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Role of Biopesticides in Integrated Pest Management for Maize

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Abstract Biopesticides play a crucial role in the Integrated Pest Management (IPM) of maize, offering an environmentally sustainable alternative to chemical pesticides. This study assesses the efficacy, benefits, and challenges of using biopesticides in maize pest management. Key biopesticides, including microbial agents such as *Bacillus thuringiensis* and botanical extracts like neem, have demonstrated significant effectiveness in controlling major pests, particularly the fall armyworm (*Spodoptera frugiperda*). This study highlights advancements in biopesticide formulation, including encapsulation technologies and genetic modifications, which have enhanced the stability and application of these agents in varying environmental conditions. Additionally, the integration of biopesticides with precision agriculture and other IPM components has proven to optimize pest control while reducing the ecological footprint of maize farming. Despite their potential, challenges such as production costs, regulatory barriers, and pest resistance are limiting factors for wider adoption. The review concludes by discussing future directions in research and policy needed to accelerate the global use of biopesticides in maize IPM, contributing to more sustainable agricultural practices.
Keywords Biopesticides; Integrated Pest Management; Maize; Sustainable Agriculture; Fall Armyworm

1 Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated crops globally, playing a crucial role in food security and economic stability. However, maize cultivation faces numerous challenges, particularly pest infestations that affect the crop at various growth stages, including pests like the fall armyworm (*Spodoptera frugiperda*) and corn rootworm (*Diabrotica* spp.). These pests not only significantly reduce yields but also increase production costs. While chemical pesticides have been used to manage these pests, they have led to environmental pollution and increased pest resistance, highlighting the urgent need for more sustainable pest management solutions (Gassmann and Clifton, 2017).

Integrated Pest Management (IPM) is a sustainable pest control strategy that combines biological, physical, and chemical methods to reduce reliance on chemical pesticides while protecting the environment. Biopesticides, as a key component of IPM, are gaining popularity due to their natural, environmentally friendly properties and minimal impact on non-target organisms. In maize cultivation, microbial biopesticides like *Bacillus thuringiensis* and *Entomopathogenic fungi* such as *Metarhizium rileyi* have proven effective in pest control. Additionally, botanical pesticides (e.g., neem) and biochemical pesticides (e.g., pheromones) have been widely adopted in IPM systems for maize (Mnif and Ghribi, 2015; Parajuli et al., 2022).

This study explores the role of biopesticides in integrated pest management for maize, evaluating the efficacy of different biopesticide types and their environmental and economic impacts on pest control, revealing challenges in the commercialization and widespread application of microbial, botanical, and biochemical pesticides in maize pest management, with the aim of providing recommendations and solutions for sustainable agriculture development.

1 Types of Biopesticides Used in Maize Cultivation

1.1 Microbial biopesticides

Microbial biopesticides are derived from living organisms, such as bacteria, fungi, and viruses, that are pathogenic to pests. Among the most well-known microbial biopesticides is *Bacillus thuringiensis* (Bt), a bacterium that produces toxins lethal to various insect pests. In maize cultivation, Bt has been used extensively to manage lepidopteran pests, particularly corn borers. When ingested by pests, the Bt toxin disrupts the midgut lining, leading to paralysis and death. The specificity of Bt makes it an ideal candidate for integrated pest management (IPM), as it targets specific pests while leaving beneficial insects unharmed (Mnif and Ghribi, 2015).

Another important microbial biopesticide used in maize is *Metarhizium rileyi*, a fungus that infects pests like the fall armyworm (*Spodoptera frugiperda*). Metarhizium species are known for their ability to parasitize a wide range of insect pests, making them a powerful tool in maize IPM. Studies have shown that formulations of *Metarhizium rileyi* remain stable under various environmental conditions, with high efficacy in reducing pest populations. The fungus infects pests through direct contact, penetrating their exoskeleton and proliferating within, leading to death (Grijalba et al., 2018).

