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Utilization of Microorganism-Based Biopesticides to Increase Crop Productivity

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ABSTRACT

The increased global emphasis on sustainable farming has accelerated interest in microorganism-based biopesticides as an alternative to chemical pesticides. This systematic literature review of 65 articles acquired from the Scopus database explains research trends, top journals, affiliations, and actual applications of microorganism-based biopesticides in increasing crop production. The results show a marked escalation in publications since 2018, with India, the United States, and Europe leading the research. Top journals such as Microorganisms for Sustainability and Crop Protection are essential for knowledge dissemination. Leading academic institutions, such as Banaras Hindu University, and governmental institutions, such as the USDA Agricultural Research Service, drive innovation in the field. This study chronicles the increasing global recognition of biopesticides as a contribution to sustainable agriculture and identifies the major areas requiring additional research, such as field efficacy, scalability, and regulation. These findings are valuable to policymakers, researchers, and agricultural stakeholders interested in introducing biopesticides into conventional farming systems.

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1. INTRODUCTION

The increasing population in the world and the resulting necessity for additional productivity in agriculture have subjected traditional modes of farming to a tremendous strain. Pesticides made from chemicals have dominated pest control practices for several decades, with short-term solutions in curtailing crop infestations. Their rampant and most times indiscriminate use has had significant environmental and health effects, including soil erosion, water pollution, loss of ecosystem diversity, and detrimental consequences for human health [1], [2]. These problems underscore the importance of sustainable alternatives that can manage pests effectively and minimize ecological and health risks [3].

Microorganism-based biopesticides have emerged as a solution to the problem of sustainable agriculture [4]. Derived from naturally occurring microorganisms like bacteria, fungi, viruses, and other microbes, biopesticides offer pest control mechanisms that are ecologically friendly and IPM-compatible. Unlike their chemical equivalents, biopesticides are less toxic to non-target organisms, less persistent in the environment, and have the ability to improve soil and plant well-being [5]. In addition, their application is in line with the global move towards environmentally friendly agriculture that will bring about long-term food security [6], [7].

While they are promising, microorganism-based biopesticide use remains limited in most regions due to problems such as inconsistent efficacy, production cost, and regulatory problems. Addressing these problems requires a comprehensive understanding of their mode of action, factors influencing their performance, and how to optimize their use in different agricultural systems. A systematic review of the literature can provide critical information on these aspects, resulting in greater adoption and utilization.

This article is a literature systematic review drawn from the Scopus database for an examination of the role of biopesticides derived from microorganisms towards improved crop productivity. The review also seeks to aggregate available information, identify prevalent trends and knowledge gaps in the literature, and provide practical recommendations for practice and future research. By determining the pros and cons of microorganism-based biopesticides, this study hopes to contribute to the growing body of literature in favor of sustainable agriculture and to inform policymakers, researchers, and practitioners.

2. LITERATURE REVIEW

2.1 Microorganism-Based Biopesticide Classifications

Microorganism-based biopesticides are categorized into three based on the type of microorganisms used [8]. Bacterial biopesticides such as Bacillus thuringiensis (Bt) share a common application due to the ability to produce toxins to interfere with pests' digestive processes that ultimately lead to death, while bacteria Pseudomonas fluorescens and Bacillus subtilis suppress plant disease by competition as well as antibacterial metabolites. Fungal biopesticides such as Beauveria bassiana and Metarhizium anisopliae act as entomopathogens that infect and lead to death in insect pests, and their species such as Trichoderma spp [9]. also controlling soil-borne diseases, enhancing nutrient uptake, and enhancing plant health. Viral biopesticides, for example, baculoviruses, are host-specific and are highly effective against lepidopteran insects by infecting and multiplying within the host, ultimately leading to pest death [10].

