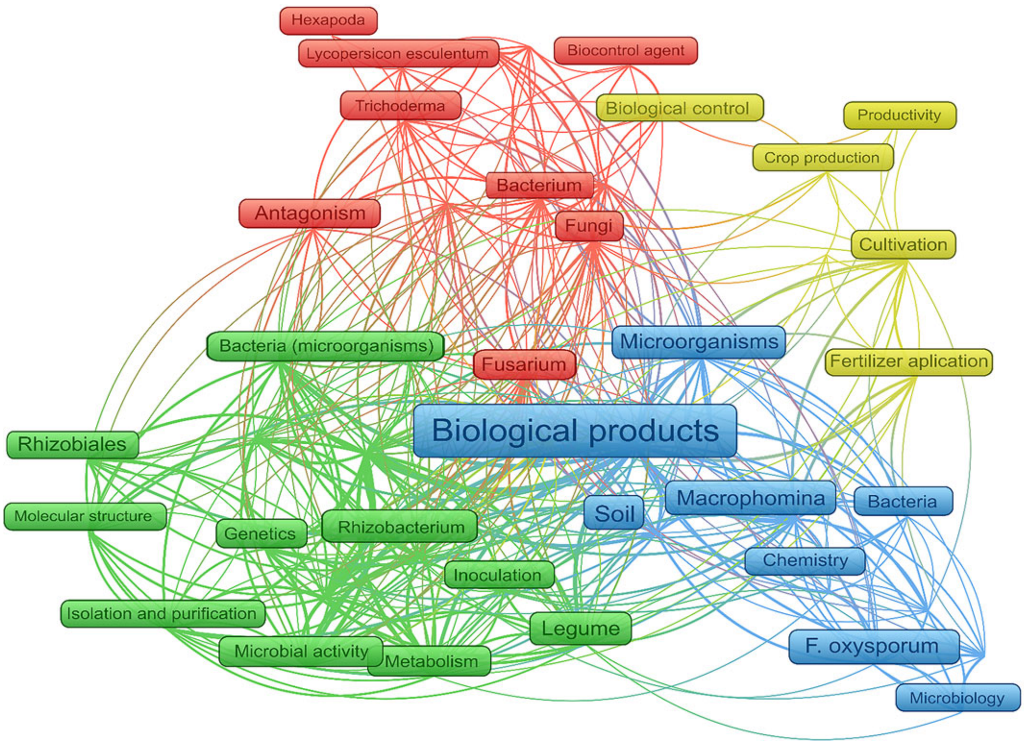

Figure 4. Most frequently occurring keywords in research on biological products in agriculture influencing soil health.

'*Trichoderma*', reflects research focused on biocontrol agents and antagonistic microorganisms targeting soilborne pathogens. Finally, the yellow cluster highlights broader terms like 'biological control', 'fertilizer application', and 'productivity', which connect across themes, suggesting multifunctionality as a central concept. These groupings demonstrate how research on biological products is diversified into distinct but interconnected domains, each contributing to our understanding of how biological products affect different dimensions of soil health.

Discussion

South American scientific contribution to the biological products market

Given the growing challenges in agriculture, particularly concerning food security and environmental sustainability, the development and application of biological products have emerged as a promising soil management strategy. This biologically based approach aims to provide effective solutions to current agricultural challenges while minimizing the adverse environmental impacts associated with conventional practices. However, to fully capitalize on the potential of biological products and address emerging challenges, it is essential to overcome farmers' resistance to adopting these products, strengthen relevant regulations, and optimize application practices.

An analysis of the most influential papers in the field reveals a significant contribution from South American authors (two from Argentina and one from Brazil), highlighting not only the region's prominence in biological products research and regulation but also the importance of considering specific regional contexts, such as the continent's vast agricultural landscapes, longstanding interest in sustainable practices, and supportive policy frameworks – when

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evaluating the efficacy and applicability of these products. Among the three most cited articles, the first is a comprehensive review that explores the benefits of bioinoculation in relation to key attributes such as initial growth, root development, and increased crop yields (Cassán and Diaz-Zorita, 2016). One of the highlighted results in this review is the commercial use of inoculants based on *Azospirillum sp*., which are applied to approximately 3.5 million hectares, primarily in cereal crops in South America (Cassán and Diaz-Zorita, 2016).

