Biopesticides in sustainable agriculture: advantages, limitations and ecotoxicological implications

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Abstract. Biopesticides are considered one of the most promising alternatives to synthetic pesticides within the framework of sustainable agriculture. Due to their natural origin, high biodegradability, and compatibility with integrated pest management strategies, they contribute to reducing the environmental impact of agricultural activities. This review paper analyzes recent scientific literature on the use of biopesticides in sustainable agriculture, focusing on their classification, advantages and limitations, as well as their ecotoxicological implications for non-target organisms, soil microorganisms, and aquatic ecosystems. The analysis highlights the significant potential of biopesticides to reduce dependence on conventional pesticides and support biodiversity conservation; however, their effectiveness may be influenced by environmental conditions, formulation stability, and target organism characteristics. Current research trends are also discussed, including the development of microbial biopesticides, botanical biopesticides, and nano-biopesticides. The reviewed literature supports the role of biopesticides in the transition toward environmentally sustainable agricultural systems while emphasizing the need for further research regarding their long-term effectiveness and safety.
Keywords: biopesticides, sustainable agriculture, ecotoxicology, biodiversity, integrated pest management.

Introduction. Modern agriculture relies heavily on the use of pesticides to control pests and maintain crop productivity (Qosim et al., 2018; Thanh et al., 2022; Thao et al., 2023). Although these substances have significantly contributed to increasing agricultural yields, the intensive use of synthetic pesticides has been associated with negative effects on the environment and human health, including soil and water contamination, adverse impacts on non-target organisms, and biodiversity loss (Samada & Tambunan, 2020; Zhou et al., 2025).

In the context of sustainable agriculture, interest in alternative plant protection methods has increased considerably (Hezakiel et al., 2024). Biopesticides represent one of the most important research and application directions due to their natural origin, high biodegradability, and compatibility with modern Integrated Pest Management (IPM) strategies (Acheuk et al., 2022; Fenibo et al., 2021). The development of microbial, botanical, and biochemical biopesticides is driven both by the need to reduce the ecological impact of agriculture and by the growing demand for sustainable production systems.

However, biopesticides cannot be regarded as a universal solution for replacing conventional pesticides. The scientific literature highlights several limitations related to field efficacy, formulation stability, production costs, and the need for rigorous assessment of their effects on non-target organisms and ecosystems (Ayilara et al., 2023; Cai & Dimopoulos, 2025). Furthermore, the emergence of new technologies, such as nano-biopesticides, offers promising opportunities while also raising new questions regarding their safety and ecotoxicological impact (Vinci et al., 2025).

The aim of this review paper is to analyze recent literature on the use of biopesticides in sustainable agriculture, with a particular focus on their advantages,

limitations, and associated ecotoxicological implications. In addition, the paper seeks to highlight the main research directions and future development prospects of biopesticides within the transition toward environmentally sustainable agricultural systems.

Literature Review Methodology. This review paper was developed based on the analysis of scientific literature on the use of biopesticides in sustainable agriculture and their associated ecotoxicological implications. The documentation was carried out using scientific articles published in internationally indexed journals and available through databases such as ScienceDirect, PubMed, Google Scholar, Frontiers and MDPI.

Studies published between 2020 and 2025 were selected with priority, to reflect recent developments in the field. The documentation process aimed to identify works that address microbial, botanical and biochemical biopesticides, their integration into sustainable agriculture, environmental impact and development prospects of new generations of biopesticides.

The literature analysis was carried out by comparing the results and conclusions reported in different studies, with a focus on the advantages, limitations and ecotoxicological implications of the use of biopesticides. The information was synthesized and organized thematically to highlight the main research directions and current trends in the field. Minor adjustments and further bibliographic updates have improved the final text of the paper.

Biopesticides in Sustainable Agriculture. Biopesticides are products used to control pests and pathogens, obtained from living organisms or natural compounds. Interest in these products has increased significantly in recent years, amid concerns about the impact of synthetic pesticides on the environment and human health (Samada & Tambunan, 2020; Acheuk et al., 2022).