2.2 Modes of Action

Microorganism-derived biopesticides control pests and pathogens through diverse modes of action, including toxin production, parasitism, competition, and induced resistance [11]. Bacterial and fungal biopesticides are insecticidal, e.g., Bt toxins that bind to insect gut receptors causing cell lysis and death. Entomopathogenic fungi and viruses infect and multiply within the host, causing systemic infections and death [12]. Beneficial microbes suppress pathogens by competing for space and nutrients, whereas some biopesticides elicit plant defenses by activating natural resistance against pests and pathogens [13].

2.3 Agricultural Applications

Use of microorganism-based biopesticides is versatile across a wide range of crops and agricultural systems. Their efficacy has been established in controlling pests in cereals, vegetables, fruits, and plantation crops. For instance, application of Trichoderma spp. has been utilized in controlling root rot in soybean crops, whereas Bacillus subtilis manages powdery mildew in grapes. Biopesticides also provide improved crop yields by activating plant growth and soil health [14], [15].

2.4 Advantages of Microorganism-Based Biopesticides

Microbial biopesticides yield multi-dimensional advantages, including safety to the environment, as they have very limited impact on non-target species and reduce ecological disturbances [16]. Their compatibility with organic agriculture and biodegradability confirm their compatibility for sustainable agriculture. Unlike chemical pesticides, their complex modes of action guarantee resistance management by reducing opportunities for pest resistance [17]. Biopesticides also enhance soil health through ensuring microbial diversity and nutrient cycling, thereby contributing to agricultural sustainability [18].

2.5 Gaps in the Research

Research has noted a series of gaps that should be addressed, e.g., formulation optimization to enhance the stability and performance of biopesticides in diverse environmental conditions. There should be research incorporating biopesticides into IPM strategies and examining their synergistic effect with other pest control means for broader implementation. It should also be explored to examine the economic viability of biopesticides compared to chemical pesticides to support adoption. Microbial interaction, particularly between biopesticides and native soil microbiota, is another critical area that can be utilized for the optimal use and efficiency of biopesticides.

3. METHODS

This study applied the systematic literature review (SLR) to explore the usage of microorganism-based biopesticides in promoting crop productivity as a whole. Through the application of the SLR method, relevant studies were determined, evaluated, and consolidated, creating a robust foundation for understanding current knowledge, trends, and discrepancies in the study topic. The research design was as per the PRISMA guidelines to ensure transparency and replicability, with the primary aim of comparing peer-reviewed literature on the applications, benefits, challenges, and impacts of microorganism-based biopesticides in agriculture. Data were collected through the Scopus database, chosen for its extensive coverage of high-quality literature, with keywords "microorganism-based biopesticides," "biological control agents," and "microbial pesticides." The search was restricted to 2000-2025 to reflect recent trends and advances in the topic area and included original research articles and review articles. The criteria for selection were relevance to the objectives of the study to provide a representative dataset for analysis.

Table 1. Criteria Review

Criteria	Details
Inclusion Criteria	- Studies focusing on microorganism-based biopesticides and their impact on crop productivity.
	- Articles published in peer-reviewed journals.
	- Papers written in English.
	- Research presenting experimental, case study, or review-based findings.
Exclusion Criteria	- Studies that exclusively discussed chemical pesticides or non-microbial biopesticides.
	- Publications lacking empirical evidence or detailed analysis.
	- Duplicates, editorials, conference abstracts, and grey literature.

The study employed a multi-stage screening and selection process to determine the utilization of quality and relevant literature. The titles and abstracts were first screened against the inclusion criteria for studies that may be potentially relevant. Articles that passed through this stage were then screened for full-text review in order to determine their adherence to the research objective. Subsequently, quality appraisal was conducted using the Critical Appraisal Skills Programme (CASP) checklist to assess methodological quality and reliability. 65 documents met inclusion criteria and were analyzed finally. Descriptive statistics tallied study characteristics such as microorganism types, target pests, and crops, for data analysis. Thematic analysis brought together qualitative data under themes like mechanism of action, benefits, drawbacks, and research gaps. The results were reported in narrative form, aided by visual tools such as tables and charts, and situated in the broader context of sustainable agriculture and pest management.

