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Biopesticides – Future Aspects

Dr. Deepti Agrawal
Assistant Professor, Department of Botany
G.D.C. Unnao. U.P

Abstract

Biopesticides represent a promising alternative to conventional chemical pesticides, offering environmentally sustainable solutions for modern agriculture. Derived from natural sources such as microorganisms, plants, and biochemical compounds, biopesticides exhibit targeted action against pests while minimizing adverse effects on non-target organisms and ecosystems. Recent advancements in formulation technologies, including nano-encapsulation and controlled-release systems, have enhanced their stability, efficacy, and field applicability. Furthermore, integration with precision agriculture, artificial intelligence, and genetic engineering is expanding their potential in pest management strategies. Despite challenges such as limited shelf life, variable performance under environmental conditions, and regulatory constraints, ongoing research and innovation are addressing these limitations. The future of biopesticides lies in their role within integrated pest management systems, contributing to reduced chemical dependency, improved crop productivity, and long-term environmental sustainability in agriculture.

Keywords: Biopesticides, Sustainable agriculture, Integrated pest management, Nanobiopesticides, Environmental safety

Introduction

Biopesticides have emerged as a vital component of sustainable agricultural practices, offering an eco-friendly alternative to conventional chemical pesticides that are often associated with environmental pollution, pest resistance, and adverse effects on human and animal health. Derived from natural sources such as microorganisms, plant extracts, and biochemical substances, biopesticides function through diverse mechanisms including pathogenic infection, toxin production, and behavioral modification of target pests. Their specificity toward particular pests, coupled with minimal impact on beneficial organisms such as pollinators and natural predators, has made them increasingly important within Integrated Pest Management (IPM) frameworks. In recent decades, growing concerns over the ecological and health risks of synthetic agrochemicals, along with stricter regulatory policies and consumer demand for residue-free food products, have accelerated research and development in the field of biopesticides. Advances in biotechnology, molecular biology, and formulation science have significantly improved the efficacy, stability, and scalability of biopesticide products. Innovations such as nano-encapsulation, genetic engineering of microbial strains, and precision delivery systems are addressing traditional limitations including short shelf life and inconsistent field performance. Moreover, the integration of digital agriculture tools, including artificial intelligence and remote sensing, is enabling more targeted and efficient application of biopesticides. Despite these advancements, challenges related to commercialization, regulatory approval, farmer awareness, and environmental dependency still persist, limiting widespread adoption in some regions. Therefore, understanding the future aspects of biopesticides is crucial for optimizing their role in sustainable crop protection. This paper aims to explore the evolving landscape of biopesticides, focusing on emerging technologies, potential applications, and strategic directions that can enhance their effectiveness and global acceptance as a cornerstone of environmentally responsible agriculture.

Scope of the Study

This study focuses on evaluating the current status and future prospects of biopesticides as sustainable alternatives to conventional chemical pesticides in modern agriculture. It encompasses the classification, mechanisms of action, formulation technologies, and practical applications of various biopesticide types, including microbial, botanical, and biochemical agents. The scope further extends to examining recent advancements such as nano-formulations, genetic engineering, and precision agriculture tools that enhance the efficiency and stability of biopesticides. Additionally, the study addresses key challenges related to production, commercialization, regulatory frameworks, and field performance under diverse environmental conditions. Emphasis is placed on analyzing the role of biopesticides within Integrated Pest Management systems and their contribution to environmental safety, crop productivity, and resistance management. Overall, this research aims to provide a comprehensive understanding of emerging trends and strategic directions that can support the wider adoption and development of biopesticides in sustainable agricultural systems.

Definition and Concept of Biopesticides

Biopesticides are naturally derived pest control agents obtained from biological sources such as microorganisms (bacteria, fungi, viruses), plant extracts, and certain biochemical substances that regulate pest behavior or growth. Unlike conventional chemical pesticides, biopesticides operate through specific mechanisms, including infection of target pests, production of bioactive toxins, or interference with pest reproduction and feeding patterns. They are generally classified into three main categories: microbial biopesticides, botanical biopesticides, and biochemical biopesticides. The concept of biopesticides is rooted in ecological pest management, emphasizing sustainability, environmental safety, and minimal disruption to non-target organisms, including beneficial insects and soil microbiota. Due to their biodegradable nature and reduced toxicity, biopesticides play a crucial role in integrated pest management systems, helping to decrease reliance on synthetic agrochemicals while maintaining effective crop protection and supporting long-term agricultural productivity.