In the second most cited article (Domenech *et al.*, 2006), evidence was presented of a synergistic effect in promoting plant growth and enhancing resistance to pathogens (biocontrol) when using a combination of two biological products based on *Bacillus subtilis* and *B. amyloliquefaciens*. This combination enhanced resistance by up to 70%. Lastly, the third most cited article demonstrated the positive effect of bioinoculation with *Bacillus subtilis* on the emergence rate, growth, and nutrition of plants (Araujo, 2008). These *Bacillus* strains increase plant resistance through multiple mechanisms, including the production of antifungal antibiotics and the solubilization of nutrients such as phosphorus. In addition, certain strains, such as *B. amyloliquefaciens* and *B. subtilis*, have been shown to induce systemic resistance, helping plants to respond more effectively to soil-borne pathogens such as *Fusarium* and *Rhizoctonia spp*. The high scientific output from Brazil on this topic suggests that the country may be emerging as a leader not only in the consumption of biological products but also in the generation of knowledge and technology, something that is not common across many sectors of the economy. The development of the bio-input market could be strategically important in the recent context of rising prices for chemical fertilizers and petroleum-derived products.

The most frequent terms in the surveyed publications highlight the most commonly used and researched biological products: biological control products, with emphasis on wilts caused by the fungus *Fusarium* and insects (Hexapoda), as well as inoculants for legumes (especially soybeans), aimed at biological nitrogen fixation. Nonetheless, despite the considerable growth of the market, it is possible to identify a scarcity of publications that integrate biological products and their relationship with aspects beyond plant productivity and morphology.

The keyword co-occurrence map (Figure 4) reveals a fragmented landscape in biological products research, structured into distinct thematic clusters. The red cluster encompasses terms related to biocontrol and biopesticides (e.g., *Trichoderma*, *Fusarium*, biocontrol agent, and *Hexapoda*), reflecting a strong focus on pest and pathogen management. The green cluster includes terms such as rhizobiales, inoculation, and legume, associated with microbial inoculants used to promote plant growth, particularly via nitrogen fixation. The blue cluster, built around biological products, bacteria, chemistry, and microbiology, suggests a broader focus on microbial processes and their chemical interactions in soil systems.

These groupings are not arbitrary; they likely reflect how research projects, funding, and regulatory frameworks have historically approached biological products as tools with distinct and compartmentalized functions: either for plant protection, nutrient supply, or productivity enhancement. The limited overlap among clusters points to a lack of integrative studies that simultaneously address the biological, chemical, and physical dimensions of soil health. While biological products act as a central connector in the network, the surrounding clusters remain only loosely integrated.

This pattern raises important hypotheses. One possibility is that researchers and institutions tend to operate within disciplinary silos, plant pathology, microbiology, and agronomy, limiting cross-domain synthesis. Another is that methodological challenges or the absence of standardized indicators for soil health have discouraged more comprehensive assessments. Regardless of the cause, the result is a fragmented body of literature, where the multifunctionality of biological products is underexplored.

While the significant increase in the number of publications over the last 10 years is undeniable, this thematic fragmentation also reveals a critical limitation: the decline in studies that explicitly contribute to understanding soil health. Despite the central role of soil in sustainable agriculture, most publications remain concentrated on isolated effects, such as pest control or nutrient availability, rather than on integrated soil system functioning. Within the categories considered in the review, biocontrol products were the most frequently addressed biological products (51%), followed by biofertilizers (34%), further reinforcing the prevalence of targeted approaches over holistic evaluations.

Soil health and biological products: scientific basis

Most of these studies focus on evaluating the effectiveness of control over target species and on grain and fruit production, respectively. Only 2 of the 85 studies available after screening, or less than 3%, effectively assessed physical, chemical, and biological soil indicators, thereby limiting the results to the plant's response to the biological product entering the system. Without holistic data, it's challenging to confirm the long-term soil health benefits of these biological products. This gap hinders our ability to evaluate potential trade-offs, cumulative effects, or sustainability outcomes associated with repeated or large-scale applications. Despite the growing adoption and visibility of these inputs, there remains a lack of solid scientific foundation regarding the effects – whether beneficial or otherwise – of these products on overall soil health, both in the short and long term. It is worth noting, however, that there is a noticeable effort to evaluate the impact of biocontrol products on non-target organisms. These often include soil organisms, particularly arthropods, which can be considered an indicator of soil health (González-Núñez *et al.,* 2022; Temreshev *et al.,* 2023).