4. RESULTS AND DISCUSSION

This section presents the findings of the systematic review of literature and discusses the implications of microorganism-based biopesticides application for increasing crop productivity. The findings are summarized into thematic categories with emphasis on the mode of action, advantages, disadvantages, and trends from the studies reviewed.

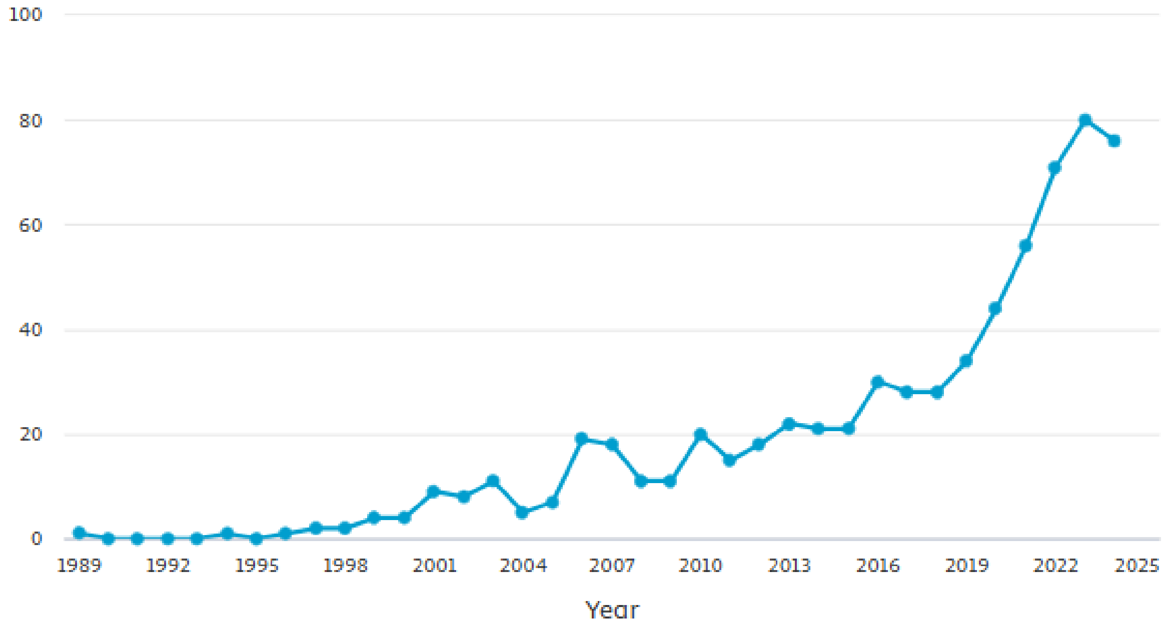

Figure 1. Trend Research

The trend analysis of microorganism-based biopesticide research highlights distinct phases: stagnant growth from 1989 to 2004, gradual increases from 2005 to 2017 due to advancements in microbiology and IPM strategies, and a surge from 2018 to 2023 driven by sustainability efforts and breakthroughs in molecular biology. A slight plateau in 2024–2025 suggests field maturation or challenges in scaling practical applications.