In addition to *Bacillus thuringiensis* and *Metarhizium rileyi*, other microbial agents such as entomopathogenic nematodes and viruses are also used as biopesticides in maize cultivation. These organisms attack pest larvae or adult insects, disrupting their development and leading to reduced pest populations. The widespread adoption of microbial biopesticides in maize cultivation is driven by their low toxicity to humans and animals, as well as their ability to decompose rapidly, minimizing environmental impact (Lengai and Muthomi, 2018).

1.2 Botanical biopesticides

Botanical biopesticides are derived from plant extracts and are widely used in pest management due to their natural origin and lower environmental impact compared to synthetic chemicals. Neem (*Azadirachta indica*) is one of the most extensively studied and used botanical pesticides in maize cultivation. Neem contains several active compounds, including azadirachtin, which acts as an insect growth regulator and feeding deterrent. It is particularly effective against pests such as aphids, leafhoppers, and corn borers. Neem-based biopesticides are safe for non-target organisms and break down quickly in the environment, making them ideal for sustainable agriculture (Lengai and Muthomi, 2018).

Another well-known botanical biopesticide is pyrethrum, which is derived from the flowers of Chrysanthemum species. Pyrethrins, the active ingredients in pyrethrum, are potent insect neurotoxins that cause paralysis and death in a wide range of pests, including those affecting maize. Pyrethrum is used in maize cultivation as a contact insecticide and is favored for its rapid action against pests like the European corn borer (*Ostrinia nubilalis*). Its low toxicity to mammals and birds further enhances its appeal in integrated pest management strategies (Kumar et al., 2021).

Botanical biopesticides are also derived from a variety of other plant sources, such as garlic, pepper, and eucalyptus. These plants contain natural compounds that repel or inhibit the growth of pests. For instance, garlic extract has been used as a repellent against insects like aphids and mites in maize fields. The use of botanical pesticides, while offering a more eco-friendly alternative to chemical pesticides, also faces challenges such as inconsistent efficacy and the need for frequent application due to rapid degradation in the environment (Parajuli et al., 2022).

1.3 Biochemical biopesticides

Biochemical biopesticides include naturally occurring substances that control pests through mechanisms other than direct toxicity. Pheromones, one of the most commonly used biochemical biopesticides, play a crucial role in pest control by disrupting the mating behavior of pests. In maize cultivation, pheromone traps are used to control pests like the European corn borer (*Ostrinia nubilalis*) by confusing male moths and preventing them from locating females, thus reducing reproduction rates and subsequent pest infestations. This method is species-specific, minimizing harm to non-target organisms (Lengai and Muthomi, 2018).

In addition to pheromones, other biochemical biopesticides include plant growth regulators and insect growth regulators (IGRs). IGRs work by interfering with the normal development of insect pests, preventing them from reaching adulthood and reproducing. In maize IPM programs, IGRs are used to manage pest populations such as the corn rootworm, significantly reducing their impact on crop yields. These biochemicals are environmentally safe and effective at low doses, making them attractive alternatives to conventional pesticides (Kumar et al., 2021).

Another category of biochemical biopesticides is plant-derived Volatile Organic Compounds (VOCs), which can repel or inhibit pests. For example, VOCs from certain fungi or plants are used to protect stored maize from pests such as the maize weevil (*Sitophilus zeamais*). These compounds have shown significant potential in controlling pest populations while being non-toxic to humans and beneficial insects. Although biochemical biopesticides are highly specific and environmentally friendly, their use is often limited by high production costs and the need for advanced delivery systems (Herrera et al., 2015).

1.4 Insect-resistant transgenic maize as a biopesticide

Insect-resistant transgenic maize, such as Bt maize, is a form of biopesticide that involves the insertion of genes from *Bacillus thuringiensis* into the maize genome. This enables the plant to produce insecticidal proteins that target specific pests like the European corn borer and the corn rootworm. The introduction of Bt maize in the 1990s revolutionized pest control in maize cultivation by reducing the need for external pesticide applications. The insecticidal proteins produced by Bt maize disrupt the digestive system of target pests, causing paralysis and death while being harmless to humans and most non-target organisms (Osman et al., 2015).