Some authors have observed a positive effect on plants and soil when using biocontrol products, resulting in reduced pest and disease pressure, increased productivity, and improved biological quality of the soil (Bourbos and Barbopoulou, 2005; Frederic *et al.,* 2020; Hnoosh and Aljuaifari, 2020; Vörös and Ledóné, 2023). These biological products can improve soil biological quality by enhancing microbe–microbe interactions, stimulating induced systemic resistance in plants, and promoting nutrient cycling through microbial activity. Leles et al. (2022) conducted a study that demonstrated the effectiveness of using biofungicides alone for controlling fungi responsible for grape rot, achieving a control rate of up to 51.5%. Additionally, by combining these biofungicides with chemical control, it was possible to achieve a control efficiency of 100%. These results were also observed in crops of significant economic importance, such as corn (Vörös and Ledóné, 2023), as well as in soybean and wheat, where integrated approaches enhanced disease suppression and yield (Borah *et al.,* 2023; Kashyap *et al.,* 2025).

Furthermore, there are studies highlighting the versatility of a single biological product as a biological control agent for various pests, diseases, and crops. This is evidenced by Grishechkina (2015), whose research evaluated the action spectrum of a biological product and demonstrated its effectiveness both as an insecticide and as an antifungal against various pests and pathogens. The efficiency percentage ranged from 42% to 100%, demonstrating the broad range of action of this product with minimal environmental impact. Conversely, some studies observed effects on non-target organisms (Temreshev et al., 2022), indicating that some biocontrol products may not be entirely selective. Rigorous field trials and multi-season evaluations are essential to identify potential unintended impacts of these products on soil biodiversity. With the advancement of research, biological products, which have a lower environmental impact compared to synthetic ones, should become even more selective with reduced disturbance to ecological balance. To achieve this, it is important to evaluate additional indicators beyond plant response and the effects on the target pest population.

There is a wide diversity of biofertilizers evaluated, with most being growth-promoting bacteria, followed by organic fertilizers, accelerators of residue decomposition (Ivenin *et al.,* 2022; Sviridova *et al.,* 2022), and only one study involving probiotics (Bazar et al., 2022). Biofertilizers can be used for production purposes (e.g., Jadhav *et al.,* 2023; Płaza *et al.,* 2021) and bioremediation (e.g., Chetverikov and Sharipov, 2022; Ryazanova and Fedorova, 2020). In this

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review, inoculants are considered biofertilizers that are applied to seeds. In this context, most studies refer to nitrogen-fixing bacteria, but also to bacteria that solubilize other nutrients, such as phosphorus and micronutrients (Adoko *et al.,* 2022; Horodyska *et al.,* 2021).

The only two articles that evaluated all three dimensions of soil health (chemical, physical, and biological) focus on biofertilizers. Scharenbroch and Watson (2014) assessed four biofertilizers for urban forestry, including three organic fertilizers and one commercial product with growth-promoting microorganisms. They analysed, in addition to plant growth, eight soil indicators: density and moisture (physical indicators); pH, total nitrogen, available phosphorus, and exchangeable potassium (chemical indicators); and soil organic matter and microbial respiration (biological indicators). The authors concluded that, overall, the organic compost and the wood chip-based fertilizer had the best effects on soil health.

Jadhav et al. (2023) evaluated seven types of biofertilizers (organic fertilizers) for organic cotton production and analysed, in addition to plant responses, 10 soil indicators. They found that, over the two years of evaluation, there was no significant difference in the physical properties, but the chemical and biological indicators generally improved. These findings suggest that biofertilizers can improve soil health by enhancing chemical and biological properties. Therefore, incorporating such products into soil management practices, particularly in organic or low-input systems, may be an effective strategy for promoting more sustainable and resilient agroecosystems.

It is evident that, in general, studies with biofertilizers analyse a greater number of soil indicators compared to studies with biocontrol products. The latter focuses solely on assessing off-target effects in the soil, which, as mentioned earlier, while it can be considered an evaluation of soil biological quality, is insufficient to be regarded as a comprehensive assessment of soil health. In studies on biofertilizers, it is more common to evaluate at least two dimensions, typically chemical and biological, because these products directly interact with soil microbial communities and nutrient availability, affecting both the biotic and abiotic components of the soil system (e.g., Ivenin *et al.,* 2022; Mustafayev *et al.,* 2022).