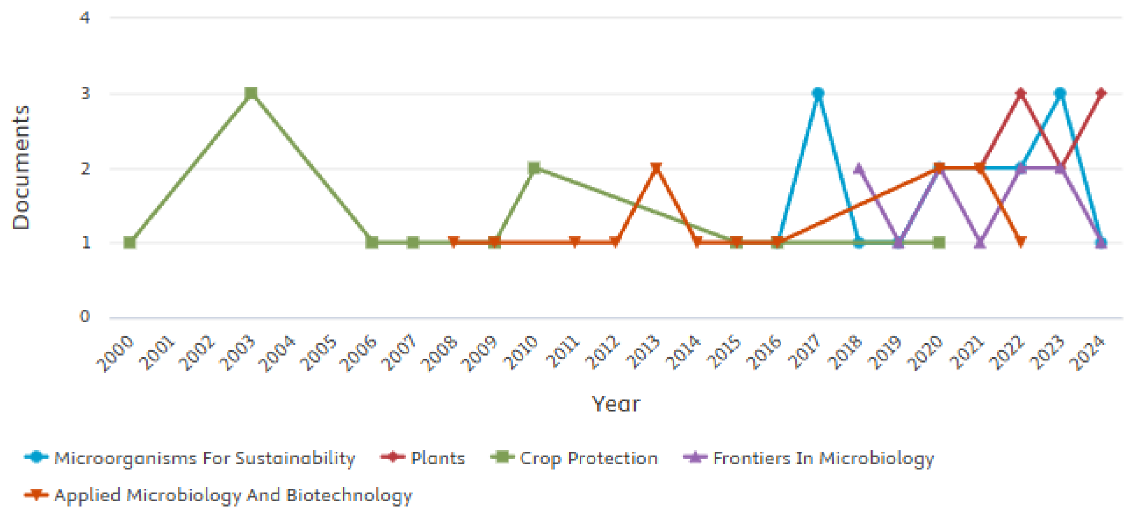

Figure 2. Trend Journal Contributions

The trend analysis of journals contributing to microorganism-based biopesticide research reveals distinct focuses and growth patterns. Microorganisms for

Sustainability has gained prominence since 2018, emphasizing microbial solutions for sustainable agriculture. Plants shows consistent growth post-2015, peaking in 2023, with research on microbial biopesticides and plant health. Crop Protection has contributed steadily since the early 2000s, with peaks in 2004 and 2017, reflecting its focus on pest management. Frontiers in Microbiology emerged around 2017, supporting cutting-edge studies on microbial technologies and their agricultural applications. Meanwhile, Applied Microbiology and Biotechnology demonstrates early and intermittent contributions, focusing on microbial strain development and biotechnological advancements in agriculture.

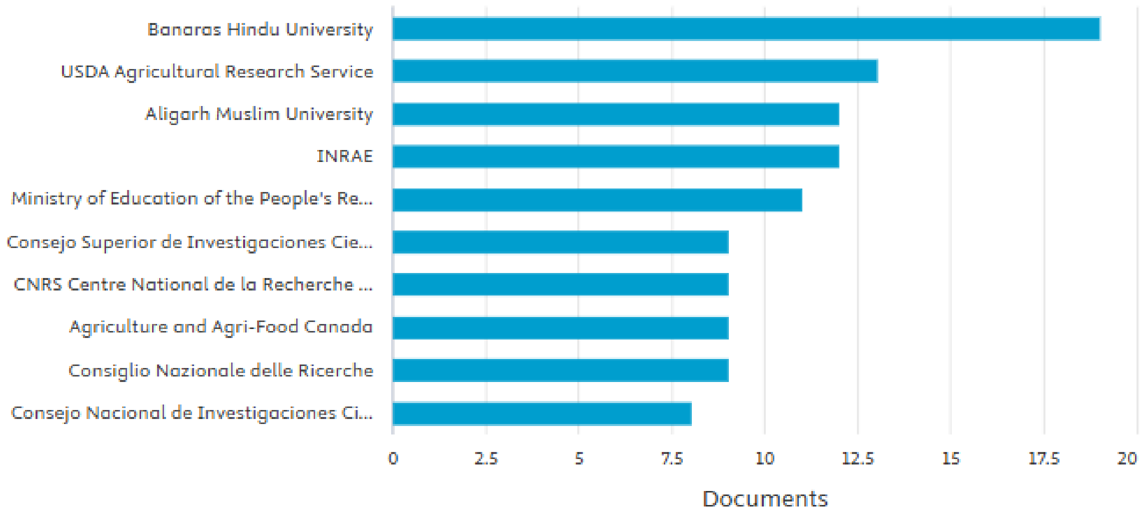

Figure 3. Affiliation Contributions

The affiliation analysis showcases global contributions to biopesticide research, led by Banaras Hindu University (BHU) and Aligarh Muslim University, reflecting India's strong focus on sustainable pest management. The USDA Agricultural Research Service highlights the U.S. effort to reduce chemical pesticides, while INRAE in France and China's Ministry of Education emphasize microbial technologies for sustainable agriculture. Spanish, Canadian, Italian, and Mexican institutions also contribute significantly, underlining the global interest in biotechnological solutions.