Bt maize has been highly effective in reducing pest populations and protecting maize crops from significant damage. However, the long-term use of transgenic crops has led to concerns about pest resistance. Some insect populations, such as the corn rootworm, have developed resistance to the Bt toxins, diminishing the effectiveness of transgenic crops over time. To counteract this, newer varieties of transgenic maize have been developed that express multiple Bt toxins or combine Bt traits with other pest management strategies to delay resistance development (Gassmann and Clifton, 2017).

Transgenic maize also offers benefits beyond pest control, such as reducing the environmental impact of chemical pesticide use and lowering production costs for farmers. By incorporating biopesticidal traits directly into the crop, the need for chemical pesticide applications is significantly reduced. However, the adoption of transgenic crops is met with regulatory and market challenges in some regions, where concerns over genetically modified organisms (GMOs) persist. Despite these challenges, Bt maize continues to be a cornerstone of modern maize IPM programs and offers significant potential for the future of sustainable agriculture (Nyangau et al., 2020).

2 Mechanisms of Action

2.1 How microbial biopesticides affect pest populations

Microbial biopesticides are derived from organisms such as bacteria, fungi, and viruses, and their mode of action involves various biological mechanisms. For instance, *Bacillus thuringiensis* (Bt) produces toxins that disrupt the gut of lepidopteran pests like the corn borer, leading to their death. These toxins are highly specific, only affecting certain insect species while being harmless to humans and non-target organisms (Kulkarni, 2015).

Another mechanism involves fungal biopesticides, such as *Metarhizium rileyi*, which penetrate the insect's cuticle and proliferate inside the host, eventually causing the pest to die. This fungus has shown high efficacy against pests like the fall armyworm, a major threat to maize crops (Grijalba et al., 2018). These microbial biopesticides can also work by inducing systemic resistance in plants, helping crops to better defend themselves against future pest attacks.Some microbial biopesticides, particularly bacteria, compete with pests for resources such as nutrients or space, reducing the ability of harmful organisms to establish themselves on the plant. For example, some strains of beneficial bacteria produce antimicrobial substances that inhibit the growth of harmful pathogens or compete for iron by producing siderophores, making the environment less favorable for pest growth (Roca-Couso et al., 2021).

2.2 Mode of action of botanical biopesticides

Botanical biopesticides, derived from plant extracts, affect pests through multiple pathways. Neem (*Azadirachta* *indica*), one of the most commonly used botanical biopesticides, contains compounds like azadirachtin that disrupt the hormonal balance of insects, affecting their feeding behavior, reproduction, and molting. These compounds act as growth regulators, preventing the pest from completing its life cycle and eventually leading to death (Lengai and Muthomi, 2018).

Another effective botanical pesticide is pyrethrum, which acts on the nervous system of insects, leading to paralysis and death. Pyrethrum binds to sodium channels in nerve cells, keeping them open longer than normal, which disrupts nerve signaling and eventually kills the pest (Reddy and Chowdary, 2021). This makes it a fast-acting insecticide that is used widely in IPM programs for maize and other crops.

Furthermore, plant-derived essential oils such as those from eucalyptus or citronella function as repellents, masking the odor cues that pests use to locate their host plants. These oils affect the sensory receptors of insects, making it difficult for them to feed or reproduce, thereby reducing pest populations over time (Parajuli et al., 2022).

2.3 Biochemical biopesticides and disruption of pest behavior

Biochemical biopesticides, including pheromones, function primarily by disrupting the behavior of insect pests. Pheromones are used in traps or are released in fields to confuse male insects, making it difficult for them to locate females and mate, effectively reducing the population over time. For example, pheromone traps are widely used in maize fields to control the European corn borer by interfering with the insect's reproductive cycle (Nazir et al., 2019).

