Biopesticides in Sustainable Agriculture: Enhancing Targeted Pest Control and Ecosystem Health

Ayesha Areej[1], Muhammad Usama[1], Umer Zulfiqar[1], Fatima Sarwar[1], Maryam[1], Aneela Ashiq[1*]

Abstract

The growing demand for environmentally sustainable agriculture has increased the adoption of biopesticides in Integrated Pest Management (IPM). Derived from microorganisms, plants, or biological materials, biopesticides provide a safer, eco-friendly alternative to synthetic pesticides by targeting specific pests without harming non-target species. This review explores the efficacy and role of biopesticides in promoting sustainable agricultural practices. A selection of biopesticides, including Bacillus thuringiensis (Bt), neem extract, and insect growth regulators, is reviewed for their preparation and application. Field trials using randomized complete block designs with treatment and control plots are examined to evaluate the impact on pest populations, crop health, and yield. Microbial, biochemical, and plant-based biopesticides demonstrates effective pest population reductions. Microbial biopesticides like Bt exhibits high specificity, preserving beneficial organisms. Biochemical agents, including neem, disrupted pest cycles through non-lethal mechanisms. Combined treatments enhanced pest control and delayed resistance, further supporting their role in IPM. Biopesticides offer a promising alternative in IPM, contributing to improved soil health and reduced chemical pesticide reliance. Despite economic and environmental challenges, ongoing advances in biotechnology are expected to enhance their efficacy and adoption. Integrating biopesticides with biofertilizers provides a holistic approach to sustainable agriculture, promoting ecosystem balance and long-term agricultural resilience.

Keywords: Biopesticides, Integrated Pest Management (IPM), Sustainable agriculture, Microbial pesticides, Eco-friendly pest control.

Significance | This review discusses the biopesticides' potential in sustainable agriculture, offering targeted pest control, preserving ecosystems, and reducing reliance on synthetic chemicals.

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Introduction

In recent years, there has been a marked shift toward environmentally sustainable practices in agriculture, driven by a global demand for safer food and the pressing need to protect ecosystems from the harmful effects of chemical pesticides (Singh, Singh, & Prabha, 2016). A key development in this arena is the growing adoption of biopesticides natural pest control solutions derived from microorganisms, plants, or other biological materials. Unlike synthetic pesticides, which often leave persistent residues in soil and water and can harm non-target species, biopesticides present a safer alternative by targeting specific pests without disrupting ecological balance (Kour et al., 2020). This eco-friendly characteristic of biopesticides has sparked interest in their role within Integrated Pest Management (IPM) systems, which promote sustainable pest control through a combination of biological, cultural, physical, and chemical approaches (Kumar et al., 2022). The selective modes of action in biopesticides contribute significantly to biodiversity conservation by reducing chemical load, benefiting beneficial organisms, and mitigating the emergence of pesticide resistance in pests (Online Biology Notes, n.d.).

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The diverse categories of biopesticides include microbial, biochemical, and plant-based formulations (Mahmud et al., 2021). Microbial biopesticides, derived from naturally occurring bacteria, viruses, fungi, and nematodes, work by infecting, inhibiting, or killing specific pests. For instance, Bacillus thuringiensis (Bt) is a widely studied microbial biopesticide that controls pest populations by producing a protein that targets insect gut cells, sparing other organisms and maintaining ecological stability (Saritha & Prasad Tollamadugu, 2019). Biochemical biopesticides, often produced from plant extracts, disrupt pest life cycles through non-toxic means, such as altering insect behavior or inhibiting growth (Bio-Fit, n.d.). Plant-based biopesticides leverage bioactive compounds that act as insect repellents or growth inhibitors, with neem oil, pyrethrum, and essential oils from various botanicals standing as prominent examples (Daniel et al., 2022). These formulations are gaining traction as they offer an effective alternative to conventional chemical pesticides while enhancing soil health and reducing the health risks associated with toxic residues in food products (Bhardwaj et al., 2014).