4.1 Distribution of Microorganism-Based Biopesticides

From the analysis of 65 documents, three primary categories of microorganism-based biopesticides were identified. Microorganisms such as bacteria, fungi, and viruses play a vital role in biocontrol by producing secondary metabolites with antifungal, antibacterial, and insecticidal properties, offering an environmentally friendly alternative to synthetic pesticides and supporting sustainable agricultural practices. Their effectiveness arises from diverse mechanisms, including antibiosis, competition, and the induction of systemic resistance in plants. For instance, bacterial genera such as Bacillus, Pseudomonas, and Streptomyces exhibit antagonistic activity against phytopathogenic fungi like Fusarium by producing lipopeptide antibiotics and phenazine derivatives, with Bacillus species particularly effective against tomato diseases through antimicrobial compounds and nutrient competition [19]. Similarly, fungi like Trichoderma and Beauveria bassiana suppress pests and pathogens through mechanisms such as mycoparasitism and enzymatic degradation, with Trichoderma also promoting plant growth and supporting integrated pest management strategies [20]. Additionally, baculoviruses serve as viral biopesticides that target specific insect pests, causing mortality through host infection and replication, offering a sustainable pest control option [12].

4.2 Target Pests and Crops

Microbial biopesticides have shown remarkable versatility and effectiveness across various crops, including cereals, fruits, and vegetables, providing an eco-friendly alternative to chemical pesticides and supporting sustainable agriculture and food security. Derived from natural sources like bacteria, fungi, viruses, and nematodes, these biopesticides target a range of pests, such as aphids, nematodes, whiteflies, and fungal pathogens like Fusarium and Phytophthora, making them integral to integrated pest management (IPM) strategies. In cereals such as rice, wheat, and maize, microbial biopesticides help control pests and diseases, enhancing sustainability [21], [22]. Similarly, in fruits like apples, grapes, and bananas, they protect against pests and improve fruit quality [17], while in vegetables like tomatoes, cucumbers, and potatoes, they manage pests and reduce disease incidence [23]. These biopesticides are highly effective against insect pests like aphids and whiteflies, reducing dependency on chemical insecticides [22], [23], and offer a biological solution to nematode infestations, which are otherwise challenging to control [18]. Additionally, they combat fungal diseases caused by Fusarium and Phytophthora, ensuring crop health and yield [24]. Beyond their agricultural benefits, microbial biopesticides are environmentally safe with minimal residual impact, supporting organic farming [23], and offer a cost-effective alternative to chemical pesticides, appealing to farmers seeking sustainable solutions.

4.3 Mechanisms of Action

Microorganism-based biopesticides employ diverse mechanisms, including direct antagonism, induction of plant defense, competition for nutrients and space, and parasitism or predation, providing an eco-friendly alternative to chemical pesticides and supporting sustainable agriculture. Direct antagonism involves the production of antimicrobial compounds by microbes, such as actinomycetes generating secondary metabolites like avermectins and milbemycins, and fungi like Beauveria bassiana producing toxic mycopesticides that target pests [25]. These biopesticides also induce plant defenses by stimulating immune responses, enhancing resistance to biotic stressors, and reducing reliance on chemical inputs [22], [23]. By occupying ecological niches, microbial biopesticides outcompete pathogens for resources, a critical aspect of integrated pest management. Additionally, certain fungi and bacteria parasitize or prey on pests, providing a natural and environmentally sustainable pest control solution.