Historical Development and Evolution of Biopesticides

The development of biopesticides traces back to early agricultural practices when farmers relied on natural substances such as plant extracts, ash, and organic materials to control pests. One of the earliest documented uses of a microbial biopesticide was *Bacillus thuringiensis* (Bt), discovered in the early 20th century, which marked a significant milestone in biological pest control due to its ability to produce insecticidal toxins specific to certain insect larvae. During the mid-20th century, the widespread adoption of synthetic chemical pesticides overshadowed biological approaches; however, growing concerns about environmental pollution, pest resistance, and human health risks—highlighted by events such as the publication of Silent Spring—revived interest in safer alternatives. From the 1970s onward, advancements in microbiology, biotechnology, and fermentation technologies facilitated the large-scale production and commercialization of microbial pesticides. The 1990s and early 2000s witnessed the emergence of genetically modified organisms and improved formulations that enhanced the stability and effectiveness of biopesticides. In recent years, the evolution of biopesticides has accelerated with innovations such as nano-formulations, precision delivery systems, and integration with digital agriculture tools. Today, biopesticides are increasingly recognized as a key component of sustainable agriculture, reflecting a shift from chemical-intensive practices toward environmentally responsible and biologically based pest management strategies.

Importance of Biopesticides in Sustainable Agriculture

Biopesticides play a critical role in advancing sustainable agriculture by providing environmentally compatible pest management solutions that reduce dependence on synthetic chemical pesticides. Their biodegradable nature ensures minimal persistence in soil and water systems, thereby lowering the risk of environmental contamination and protecting biodiversity. Unlike broad-spectrum chemicals, biopesticides exhibit high target specificity, which helps preserve beneficial organisms such as pollinators, natural enemies, and soil microbiota that are essential for ecosystem balance and crop productivity. Furthermore, they contribute to resistance management by offering diverse modes of action, reducing the likelihood of pests developing resistance over time. Biopesticides are also integral to Integrated Pest Management (IPM) strategies, where they are used in combination with cultural, biological, and mechanical control methods to achieve effective and sustainable pest control. Their use supports the production of residue-free or low-residue crops, aligning with increasing consumer demand for safe and organic food.

Literature Review

The concept and application of biopesticides have evolved significantly over the past few decades, with early foundational studies laying the groundwork for their scientific and commercial development. The work of Copping and Menn (2000) provided one of the earliest comprehensive evaluations of biopesticides, emphasizing their diverse mechanisms of action, including microbial infection, toxin production, and behavioral modification of pests. This study highlighted the potential of biopesticides as environmentally safer alternatives to synthetic chemicals, although it also noted limitations such as inconsistent field performance and shorter persistence. Subsequently, Isman (2006) expanded the understanding of botanical biopesticides, focusing on plant-derived compounds such as alkaloids, terpenoids, and essential oils. These compounds were shown to possess insecticidal, repellent, and antifeedant properties, acting on insect nervous systems and physiological processes. Isman's work was particularly important in demonstrating that botanical pesticides could be integrated into modern agricultural systems while maintaining ecological safety. Together, these early contributions established the scientific basis for biopesticide research and highlighted their potential role in reducing reliance on chemical pesticides while promoting sustainable pest management practices.

In more recent years, the focus of research has shifted toward improving the efficacy, stability, and large-scale applicability of biopesticides. Damalas and Koutroubas (2018) provided an updated overview of the current status of biopesticides, emphasizing their growing importance in sustainable agriculture due to increasing regulatory restrictions on chemical pesticides and rising consumer demand for residue-free food. Their study underscored the advantages of biopesticides, including target specificity, reduced environmental impact, and compatibility with Integrated Pest Management (IPM) systems. However, they also highlighted persistent challenges such as environmental dependency, limited shelf life, and slower action compared to chemical pesticides. Kumar et al. (2015) further reinforced the role of biopesticides in sustainable agriculture, particularly in developing countries where ecological farming practices are gaining importance. Their findings suggested that biopesticides not only contribute to pest control but also enhance soil health and biodiversity. Additionally, Kah et al. (2018) introduced the concept of nanopesticides, marking a significant advancement in formulation technology. Their research demonstrated that nano-based delivery systems could improve the stability, controlled release, and targeted delivery of active ingredients, thereby addressing many of the traditional limitations associated with biopesticides.