In the specialized literature, biopesticides are classified into three main categories: microbial biopesticides, botanical biopesticides, and biochemical biopesticides (Glare & Nollet, 2023). Microbial biopesticides use bacteria, fungi, viruses, or other microorganisms capable of inhibiting the development of target organisms. Of these, products based on *Bacillus thuringiensis* are some of the most widely used examples globally (Ayilara et al., 2023; Verma et al., 2024).

Botanical biopesticides are derived from plant extracts and secondary metabolites produced by plants, and are valued for their diverse mechanisms of action and potential for integration into organic farming systems (Catania et al., 2023). *Azadirachta indica* (neem) extracts and natural pyrethrins are among the best-known examples used in practice (Acheuk et al., 2022; Zhao et al., 2022).

A third category is represented by biochemical biopesticides, which include pheromones, growth regulators, and other natural substances that influence the behavior or development of target organisms without acting through direct toxic mechanisms (Samada & Tambunan, 2020).

The recent development of biotechnologies and modern formulation systems has contributed to the emergence of more effective and stable biological products, including nano-biopesticides (Butu et al., 2022; Hazafa et al., 2022; Shourove et al 2024). These innovations aim to increase the efficiency of biological products and expand their applicability in real-world conditions, representing one of the most dynamic research directions in the field (Vinci et al., 2025).

The Role of Biopesticides in Sustainable Agriculture and Integrated Pest Management. The interest in biopesticides is closely linked to the development of sustainable agriculture and the need to reduce the impact associated with the intensive use of synthetic pesticides. Compared to conventional pest control methods, biopesticides offer the possibility of limiting environmental contamination and conserving biodiversity, being considered compatible with current objectives regarding the protection of natural resources and the reduction of the ecological footprint of agriculture (Fenibo et al., 2021; Acheuk et al., 2022).

An important role of biopesticides is their integration into Integrated Pest Management (IPM) strategies (Zhang & Wang 2024). These strategies aim at the combined use of biological, cultural, physical and chemical methods to control pest populations, reducing dependence on conventional treatments. In this context, biopesticides contribute to diversifying control measures and reducing the selective pressure that favors the emergence of pesticide resistance (Marrone, 2025).

Recent literature highlights that the use of biopesticides can support the maintenance of ecosystem services by protecting pollinators, beneficial microorganisms and other organisms involved in the functioning of agroecosystems. This is particularly important in agricultural systems that aim to reduce chemical inputs and preserve soil fertility in the long term (Ayilara et al., 2023; Cai & Dimopoulos, 2025).

However, the effectiveness of biopesticides is influenced by numerous factors, including climatic conditions, formulation stability and the characteristics of the target organisms. For this reason, most authors consider that the success of their use depends on their integration into a complex crop management strategy and not on their use as a single solution for pest control (Lahlali et al., 2025) (Table 1, Figure 1).

Table 1

Main categories of biopesticides and their characteristics

Category	*Biological source*	*Exemples*	*Main mode of action*
Microbial biopesticides	Bacteria, fungi, viruses	*Bacillus thuringiensis, Beauveria bassiana*	Direct control of pests and pathogens through biological activity.
Botanical biopesticides	Plant extracts and secondary metabolites	Neem extracts, pyrethrins	Insecticidal, fungicidal, or repellent activity.
Biochemical pesticides	Naturally occurring compounds	Pheromones, growth regulators	Modification of behaivor, reproduction, or development of target organisms.
Nano-biopesticides	Nano-formulated biological compounds	Nano-emulsions, nano-encapsulated products	Controlled release and improved stability of actives substances.

Source: Adapted from Samada & Tambunan (2020), Acheuk et al. (2022), and Vinci et al. (2025).