4.4 Benefits Reported

Microorganism-based biopesticides provide significant benefits that align with sustainable agriculture by offering effective pest and pathogen control, enhancing crop productivity and quality, and contributing to environmental safety. Derived from bacteria, fungi, viruses, and nematodes, these biopesticides control a broad range of pests and diseases, such as entomopathogenic fungi (EPF), which manage insect pests and suppress pathogens, thereby increasing yields and supporting SDG 2 (Zero Hunger) through sustainable agriculture [26]–[28]. Their target-specificity and low residual impact promote environmental safety by reducing chemical pesticide reliance, preserving beneficial insects, and maintaining ecological balance [22]. Moreover, biopesticides integrate seamlessly into IPM practices, fostering long-term agricultural sustainability, supporting soil health, and conserving biodiversity [29].

4.5 Challenges and Limitations

Microbial-based agricultural solutions, such as bioherbicides and bioinoculants, present sustainable alternatives to chemical inputs but face challenges like variable efficacy, short shelf life, and adoption barriers, which are influenced by environmental conditions, formulation stability, and socio-economic factors. The efficacy of microbial products depends on environmental conditions, such as temperature, humidity, and soil type, necessitating the development of robust strains adaptable to diverse conditions [30], [31]. Additionally, the limited shelf life of microbial formulations reduces their effectiveness over time, prompting the need for innovative strategies to enhance stability and delivery efficiency [30], [32]. Adoption barriers, including high costs, limited farmer awareness, and regulatory hurdles, further hinder widespread use, with economic and regulatory challenges delaying commercialization [31], [33].

DISCUSSION

The growing emphasis on microorganism-derived biopesticides is a function of their potential as environmentally friendly alternatives to traditional synthetic pesticides. Advances in formulation technologies like encapsulation and freeze-drying have greatly enhanced the stability and efficacy of these microbial products. Genomic technologies have also played an important role in the identification of new microbial strains with great biocontrol potential, and this has created opportunities for more efficient and targeted pest control methods.

Microbial biopesticides play a great role in the development of sustainable agriculture because they assist in reducing the application of chemical pesticides. This reduction helps make ecosystems healthier, lowers pesticide levels in food, and reduces the risk of resistance in pests. Their capacity to fit into organic farming systems is also a desirable aspect for farmers who are looking for environmentally friendly pest control measures, which also favors sustainable agriculture goals.

Despite being beneficial, microbial biopesticides come with obstacles that need to be overcome to realize their full potential. Strategies involve investing in research to develop robust and easy-to-handle formulations, conducting farmer training programs to promote greater awareness of their usefulness and application, and providing policy and regulatory incentives to streamline the process of approvals and stimulate production. However, there are major research gaps, particularly the scalability of microbial biopesticides and their long-term effects on soil health. Future studies need to address these issues and explore the economic viability of integrating microbial biopesticides into large-scale agricultural systems to enable their mass application.

IMPLICATIONS FOR PRACTICE AND POLICY

Application of microorganism-based biopesticides is a paradigm change in pest control. Policymakers, scientists, and business people must collaborate to promote their adoption through facilitating frameworks, public-private partnerships, and incentives for sustainable agriculture.

5. CONCLUSION

Microorganism-based biopesticides hold promise as a replacement for the challenges posed by chemical pesticides, aligning with the worldwide trend towards sustainable agriculture. The sudden surge in research papers in recent years reflects a growing interest and commitment to this field. India, the United States, and European countries are among the leading contributors, supported by large academic and government institutions. High-impact journals and diverse affiliations reflect the interdisciplinary and international nature of this research. While the potential of biopesticides is evident, more research must focus on how to overcome practical issues, including large-scale field application, cost-effectiveness, and regulatory policies. There is a need for concerted effort among researchers, policymakers, and industry players to realize the full potential of biopesticides to enhance world agricultural productivity and sustainability.

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