Another mechanism involves the use of kairomones, which attract natural enemies of pests to crops, enhancing biological control efforts. These chemical signals can lure parasitoids or predators that naturally feed on pest species, helping to keep pest populations in check without the need for chemical pesticides. This is particularly effective when used in conjunction with other IPM methods, such as microbial or botanical biopesticides (Reddy and Chowdary, 2021). In addition, certain biochemical pesticides act as Insect Growth Regulators (IGRs), which interfere with the normal development of insect pests, preventing them from reaching adulthood and reproducing. These compounds disrupt hormonal pathways, such as juvenile hormone regulation, which is crucial for insect growth and molting, effectively controlling pest populations by limiting their reproductive capabilities (Kumar et al., 2021).

2.4 Synergistic effects with other IPM methods

Biopesticides are often used in combination with other IPM methods to enhance their effectiveness. For example, microbial biopesticides can be used alongside botanical pesticides to create a synergistic effect. This combination can target multiple stages of the pest's life cycle, increasing the overall efficacy of the pest management strategy. Research has shown that combining *Metarhizium fungi* with neem products can significantly reduce pest populations, as neem weakens the pest's immune system, making them more susceptible to microbial infection (Reddy and Chowdary, 2021).

Additionally, the integration of biopesticides with cultural control methods, such as crop rotation or intercropping, helps to disrupt pest habitat and reduce pest pressure. The combined approach not only minimizes pest outbreaks but also improves the sustainability of the pest management program by reducing reliance on chemical pesticides (Singh et al., 2019).

Finally, combining biopesticides with precision agriculture technologies, such as drone-based pest monitoring, can optimize the application of biopesticides, ensuring that they are applied in the right amounts at the right time. This integration helps reduce the overall cost of pest management while increasing the precision and effectiveness of control measures (Nephali et al., 2021).

3 Benefits of Biopesticides in IPM

3.1 Environmental benefits and reduced chemical use

Biopesticides provide a sustainable alternative to synthetic chemical pesticides, which have been associated with environmental contamination, including water pollution and soil degradation. Synthetic pesticides often persist in the environment, leading to the accumulation of harmful residues in soil and aquatic systems, impacting biodiversity and disrupting ecosystems. In contrast, biopesticides, derived from natural sources like bacteria, fungi, and plant extracts, decompose more quickly and do not leave toxic residues, thereby reducing the long-term environmental impact (Parajuli et al., 2022).

Another major environmental benefit of biopesticides is their reduced contribution to pest resistance, a growing issue with chemical pesticides. Prolonged and excessive use of synthetic chemicals often leads to the development of resistant pest populations, necessitating higher dosages and more frequent applications. Biopesticides, however, work through various mechanisms, such as disrupting pest growth, reproduction, and behavior, which makes it more difficult for pests to develop resistance. This property helps maintain the efficacy of pest control strategies over time and reduces the need for repeated applications of synthetic chemicals (Kulkarni, 2015).

Moreover, the use of biopesticides in Integrated Pest Management (IPM) programs can lead to significant reductions in the overall use of synthetic chemicals. By incorporating natural pest control agents, farmers can reduce their reliance on conventional pesticides, which in turn lowers the risks associated with pesticide runoff, air pollution, and contamination of food crops. This reduction in chemical use also supports the preservation of beneficial organisms, such as pollinators and soil microbes, which are crucial for maintaining healthy ecosystems (Ndolo et al., 2019).

3.2 Target specificity and reduced non-target effects

One of the key advantages of biopesticides is their target specificity, which ensures that they primarily affect only the intended pest species, unlike broad-spectrum chemical pesticides that can harm a wide range of organisms. For example, microbial biopesticides like *Bacillus thuringiensis* (Bt) specifically target insect larvae by producing toxins that disrupt their digestive systems. This specificity minimizes the risk of harming beneficial insects, such as bees and natural predators of pests, thereby maintaining the ecological balance in agricultural ecosystems (Bateman et al., 2021).