However, studies related to bioinoculants follow the same approach found in biocontrol studies, focusing on the assessment of a specific group of indicators, usually chemical, with an emphasis on increasing productivity. Chernikova et al. (2021) investigated the effects of using bio-stimulants in seed treatment, demonstrating that liquid bioinoculants contribute to improved performance in different soil types. Similar results were observed by Araujo (2008), who found improvements in plant emergence and development, as well as higher levels of phosphorus and nitrogen concentration in the leaves, when bioinoculants were used across various crops.

Studies addressing the use of bioinoculants often reveal a correlation between the chemical and biological aspects of soil, even if the authors do not discuss this relationship. Physical indicators are often undervalued in the context of biological products, which reduces the opportunities for a comprehensive assessment of soil health through an index. This review shows that none of the biological product categories analysed have been the subject of studies assessing soil health considering all three pillars of indicators (i.e., physical, chemical, and biological), as most research has predominantly focused on yield. This lack of correlation between attributes and yield represents an opportunity for future studies with biological products.

Although not explicitly mentioned in the studies, as very few actually assessed soil health in the strict sense, it is important to highlight that the results obtained may be directly related to soil health and the potential improvements caused by the incorporation of the respective inputs into the system. The positive responses observed in biological products (primarily biocontrol) can be attributed to the stimulation of soil microbiota, which plays a crucial role in plant defence against diseases and other stresses.

By appropriately stimulating this population, biological products have the potential to enhance productivity. A balanced soil biological community plays a key role in supporting plant development by regulating enzymatic activity, enhancing nutrient cycling, and influencing soil physical and chemical properties. Microbial groups such as bacteria, fungi, and archaea contribute to essential soil functions, including organic matter decomposition, nitrogen fixation, and disease suppression (Bünemann *et al.*, 2018). In recent years, the growing number of publications focusing on plant–microbiome interactions and biological products reflects increased scientific and commercial interest. This trend highlights the growing potential of biological products in leveraging plant–microbiome interactions for improved soil health. In particular, combinations of microorganisms have shown synergistic effects, improving nutrient availability, enhancing stress tolerance, and suppressing pathogens, thereby contributing to a more resilient and productive soil environment.

Soil health and knowledge gaps

Soil health is commonly understood as the result of a dynamic balance among three fundamental and interdependent pillars: physical structure, chemical composition, and biological activity. Improvements in soil microbiota impact both physical and chemical components, due to the active involvement of microorganisms in physical and chemical transformations. A clear example of this process is enzymes, which act as biological indicators of soil health by converting initially non-assimilable nutrients into forms that can be absorbed by plants and organisms. This enzymatic activity indirectly leads to enhanced soil fertility, which can be optimized through the use of biofertilizers. Thus, understanding and promoting the interaction between soil microbiota, chemical composition, and physical properties is essential for a comprehensive and effective approach to soil health in relation to the application of biological products.

Future perspectives

This knowledge gap underscores the need to expand the diversity of microbial strains used in agriculture and to conduct field trials that assess their performance under variable conditions. Investing in technologies for the cultivation, formulation, and preservation of live microorganisms is also essential to ensure the stability and efficacy of biological products under environmental stress. The soil microbiome, comprising the entire community of microorganisms associated with soil and plant roots, plays a critical role in nutrient cycling, pathogen suppression, and resilience to abiotic stress. Biological products can manipulate the structure and function of the soil microbiome, enhance beneficial interactions, and restore ecological balance. In summary, a comprehensive approach that considers and recognizes the diversity and interactions of organisms within the microbiome can make a significant contribution to promoting soil health and moving towards more sustainable agricultural systems.

Conclusions

Our study revealed a significant increase in the number of publications on biological products in recent years, reflecting the growing interest and potential of these tools in promoting sustainable agricultural practices. This trend highlights the increasing importance of biological products, particularly those involving combinations of plant-associated microorganisms. However, the relationship between biological products and soil health remains understudied, especially regarding their long-term effects on key soil functions.

This study is limited by its bibliometric approach, which identifies trends but does not validate biological product effects experimentally. Nonetheless, the findings offer a useful framework for future research. While the literature supports the potential of these products to improve soil fertility and plant growth, it remains fragmented. More integrative, long-term studies are needed to maximize their benefits for sustainable agriculture.

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