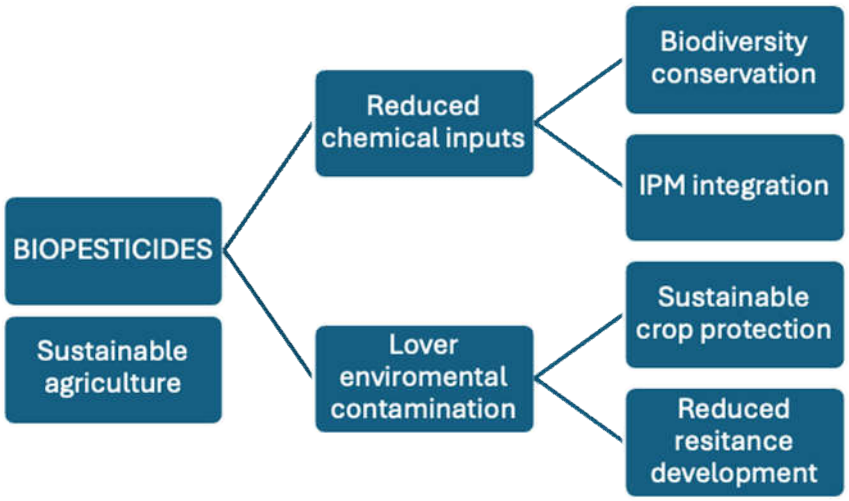

Figure 1. Main contributions of biopesticides to sustainable agriculture. Source: Adapted from Fenibo et al. (2021), Acheuk et al. (2022), Ayilara et al. (2023), Cai & Dimopoulos (2025).

Advantages of Using Biopesticides. The main argument in favor of using biopesticides is their reduced environmental impact compared to synthetic pesticides. Due to their biological origin and high biodegradability, these products tend to have a lower persistence in soil and water, reducing the risk of residue accumulation and contamination of ecosystems (Samada & Tambunan, 2020; Fenibo et al., 2022).

Another advantage frequently highlighted in the literature is specificity towards target organisms. Unlike many conventional broad-spectrum pesticides, many biopesticides selectively affect certain groups of organisms, thus reducing the impact on pollinators, natural predators and other beneficial organisms (Acheuk et al., 2022; Ayilara et al., 2023).

Biopesticides also contribute to reducing the risk of resistance development. The diversity of mechanisms of action and the possibility of their use in combination with other control methods facilitate the implementation of more effective resistance management programs than those based exclusively on synthetic pesticides (Marrone, 2025).

From an economic and social perspective, the development of biopesticides is supported by the growing demand for agricultural products obtained through sustainable practices and by policies aimed at reducing the use of chemicals in agriculture. In addition, their integration into organic production systems offers opportunities for the development of agricultural models that are more compatible with the objectives of environmental protection and biodiversity conservation (Fenibo et al., 2021; Fenibo & Matambo, 2025).

Ecotoxicological Implications. The ecotoxicological implications of biopesticides represent one of the most dynamic areas of research in recent years. Although these products are promoted as safer alternatives to synthetic pesticides, the literature highlights the need to assess their impact on non-target organisms and ecosystem functioning. Compared to conventional pesticides, biopesticides tend to have reduced persistence and lower ecological risk, but their effects depend on the product composition, the applied dose and environmental conditions (Daraban et al., 2023; Cai & Dimopoulos, 2025) (Table 2).

Table 2

Ecotoxicological implications of biopesticide use

Environmental compartment	*Potential benefits*	*Potential concerns*
Non-target organisms	Greater selectivity compared with many synthetic pesticides	Possible sublethal effects under repeated exposure.
Soil ecosystems	Lower disturbance of microbial activity and nutrient cycling.	Limited knowledge regarding long-term impacts on soil microbiomes.
Aquatic ecosystems	Reduced persistence and lower bioaccumulation potential	Insufficient data on chronic and cumulative effects.
Biodiversity	Conservation of ecosystem services and beneficial organisms.	Need for long-term ecological monitoring.
Nano-biopesticides	Improved efficiency and controlled release of active compounds.	Uncertainties regarding nanoparticle behavior and environmental fate.

Source: Adapted from Daraban et al. (2023), Cai & Dimopoulos (2025), and Vinci et al. (2025).

Non-Target Organisms and Biodiversity. One of the main arguments in favor of biopesticides is their higher selectivity towards target organisms. Numerous studies show that they affect pollinators, natural predators and other beneficial organisms to a lesser extent compared to synthetic pesticides (Acheuk et al., 2022; Ayilara et al., 2023). This is particularly important in the context of current concerns about the decline of biodiversity and the loss of ecosystem services essential for agriculture.

However, recent literature highlights that effects on non-target organisms are not completely absent. Some studies report sublethal effects on the behavior, reproduction or development of certain species, especially in the case of repeated exposures or the use of insufficiently evaluated formulations (Daraban et al., 2023). These results suggest that ecotoxicological assessment should include not only direct mortality, but also chronic and indirect effects on biological communities.