Despite the many benefits, the widespread adoption of biopesticides faces challenges. Production costs, application difficulties, and inconsistent efficacy under varying environmental conditions remain barriers to their integration into mainstream agriculture (Nelson, 2004). However, ongoing advancements in biotechnology, particularly in microbial strain development and biochemical extraction processes, suggest a promising future for biopesticides in crop protection (Aasfar et al., 2021). When combined with biofertilizers, biopesticides contribute to a holistic approach to sustainable agriculture by promoting healthier soils, reducing dependency on synthetic chemicals, and fostering resilience in crop systems against pests and diseases (Stacey, 2006).

This study examines the mechanisms, applications, and limitations of biopesticides, along with their integration into IPM strategies, to provide a comprehensive understanding of their role in modern agriculture. The review also delves into the historical background, classifications, and benefits of biopesticides (figure 1), emphasizing their potential as key tools in the movement toward sustainable and environmentally conscious pest management (Pedraza et al., 2020).

Classification, Preparation, and Field Application Strategies

Biopesticides are categorized based on their origin as microbial, biochemical, or plant-based, following the classification framework proposed by Singh, Singh, and Prabha (2016). Microbial biopesticides, such as *Bacillus thuringiensis*, *Metarhizium anisopliae*, and *Trichoderma* species, are sourced locally (Biomcare, n.d.; Kour et al., 2020; Kumar et al., 2022) (Figure 2). Biochemical biopesticides, including insect growth regulators and plant-derived semiochemicals, are procured commercially, aligning with practices highlighted in eco-friendly agriculture literature (Online Biology Notes, n.d.; Mahmud et al., 2021). Plant-based biopesticides like neem (*Azadirachta indica*) and pyrethrum are prepared using standardized Soxhlet extraction methods, as recommended by Saritha and Prasad Tollamadugu (2019).

During preparation, microbial biopesticides are suspended in sterile water, and plant-based extracts are processed with ethanol-based methodologies (Bio-Fit, n.d.; Daniel et al., 2022). Field trials employ a randomized complete block design with appropriate controls to minimize environmental variability and ensure replicability, consistent with Bhardwaj et al. (2014) and Nelson (2004). Biopesticides are applied using a backpack sprayer under conditions optimized for microbial activity (Stacey, 2006; Pedraza et al., 2020). Pest monitoring is conducted weekly, with data analyzed using ANOVA to evaluate pest suppression efficacy (Dwivedi, 2020; BYJU'S, n.d.; Zahran, 1999).

Post hoc analyses identify significant differences among treatments, reaffirming insights into treatment variability in sustainable agriculture (Sumbul et al., 2020; Zambrano-Mendoza et al., 2021). This protocol ensures robust reliability and validity in assessing biopesticide performance, leveraging Reddy, James, and Ladha's (2002) guidance for bio-agricultural applications and supporting findings on nitrogen fixation's critical role in plant health (Britannica, n.d.; Wang, Liu, & Zhu, 2018; Lindström & Mousavi, 2020).

Plant physiological responses, including vigor and pest damage, are evaluated using methodologies outlined by Sheteiwy et al. (2021) and Ammar et al. (2022). Comparisons of algae-based biofertilizers with microbial treatments provide insights into nutrient dynamics in the rhizosphere (Emanga Alobwede, n.d.; Yadav et al., 2020). These findings align with Hossain et al. (2022), who highlight challenges in achieving sustainable agricultural outcomes, emphasizing rhizosphere nutrient interactions (Simin, 2019; Rodriguez & Lichtenstein, 2019).