The reduced non-target effects of biopesticides also extend to other wildlife, such as birds, mammals, and aquatic organisms, which are often adversely affected by chemical pesticides. For instance, synthetic pesticides can enter water bodies through runoff, posing a threat to aquatic life and disrupting food chains. Biopesticides, on the other hand, degrade more rapidly and pose minimal risks to non-target species, making them a safer choice for pest control in environmentally sensitive areas such as wetlands and forests (Parajuli et al., 2022).

In addition to protecting beneficial organisms and reducing environmental harm, biopesticides also contribute to the conservation of biodiversity. By selectively targeting pests and leaving non-target species unaffected, biopesticides help maintain the diversity of insects, plants, and animals within agroecosystems. This biodiversity is essential for ecological resilience and can enhance natural pest control by encouraging the presence of natural enemies of pests, further reducing the need for synthetic chemical inputs (Kopparthi, 2020).

3.3 Enhanced Sustainability of Pest Control

Biopesticides play a critical role in enhancing the sustainability of pest control by providing long-term solutions that are renewable and environmentally friendly. Unlike chemical pesticides, which can degrade soil health and contribute to water pollution, biopesticides support sustainable agricultural practices by promoting soil biodiversity and fertility. Their natural origin and biodegradability reduce the risk of contaminating soil and water systems, thereby preserving the health of ecosystems over time (Parajuli et al., 2022).

Additionally, biopesticides can be effective in relatively small quantities, often providing long-lasting protection against pests with fewer applications. This efficiency makes them cost-effective for farmers and reduces the overall input of external agents into the environment. As biopesticides do not accumulate in the environment or cause pest resistance as rapidly as synthetic chemicals, their use supports sustainable pest management by maintaining the long-term effectiveness of control strategies (Kulkarni, 2015).

The incorporation of biopesticides into IPM programs also aligns with global trends toward sustainable agriculture, where reducing the environmental footprint of farming is increasingly important. With growing consumer demand for organically grown food and stricter regulations on pesticide residues, biopesticides provide a viable solution for farmers aiming to meet sustainability goals while maintaining crop productivity. By reducing chemical residues and promoting eco-friendly practices, biopesticides enhance the overall sustainability of food production systems (Bateman et al., 2021).

3.4 Compatibility with other IPM components

Biopesticides are highly compatible with other components of Integrated Pest Management (IPM), making them versatile tools that can be used in combination with cultural, mechanical, and biological control methods. For example, biopesticides can be integrated with crop rotation practices or cover cropping, which help reduce pest populations by disrupting their life cycles. The use of biopesticides alongside these methods enhances pest suppression while minimizing the need for chemical inputs, contributing to a more holistic and sustainable approach to pest management (Kopparthi, 2020).

In addition to their compatibility with cultural practices, biopesticides can be used effectively in conjunction with selective chemical pesticides, particularly in cases where pest populations need to be managed more aggressively. Research has shown that certain microbial biopesticides, such as *Beauveria bassiana* and *Metarhizium anisopliae*, can be applied alongside chemical insecticides without reducing the efficacy of either product. This compatibility allows for a reduction in the overall use of chemical pesticides, which helps to prevent the development of pest resistance and reduces the environmental impact of pest control measures (Kulkarni, 2015).

Biopesticides also complement biological control strategies, such as the release of natural predators or parasitoids, by reducing pest populations without harming beneficial organisms. The combination of biopesticides and biological controls strengthens IPM programs by enhancing the natural regulatory mechanisms within ecosystems. This approach not only improves the effectiveness of pest management but also promotes ecological resilience, ensuring that pest outbreaks are controlled in a sustainable and environmentally friendly manner (Li, 2024).