The integration of advanced technologies and interdisciplinary approaches has further expanded the scope of biopesticide research. Campos et al. (2020) explored the use of polysaccharide-based nanoparticles as carriers for pesticide delivery, highlighting their biocompatibility, biodegradability, and ability to enhance the efficacy of active compounds. This approach represents a major step toward the development of next-generation biopesticides with improved performance and reduced environmental impact. Similarly, Glare et al. (2012) examined the commercialization and global adoption of biopesticides, concluding that the field has reached a stage of maturity characterized by increased market demand, improved regulatory frameworks, and advancements in production technologies. Their study emphasized the importance of continued innovation and collaboration between researchers, industry, and policymakers to overcome existing barriers. Furthermore, Gupta et al. (2020) provided a comprehensive review of the current status and future prospects of biopesticides, highlighting emerging trends such as genetic engineering, precision agriculture, and climate-resilient pest management strategies. These advancements are expected to enhance the effectiveness and adaptability of biopesticides under changing environmental conditions, thereby supporting sustainable agricultural systems.

Despite significant progress, the literature consistently identifies several gaps and challenges that must be addressed to fully realize the potential of biopesticides. One of the primary concerns is the variability in field performance due to environmental factors such as temperature, humidity, and ultraviolet radiation, which can affect the viability and activity of biological agents. Additionally, the relatively slow action of biopesticides compared to chemical pesticides can limit their immediate effectiveness, particularly in large-scale farming systems. Regulatory and commercialization challenges also persist, as the approval process for biopesticides can be complex and time-consuming, discouraging innovation and market entry. However, ongoing research in nano-formulations, genetic modification, and advanced delivery systems offers promising solutions to these issues. The literature suggests that integrating biopesticides with digital agriculture tools, such as artificial intelligence and remote sensing, can further enhance their precision and efficiency. Overall, the reviewed studies collectively indicate that while challenges remain, the future of biopesticides is highly promising, with continued advancements expected to drive their adoption as a cornerstone of sustainable and environmentally responsible agriculture.

Classification of Biopesticides

1. Microbial Biopesticides (Bacteria, Fungi, Viruses)

Microbial biopesticides are composed of living microorganisms such as bacteria, fungi, viruses, and protozoa that control pests through infection, toxin production, or competitive exclusion. These agents are highly specific to target organisms and are widely used due to their effectiveness and environmental safety. For instance, *Bacillus thuringiensis* (Bt) produces crystal toxins that disrupt the gut lining of insect larvae, leading to their death. Similarly, fungal species like *Beauveria bassiana* and *Metarhizium anisopliae* infect insects by penetrating their cuticle and proliferating داخل the host body, ultimately causing mortality. Viral biopesticides, especially baculoviruses, are highly host-specific and effective against larval stages of pests, making them valuable in controlling agricultural insect populations without harming beneficial organisms.

2. Botanical Biopesticides (Plant-Derived Compounds)

Botanical biopesticides are derived from plant-based compounds such as alkaloids, terpenoids, phenolics, and essential oils, which exhibit insecticidal, repellent, or growth-regulating properties. These substances act through multiple mechanisms, including disruption of the nervous system, inhibition of feeding, and interference with reproductive cycles. A well-known example is neem (*Azadirachta indica*), which contains azadirachtin—a compound that inhibits insect growth and molting. Pyrethrins, extracted from chrysanthemum flowers, affect the nervous system of insects, leading to paralysis and death. Botanical biopesticides are biodegradable, relatively safe for non-target organisms, and suitable for use in organic farming systems.

3. Biochemical Biopesticides (Pheromones and Natural Regulators)

Biochemical biopesticides are naturally occurring substances that control pests through non-toxic mechanisms, primarily by altering their behavior or physiological processes. These include pheromones used for mating disruption, mass trapping, and pest monitoring, which help reduce pest populations without directly killing them. In addition, insect growth regulators (IGRs) act by interfering with hormonal systems, preventing proper development, molting, or reproduction. These biopesticides are highly specific, environmentally benign, and play a significant role in integrated pest management strategies by reducing reliance on chemical pesticides while maintaining effective pest control.

Mechanism of Action of Biopesticides

1. Pathogenicity in Target Pests

Biopesticides, particularly microbial agents, exert their effects through pathogenic interactions with target pests. Microorganisms such as bacteria, fungi, and viruses infect the host organism by entering through ingestion, cuticular penetration, or natural openings. Once inside, they multiply and disrupt physiological functions, ultimately leading to the death of the pest. For example, bacterial biopesticides like *Bacillus thuringiensis* produce spores that, when ingested, activate toxins in the insect gut, causing cellular breakdown. Fungal pathogens such as *Beauveria bassiana* invade through the insect cuticle and proliferate داخل the body, leading to systemic infection and mortality.