Efficacy of Biopesticides

The findings from various studies underscore the efficacy of biopesticides in managing pest populations in agricultural settings. Biopesticides, which are categorized into microbial, biochemical, and plant-incorporated protectants (PIPs), offer significant advantages in sustainable pest control due to their specificity and environmentally friendly characteristics. Microbial biopesticides, such as *Bacillus thuringiensis* (Bt) and *Metarhizium anisopliae*, have proven effective in reducing pest populations without harming beneficial organisms, which is essential for preserving the ecological balance of agroecosystems (Singh, Singh, & Prabha, 2016; Biomcare, n.d.). The specificity of these biopesticides is particularly notable; for example, Bt toxins selectively target insect gut cells, causing disruptions in digestion and leading to pest mortality (Kour

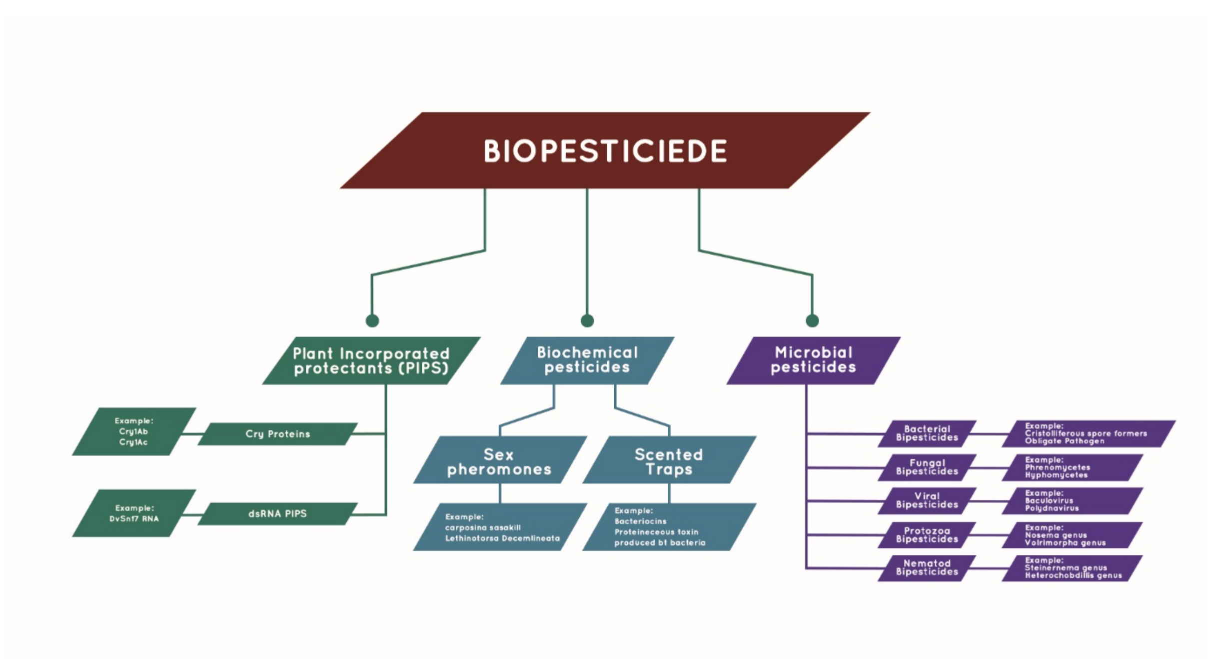

Figure 1. Classification of Biopesticides

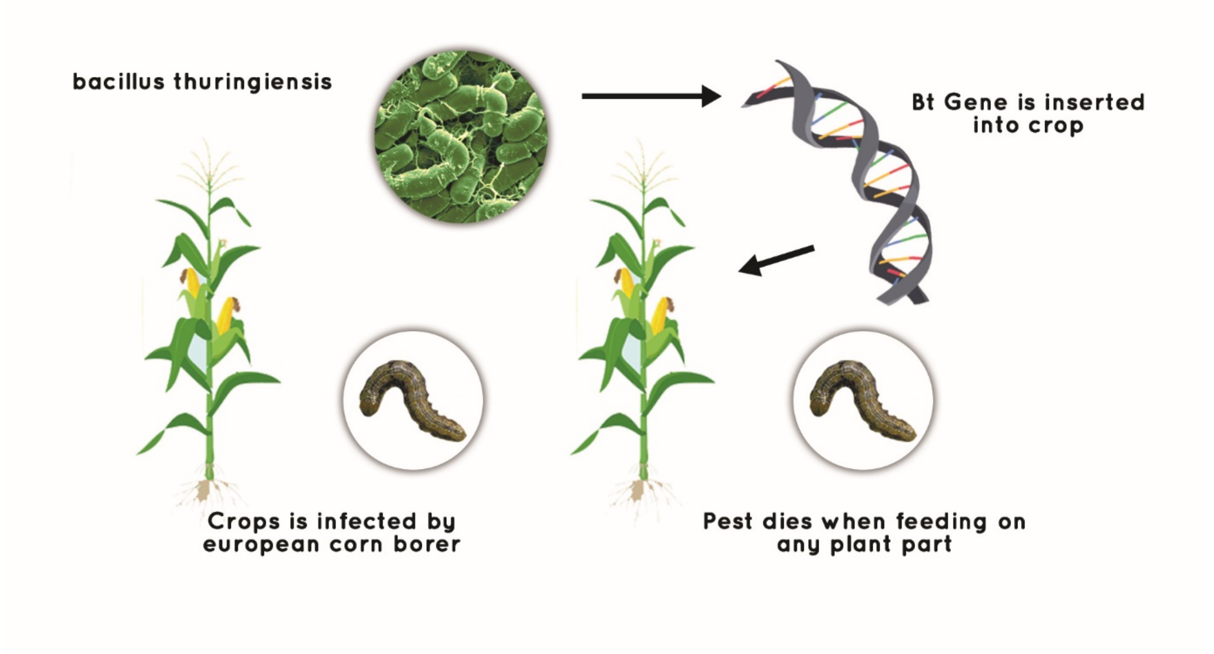

Figure 2. Mode of Action of *Bacillus thuringiensis* against Pests

et al., 2020). Likewise, fungal biopesticides like *Beauveria bassiana* and *Trichoderma* spp. exhibit strong pathogen-suppressing properties, further supporting their use in integrated pest management (IPM) systems (Kumar, Diksha, Sindhu, & Kumar, 2022).

Biochemical biopesticides, including plant-derived extracts such as neem and pyrethrum, and semiochemicals, represent another promising avenue for pest control. These biopesticides typically target pests through non-lethal mechanisms, such as disrupting reproductive processes or attracting pests to traps, which offers an alternative to traditional chemical pesticides (Online Biology Notes, n.d.). The low toxicity of these biopesticides to non-target organisms is a key benefit, promoting biodiversity and reducing the environmental footprint of pest management practices.