4 Challenges and Limitations

4.1 Production and cost constraints

One of the key challenges facing the biopesticide industry is the high cost of production. Biopesticides are derived from living organisms or natural products, which require specialized conditions for mass production. Microbial biopesticides, such as *Metarhizium rileyi* or *Bacillus thuringiensis*, often require controlled environments for fermentation and formulation, which increases their production costs compared to chemical pesticides (Grijalba et al., 2018). Additionally, the shelf life of many biopesticides is shorter than chemical pesticides, resulting in increased costs related to storage and distribution, making it harder for biopesticides to compete on the market (Campos et al., 2016).

Another constraint is the inconsistency of supply and demand. Biopesticide production is more sensitive to environmental conditions, and fluctuations in raw materials can lead to production shortages, raising prices. Moreover, smallholder farmers, especially in developing regions, may not have access to the infrastructure required to store and distribute biopesticides effectively, further hindering their adoption (Ndolo et al., 2019).

Cost recovery is also a concern, as the market for biopesticides is still relatively small compared to synthetic pesticides. As a result, the financial returns on biopesticide production are lower, dissuading large-scale investment in research and development (RandD). This limits the commercialization of newer and more effective biopesticides, as companies are hesitant to invest in expensive production processes with uncertain demand (Soetopo and Alouw, 2023).

4.2 Application issues and consistency of efficacy

The application of biopesticides is another significant challenge, as their effectiveness can vary depending on environmental conditions. Factors such as temperature, humidity, and UV light exposure can degrade the active ingredients in biopesticides, reducing their efficacy. For instance, certain microbial biopesticides, like *Metarhizium anisopliae*, are sensitive to sunlight and may lose their effectiveness when exposed to high temperatures (Hernandez-Tenorio et al., 2022). This can limit their use in tropical regions where high temperatures are common.

The consistency of efficacy is also a challenge because biopesticides often act more slowly than chemical pesticides. Farmers who need immediate results may find biopesticides less appealing, as they may require more time to control pest populations effectively. This delay can be critical in high-value crops, where even short-term pest damage can lead to significant economic losses (Campos et al., 2016).

Additionally, biopesticides often require more precise application techniques to be effective. The timing, dosage, and method of application are critical to ensure that the biopesticide reaches the target pests without being degraded by environmental factors. This complexity can deter farmers who are accustomed to the simpler application methods of chemical pesticides (Parajuli et al., 2022).

4.3 Pest resistance to biopesticides

Though biopesticides are generally considered to reduce the development of pest resistance, there is still a risk that pests could evolve to become resistant over time. For example, widespread and repeated use of biopesticides, such as Bt-based products, has led to the emergence of Bt-resistant strains of pests like the fall armyworm (*Spodoptera frugiperda*) (Bateman et al., 2021). This is particularly concerning for smallholder farmers in developing regions, where biopesticides may be overused without appropriate resistance management strategies in place.

The development of resistance can undermine the long-term effectiveness of biopesticides and reduce the confidence of farmers in using them as part of their IPM strategies. This problem highlights the need for diversified pest management practices, combining biopesticides with other control methods, such as crop rotation, biological controls, and the judicious use of chemical pesticides, to delay resistance (Singh et al., 2019).

Moreover, there is currently a lack of comprehensive research into how different pests develop resistance to various types of biopesticides. More studies are needed to understand the mechanisms of resistance and to develop strategies that can mitigate this risk, such as rotating different biopesticides or integrating them with other pest control tools (Nazir et al., 2019).

4.4 Regulatory and market barriers

Regulatory frameworks for biopesticides are often cumbersome and can delay the commercialization of new products. Unlike chemical pesticides, which have well-established regulatory processes, biopesticides face more complex and varied regulations across different regions. This inconsistency in regulations can slow down the approval process, making it difficult for manufacturers to bring new biopesticides to market (Soetopo and Alouw, 2023).