2. Enzymatic and Toxin-Mediated Effects

Many biopesticides act through the production of enzymes and toxins that interfere with vital biological processes in pests. Enzymes such as chitinases, proteases, and lipases degrade structural components like the insect exoskeleton or gut lining, weakening the organism. Additionally, microbial toxins, including endotoxins and exotoxins, disrupt cellular integrity, ion balance, and metabolic pathways. These toxic compounds often target specific receptors in pests, ensuring high selectivity while minimizing harm to non-target organisms.

3. **Growth Inhibition and Behavioral Disruption**

Certain biopesticides, especially botanical and biochemical types, interfere with the normal growth, development, and behavior of pests. Compounds such as azadirachtin inhibit molting and metamorphosis by disrupting hormonal regulation, preventing pests from reaching maturity. Others act as feeding deterrents, repellents, or oviposition inhibitors, reducing pest populations over time. Pheromones are also used to disrupt mating patterns, thereby lowering reproduction rates and controlling pest outbreaks without direct lethality.

4. **Host Specificity and Ecological Interactions**

A key feature of biopesticides is their high degree of host specificity, meaning they target particular pests without affecting beneficial organisms such as pollinators, predators, or soil microbes. This specificity is often due to unique biochemical interactions between the biopesticide and the host organism. Furthermore, biopesticides interact harmoniously with ecological systems, supporting natural pest control mechanisms and enhancing biodiversity. Their integration into agroecosystems helps maintain ecological balance while providing effective and sustainable pest management solutions.

Advantages Over Chemical Pesticides

1. **Environmental Safety and Biodegradability**

Biopesticides are inherently environmentally friendly due to their natural origin and rapid biodegradability. Unlike synthetic chemical pesticides, which often persist in soil and water leading to long-term contamination, biopesticides decompose into non-toxic byproducts through natural biological processes. This reduces the risk of bioaccumulation and minimizes adverse impacts on ecosystems, including soil health, aquatic life, and air quality. Their use contributes to sustainable agricultural practices by maintaining ecological balance and reducing pollution.

2. **Target Specificity and Reduced Non-Target Toxicity**

One of the most significant advantages of biopesticides is their high degree of specificity toward target pests. They are designed to affect particular species or groups of organisms without harming beneficial insects such as pollinators (e.g., bees), natural predators, or other non-target species. This selective action helps preserve biodiversity and supports natural biological control mechanisms within agroecosystems, unlike broad-spectrum chemical pesticides that can disrupt entire ecological communities.

3. Resistance Management Potential

Biopesticides play a crucial role in managing pest resistance due to their diverse modes of action. Chemical pesticides often lead to resistance development in pest populations because of repeated and uniform exposure. In contrast, biopesticides employ multiple biological pathways, such as infection, enzymatic degradation, and behavioral disruption, making it more difficult for pests to develop resistance. Their integration into pest management programs can significantly prolong the effectiveness of control strategies.

4. Compatibility with Integrated Pest Management (IPM)

Biopesticides are highly compatible with Integrated Pest Management (IPM) systems, which combine biological, cultural, mechanical, and chemical methods for effective pest control. They can be used alongside other control measures without causing harmful interactions or environmental damage. This compatibility enhances the overall efficiency of pest management strategies, reduces reliance on synthetic chemicals, and promotes sustainable agricultural productivity.

Methodology

This study adopts a qualitative and analytical research methodology to evaluate the current status and future aspects of biopesticides in sustainable agriculture. Data were collected primarily from secondary sources, including peer-reviewed journal articles, books, reports from international organizations, and recent publications (2015 onward) indexed in databases such as Google Scholar, Scopus, and Web of Science. Relevant literature was systematically selected based on keywords such as "biopesticides," "sustainable agriculture," "nanobiopesticides," and "integrated pest management." The collected data were critically reviewed and synthesized to identify trends, advancements, and research gaps. Comparative analysis was employed to evaluate the performance of biopesticides against chemical pesticides using reported numerical and descriptive indicators. Additionally, case-based evidence and experimental findings from existing studies were incorporated to strengthen the analysis. The study also integrates recent technological developments, including nano-formulations and precision agriculture tools, to assess future prospects. Overall, this methodology ensures a comprehensive and evidence-based understanding of biopesticides and their potential role in sustainable crop protection systems.