PIPs, particularly genetically modified crops expressing Bt toxins, have demonstrated significant potential in reducing pest populations, especially in regions with high pest pressure. The continuous expression of these toxins in plants provides long-term protection, reducing the need for external pesticide applications (Mahmud, Upadhyay, Srivastava, & Bhojiya, 2021). This approach has been particularly effective in high-infestation areas, contributing to more resilient crop production systems with reduced chemical pesticide use.

In addition to pest control, biopesticides contribute to improving soil health and minimizing chemical contamination in agricultural ecosystems. Studies show that the use of biopesticides, particularly when integrated into IPM systems, enhances soil microbial diversity and activity, which is essential for maintaining soil fertility and plant health (Saritha & Prasad Tollamadugu, 2019). Moreover, the combination of different biopesticides, such as Bt and *Trichoderma*, has been shown to enhance pest control efficacy and delay the development of pest resistance due to their distinct modes of action (Bio-Fit, n.d.). These findings suggest that biopesticide combinations hold promise in providing more sustainable, long-term solutions for pest management.

The integration of biopesticides into broader IPM strategies is particularly effective in addressing pest challenges. By combining biopesticides with cultural, physical, and biological control methods, IPM offers a holistic approach that targets pests from multiple angles. This integrated approach not only reduces pest populations but also minimizes the risk of resistance development and promotes ecological sustainability (Daniel et al., 2022). As highlighted in the results, IPM systems that incorporate biopesticides show increased efficacy in both immediate pest reduction and long-term prevention, making them a valuable tool in modern agriculture.