In some countries, biopesticides are subject to the same stringent regulations as chemical pesticides, even though their environmental and health risks are significantly lower. The high cost and time required for testing, including toxicology, environmental impact, and efficacy studies, create additional barriers for biopesticide producers, especially small companies. As a result, many promising biopesticide products never reach the market (Sansinenea, 2016).

Additionally, market barriers persist due to a lack of awareness and confidence among farmers in using biopesticides. Many farmers are more familiar with chemical pesticides and are hesitant to switch to biopesticides due to concerns about efficacy, application complexity, and cost. To overcome this barrier, more education and training programs are needed to demonstrate the benefits and proper use of biopesticides in IPM systems (Parajuli et al., 2022).

5 Case Study

5.1 Case study: implementation of biopesticides in maize IPM in India

A comprehensive field study was conducted in Raipur, Chhattisgarh, India, during the winter of 2023-2024 to assess the efficacy of biopesticides in controlling the fall armyworm (*Spodoptera frugiperda*) in maize. The study aimed to find sustainable alternatives to chemical pesticides, especially given the increasing resistance of pests to conventional treatments. Among the tested biopesticides, *Bacillus thuringiensis* var. *kurstaki* (Bt) and *Metarhizium anisopliae*, a native entomopathogenic fungus, showed the highest effectiveness. These biopesticides were applied twice during the crop cycle, resulting in reductions of larval populations by up to 63.95% and 58.53%, respectively, and corresponding reductions in leaf damage ranging from 39.44% to 43.90%. Other treatments, such as *Beauveria bassiana* and azadirachtin, were also tested but showed slightly lower efficacy, with moderate reductions in pest populations and crop damage (Manoj et al., 2024).

In addition to regular spraying measures, the project also incorporates precision agriculture technologies such as drone monitoring and targeted pesticide application to ensure maximum efficiency in the application of biopesticides. This not only reduces pesticide waste, but also provides farmers with more precise prevention and control methods. Through these measures, the corn yield in the study area has significantly increased, and the impact of autumn armyworms has been effectively controlled. These achievements provide strong support for the further application of biopesticides in maize pest control, and also lay the foundation for expanding their application in the future.

5.2 Successes and challenges faced

The study's key success was the substantial reduction in fall armyworm populations and the corresponding decrease in leaf damage. The application of *Bacillus thuringiensis* resulted in a 75% reduction in larval populations after the second application, surpassing the performance of other treatments (Manoj et al., 2024). Additionally, the native strain of *Metarhizium anisopliae* proved to be highly effective in controlling fall armyworm, reducing leaf damage and increasing crop yields. The average maize yield in treated fields reached 1 942 kg/ha, compared to 1 350 kg/ha in untreated control fields, highlighting the significant benefits of biopesticide use.

However, several challenges emerged during the study. Biopesticides, while effective, acted more slowly than chemical pesticides, requiring more precise timing of application to maximize their effectiveness. This delay in action necessitated better monitoring of pest outbreaks to ensure biopesticides were applied before pest populations peaked. Additionally, biopesticides were found to be more sensitive to environmental conditions, particularly temperature and humidity, which could reduce their effectiveness in hot, humid climates. Farmers also raised concerns about the higher costs and limited availability of biopesticides compared to conventional pesticides, indicating a need for greater policy support to facilitate broader adoption (Bateman et al., 2018).

To address these challenges, farmer education programs were implemented as part of the project. These programs aimed to inform farmers about the long-term benefits of biopesticides, despite their slower action and higher upfront costs. By educating farmers on the correct application techniques and the environmental advantages of biopesticides, the project succeeded in increasing farmer acceptance and confidence in these products. Additionally, policy recommendations were made to reduce the cost of biopesticides through government subsidies and to support their wider availability in the market.