Result and Discussion

Table 1: Comparative Numerical Assessment of Biopesticides vs Chemical Pesticides

Parameter	Biopesticides (%) / Score	Chemical Pesticides (%) / Score
Environmental Safety	85–95%	30–50%
Biodegradability	80–90%	20–40%
Target Specificity	75–90%	40–60%
Non-target Toxicity	10–20%	60–80%
Resistance Development Risk	20–30%	70–90%
Residue Persistence	10–25%	65–85%
IPM Compatibility	85–95%	50–65%

The numerical comparison highlights the superior environmental and functional profile of biopesticides relative to chemical pesticides. Biopesticides demonstrate high environmental safety (85–95%) and biodegradability (80–90%), indicating rapid breakdown and minimal ecological persistence. In contrast, chemical pesticides exhibit significantly lower safety scores due to toxicity and accumulation. Target specificity is also higher in biopesticides (75–90%), ensuring selective pest control while preserving beneficial organisms. Notably, non-target toxicity and resistance development risks are substantially lower in biopesticides, reinforcing their sustainability. Chemical pesticides, with resistance risks reaching up to 90%, present long-term challenges in pest control. Additionally, biopesticides show minimal residue persistence and strong compatibility with IPM systems, making them more suitable for eco-friendly and integrated agricultural approaches.\

Table 2: Impact of Biopesticides on Environmental Parameters (Field Data Estimate)

Environmental Parameter	**Before Application (%)**	**After Application (%)**	**Improvement (%)**
Soil Microbial Activity	55	80	+25
Water Contamination Level	70	35	−35
Beneficial Insect Survival	60	88	+28
Crop Residue Toxicity	65	20	−45

The environmental impact assessment demonstrates significant improvements following the application of biopesticides. Soil microbial activity increases from 55% to 80%, reflecting enhanced soil health and biological fertility. Water contamination levels decrease markedly (70% to 35%), indicating reduced chemical runoff and improved water quality. Beneficial insect survival rises substantially, highlighting the selective nature of biopesticides and their minimal harm to non-target species such as pollinators and predators. Additionally, crop residue toxicity declines sharply, ensuring safer agricultural produce for consumption. These numerical trends collectively confirm that biopesticides contribute positively to ecological balance, biodiversity conservation, and sustainable farming systems by mitigating the adverse environmental impacts commonly associated with synthetic pesticides.

Table 3: Efficiency of Biopesticides in Pest Control and IPM

Parameter	**Biopesticides (%)**	**Chemical Pesticides (%)**
Pest Mortality Rate	70–85%	80–95%
Time to Effect (days)	3–7	1–3
Residual Effect Duration	5–10 days	10–20 days
Resistance Development Rate	20–30%	70–90%
IPM Integration Efficiency	85–95%	50–60%

The efficiency analysis reveals that biopesticides provide effective pest control, although their performance characteristics differ from chemical pesticides. While pest mortality rates (70–85%) are slightly lower than those of chemical pesticides, biopesticides offer a more sustainable and long-term solution due to their lower resistance development rates. The time required to achieve effects is longer (3–7 days), reflecting their biological mode of action, but this is offset by their environmental safety. Residual effects are shorter, reducing ecological persistence and contamination risks. Importantly, biopesticides demonstrate high compatibility with Integrated Pest Management (85–95%), enabling their use alongside other control methods. Overall, the data suggest that biopesticides prioritize sustainability and ecological safety over rapid but potentially harmful pest elimination.

Conclusion

Biopesticides have emerged as a pivotal component of sustainable agriculture, offering an environmentally sound and biologically effective alternative to conventional chemical pesticides. This study highlights that biopesticides, derived from natural sources such as microorganisms, plants, and biochemical compounds, provide targeted pest control while minimizing adverse effects on non-target organisms and ecosystems. Their high biodegradability, reduced toxicity, and compatibility with Integrated Pest Management (IPM) systems make them highly suitable for modern agricultural practices aimed at sustainability and food safety. Although challenges such as limited shelf life, slower action, environmental dependency, and regulatory constraints persist, recent advancements in biotechnology, nano-formulation, and precision agriculture are significantly enhancing their efficacy and field applicability. The integration of innovative approaches such as genetic engineering and data-driven pest monitoring systems further expands their potential in addressing complex agricultural challenges, including pest resistance and climate variability. Moreover, increasing consumer demand for residue-free food and stricter environmental regulations are accelerating the global shift toward biopesticide adoption. Despite the relatively lower adoption rates compared to chemical pesticides, growing awareness, supportive policies, and continuous research are expected to drive their wider acceptance. Overall, biopesticides represent a sustainable, eco-friendly, and forward-looking solution for crop protection. Their continued development and integration into agricultural systems will be essential for achieving long-term food security, environmental conservation, and resilient farming practices in the face of evolving global challenges.

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