Impact on Soil and Microorganisms. Soil is one of the most complex terrestrial ecosystems, and microorganisms play an essential role in biogeochemical cycles, organic matter decomposition and fertility maintenance. From this perspective, the impact of plant protection products on microbial communities is an important criterion in assessing the sustainability of agricultural practices (Ayilara et al., 2023).

Compared to synthetic pesticides, biopesticides are considered more compatible with maintaining soil biological activity. Numerous studies highlight that their use is associated with reduced disturbances of microbial communities and a better preservation of ecosystem processes involved in nutrient cycling (Fenibo et al., 2021; Tomar et al., 2024). This aspect is particularly important in agricultural systems that aim to maintain natural fertility and reduce dependence on external inputs.

However, the literature indicates that the effects of biopesticides on the soil microbiome are not always neutral. Depending on the composition of the product, the frequency of application and local conditions, changes in the structure of microbial communities or in the interactions between microorganisms and plants may occur. Although these effects are generally lower than those reported for synthetic pesticides, the available data on long-term consequences are still limited (Cai & Dimopoulos, 2025; Verma et al., 2024). Consequently, several authors emphasize the need to integrate microbiological analyses into the ecotoxicological assessment of biopesticides, especially in the case of new formulations and products resulting from emerging technologies (Tomar et al., 2024; Vinci et al., 2025).

Impacts on Aquatic Ecosystems. Contamination of water resources is one of the main concerns associated with the use of pesticides in agriculture. Transport through surface runoff, erosion or infiltration can lead to exposure of aquatic organisms to various active substances, including biological products (Daraban et al., 2023).

Current literature suggests that biopesticides generally have lower persistence and bioaccumulation potential compared to synthetic pesticides, which contributes to the reduction of ecological risk to aquatic ecosystems (Acheuk et al., 2022). However, these characteristics do not completely exclude the possibility of adverse effects on sensitive organisms, especially in the case of repeated exposure or the use of high concentrations.

Several studies highlight that ecotoxicological assessments of biopesticides are still insufficient for certain groups of aquatic organisms, and information on chronic and cumulative effects remains limited (Daraban et al., 2023; Cai & Dimopoulos, 2025). This is particularly true for recently developed products and for complex formulations containing adjuvants or modern controlled release systems.

Consequently, the literature recommends expanding studies on the behavior of biopesticides in aquatic environments and including ecological assessments that go beyond conventional acute toxicity tests.

Nano-Biopesticides and Emerging Risks. The development of nano-biopesticides is one of the most dynamic research directions in the field of plant protection. The use of nanotechnologies aims to improve the stability, efficiency and control of the release of active substances, contributing to the reduction of the quantities required for agricultural treatments (Vinci et al., 2025).

The literature highlights numerous potential advantages of these technologies, including the protection of biological compounds against degradation and increasing the efficiency of application under field conditions. However, the ecotoxicological impact of nanoparticles used in formulations remains insufficiently known, and the available results are often contradictory (Vinci et al., 2025; Ayilara et al., 2023).

The main concerns relate to the behavior of nanoparticles in soil and water, the potential for accumulation in organisms and the effects on microorganisms and non-target organisms. For this reason, many authors believe that the development of nano-biopesticides must be accompanied by risk assessment procedures adapted to the specifics of these technologies (Vinci et al., 2025). Overall, the current literature supports that biopesticides offer important ecological advantages compared to conventional pesticides, but assessing the impact on biodiversity, soil microbiome and aquatic ecosystems remains essential to ensure long-term sustainable use.

Limitations and Challenges Associated with The Use of Biopesticides*.* Despite the obvious advantages, the literature highlights a number of limitations that restrict the widespread adoption of biopesticides. One of the most frequently reported problems is the variable efficacy under real-world conditions of use. Unlike synthetic pesticides, whose performance is often more predictable, the efficacy of biopesticides can be significantly influenced by temperature, humidity, solar radiation, and other environmental factors (Samada & Tambunan, 2020; Lahlali et al., 2025).