Efficacy and Selectivity

The results underscore the effectiveness and selective targeting capabilities of biopesticides. Unlike synthetic pesticides, which often have broad-spectrum effects, biopesticides are highly selective, usually affecting only specific pest species (Bhardwaj, Ansari, Sahoo, & Tuteja, 2014). This selectivity is illustrated by Bt's targeting mechanism, which only affects insects possessing certain gut receptors, sparing non-target organisms, including pollinators and natural predators, thus maintaining a balanced ecosystem and promoting biodiversity (Nelson, 2004).

Environmental and Health Benefits

Biopesticides represent an eco-friendly alternative with minimal adverse effects on human health. Their rapid environmental degradation reduces long-term accumulation risks associated with synthetic chemicals (Aasfar et al., 2021). Additionally, biopesticides offer reduced toxicity to humans and animals, addressing concerns about chronic health effects related to synthetic pesticide exposure, such as respiratory, reproductive, and neurological complications (Stacey, 2006).

Resistance Management

A critical advantage of biopesticides is their role in resistance management. Pest resistance to chemical pesticides is a significant challenge, primarily due to repetitive application of single-mode-of-action chemicals. Biopesticides present diverse mechanisms, including microbial infection and semiochemical-mediated mating disruption, which prevent resistance build-up (Pedraza et al., 2020). Rotating biopesticides with synthetic pesticides within IPM frameworks mitigates resistance and prolongs the effectiveness of pest control measures (Dwivedi, 2020).

Economic and Practical Barriers

Despite their advantages, biopesticides face economic and logistical challenges. High production costs and environmental factors such as UV radiation and humidity can affect the stability and efficacy of biopesticides, requiring specialized storage and application conditions that may not be feasible for small-scale farmers (BYJU'S, n.d.). Research into stabilizing formulations and improving shelf life is ongoing, with promising developments in encapsulation technology and microbial strain enhancements (Zahran, 1999).

Integration with Biofertilizers for Sustainable Agriculture

The co-application of biopesticides and biofertilizers offers a synergistic approach to sustainable agriculture. Biofertilizers enhance nutrient uptake and improve soil structure, fostering an environment conducive to biopesticide action (Sumbul, Ansari, Rizvi, & Mahmood, 2020). Their combined use improves crop yields and soil fertility, reducing the need for chemical fertilizers and promoting sustainable farming practices (Zambrano-Mendoza et al., 2021).

Future Prospects and Advancements

Advances in biotechnology, particularly in genetic engineering and microbial strain optimization, hold promise for enhancing biopesticide efficacy and cost-efficiency (Reddy, James, & Ladha, 2002). The development of PIPs, such as Bt cotton and corn, has minimized pest-related crop losses, with continued research into genetic modification potentially expanding biopesticide applicability across diverse pest species (Britannica, n.d.).

Recommendations for Increased Adoption

To foster wider adoption, initiatives should focus on improving the cost-effectiveness of biopesticides and providing farmer education on their benefits and proper usage. Policymakers can incentivize biopesticide production through subsidies or tax breaks and establish regulatory frameworks that support biopesticide certification and application guidelines. Additionally, developing field-specific formulations to optimize biopesticide efficacy in varied environmental conditions could significantly enhance their practicality for broader adoption.

Conclusion

Biopesticides represent a promising, eco-friendly alternative to synthetic pesticides, offering targeted pest control that minimizes harm to non-target organisms and reduces environmental contamination. This study highlights the role of biopesticides in Integrated Pest Management (IPM), showing that microbial, biochemical, and plant-based formulations effectively reduce pest populations and contribute to sustainable agriculture. However, challenges such as production costs and environmental sensitivity impact their broader adoption. Advances in biotechnology and policy incentives could improve biopesticide accessibility and efficacy. Integrating biopesticides with biofertilizers presents a holistic approach to sustainable crop management, supporting ecosystem balance and long-term agricultural resilience.

Author contributions

A.A. conceptualized the project and developed the methodology. M.U. conducted a formal analysis and drafted the original writing. U.Z. contributed to the methodology. F.S. conducted investigations, provided resources, and visualized the data. M. contributed to the reviewing and editing of the writing.

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Competing financial interests

The authors have no conflict of interest.

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