Another important challenge is the low stability of certain biological formulations. Many microorganisms used as biological control agents are sensitive to storage and transportation conditions, which can limit the shelf life of the products and their effectiveness after application. For this reason, the development of more stable formulations and efficient delivery systems is one of the major research directions in the field (Verma et al., 2024; Vinci et al., 2025).

The literature also highlights economic and legislative constraints. The costs associated with research, development and authorisation of biological products can represent barriers to their introduction on the market. In addition, regulatory procedures differ between regions and are not always adapted to the specificities of biopesticides, which can slow down the commercialisation and adoption process (Fenibo & Matambo, 2025; Marrone, 2025).

An aspect increasingly discussed in recent literature is the tendency to consider biopesticides as products completely free of environmental risks. Although their impact is generally lower than that of synthetic pesticides, several authors point out that certain products can generate effects on non-target organisms or on some components of ecosystems when used repeatedly or in high concentrations (Daraban et al., 2023; Cai & Dimopoulos, 2025). These observations suggest the need to evaluate each product according to its specific characteristics and not exclusively on the basis of its biological origin.

Overall, the current literature supports that biopesticides represent a valuable alternative for sustainable agriculture, but their effectiveness and safety depend on optimizing formulations, adapting application strategies, and developing evaluation frameworks that reflect the complexity of interactions between these products and the environment.

Current Trends and Future Prospects*.* The evolution of research in recent years indicates a clear orientation towards the development of more efficient, more stable and more adapted biopesticides to the requirements of modern agriculture. The literature highlights that one of the main directions of development is represented by the improvement of existing formulations, with the aim of increasing persistence in field conditions and optimizing the release of active substances (Verma et al., 2024; Vinci et al., 2025).

Particular attention is paid to microbial biopesticides, considered one of the most promising categories due to the diversity of action mechanisms and the potential for integration into integrated pest management strategies. Advances in microbiology and biotechnology facilitate the identification of new microorganisms with insecticidal, fungicidal or bactericidal properties and allow the development of more efficient and selective biological products (Ayilara et al., 2023; Verma et al., 2024).

In parallel, the development of synthetic biology and genomic technologies opens up new opportunities for the optimization of natural compounds used in plant protection.

In the case of botanical biopesticides, current research aims to identify and produce bioactive molecules with high efficiency and low impact on non-target organisms (Acheuk et al., 2022; Zhao et al., 2022).

Another expanding field is represented by nano-biopesticides and intelligent delivery systems of active substances. These technologies have the potential to reduce the quantities applied and increase the efficiency of treatments, but the literature emphasizes the need for additional assessments of their behavior and safety in the environment (Vinci et al., 2025).

From a sustainability perspective, the One Health concept is increasingly integrated into the evaluation of biological products, promoting an approach that simultaneously considers human health, animal health and ecosystem functioning. This approach is considered essential for the development of crop protection strategies that meet both agricultural productivity requirements and environmental conservation objectives (Cai & Dimopoulos, 2025).

Despite the progress made, the literature reviewed highlights the existence of important knowledge gaps. These include the low number of long-term studies on effects on biodiversity, limited information on the impact on the soil microbiome, and insufficient data on cumulative effects on aquatic ecosystems. In addition, standardization of ecotoxicological assessment methodologies remains a challenge for comparing results reported in different studies (Daraban et al., 2023; Cai & Dimopoulos, 2025).

Therefore, future research should aim not only to increase the efficiency of biopesticides, but also to better understand the interactions between these products and the ecosystems in which they are used. Such an approach is essential for the responsible integration of biopesticides into sustainable agriculture and for harnessing their potential in reducing the ecological impact of plant protection.

Conclusions. Biopesticides represent a promising alternative to synthetic pesticides and play an increasingly important role in the transition toward sustainable agricultural systems. Their use can contribute to reducing environmental pressure, supporting biodiversity conservation, and promoting more sustainable crop protection practices.

Although biopesticides offer several advantages, their effectiveness may be influenced by environmental conditions, formulation characteristics, and application methods. Furthermore, certain aspects related to their long-term effects on ecosystems require further investigation.

Overall, the available literature supports the integration of biopesticides into sustainable agriculture strategies. However, continued research is necessary to improve their performance, better understand their ecotoxicological implications, and support their wider adoption in modern agricultural systems.

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Conflicts of Interest. The author declares that there is no conflict of interest.

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