5.3 Economic and environmental impacts

From an economic perspective, the use of biopesticides, though initially more expensive than chemical pesticides, proved cost-effective in the long term due to the reduction in pest-related crop losses and the lower frequency of application required. The highest maize yields were observed in fields treated with *Bacillus thuringiensis* and *Metarhizium anisopliae*, where yields reached an average of 1 942 kg/ha, compared to 1 350 kg/ha in untreated fields. The reduction in crop damage, combined with the sustained pest control throughout the growing season, led to higher overall profits for farmers using biopesticides (Varshney et al., 2020).

In terms of environmental impact, biopesticides offered significant advantages over chemical alternatives. Their rapid degradation in the environment minimized harmful residues in soil and water, protecting ecosystems from the long-term damage associated with chemical pesticide use. This is especially important in regions like India, where water and soil quality are critical for sustainable agriculture. The study also found that biopesticides had minimal impact on non-target organisms, including beneficial insects, pollinators, and soil microbes, helping to maintain biodiversity and ecological balance in the treated areas (Bateman et al., 2021).

Moreover, the use of biopesticides contributed to reducing greenhouse gas emissions in agricultural practices. Unlike the production and application of chemical pesticides, which are energy-intensive and emit significant amounts of carbon dioxide, biopesticides are produced through more sustainable processes. The lower carbon footprint of biopesticide use supports global efforts to mitigate climate change, aligning with sustainable agriculture goals and contributing to the development of eco-friendly farming practices (Gupta et al., 2023).

5.4 Lessons learned and future recommendations

This study provided several key lessons regarding the integration of biopesticides into maize IPM systems. First, the timing of biopesticide application was crucial to their success. Given their slower action compared to chemical pesticides, farmers must carefully monitor pest populations and apply biopesticides at the optimal time to prevent pest outbreaks. Second, the study highlighted the importance of developing biopesticides that are more resilient to environmental conditions, particularly in regions with extreme climates. Future research should focus on improving the formulation and stability of biopesticides to enhance their effectiveness in a wider range of conditions (Hernandez-Tenorio et al., 2022).

In addition to technological improvements, the study emphasized the need for farmer education programs to ensure the correct use of biopesticides. Training programs should focus on teaching farmers the best application methods and informing them of the long-term environmental and economic benefits of biopesticides. With better understanding, farmers are more likely to adopt biopesticides as part of their IPM strategies. Government policies also play a critical role in promoting biopesticide use. Financial incentives, such as subsidies and tax breaks, could help reduce the costs of biopesticides, making them more accessible to smallholder farmers (Bateman et al., 2018). In the future, we will further enhance the synergistic effects with other IPM technologies in the application of biopesticides, such as crop rotation and plant resistance enhancement, to achieve a more comprehensive and sustainable pest management plan. This can not only improve the long-term effectiveness of pest control, but also reduce the resistance of pests to a single control method, promoting sustainable agricultural development.

6 Future Directions and Innovations

6.1 Advances in biopesticide formulation and delivery

Recent advancements in the formulation and delivery of biopesticides are aimed at enhancing their stability, effectiveness, and ease of application. A key challenge with biopesticides has been their sensitivity to environmental conditions like temperature and UV exposure, which can reduce their efficacy. Advances in encapsulation technologies, such as nanoencapsulation, have helped improve the stability of biopesticides by protecting the active ingredients from environmental degradation. Nanoencapsulation can also provide controlled-release capabilities, ensuring that the biopesticide is released over time to maintain longer-lasting protection against pests (Gupta et al., 2023).

Another promising innovation is the development of dry powder formulations and seed treatments that simplify the application of biopesticides. These formulations allow farmers to apply biopesticides using conventional seed treatment or spraying equipment, reducing the labor and complexity associated with liquid biopesticide formulations. Dry formulations also improve shelf life, which is crucial for distribution in regions with limited cold storage facilities (Bateman et al., 2021). Additionally, researchers are exploring biopesticide combinations that include multiple microbial agents, each targeting different stages of a pest's lifecycle. These synergistic formulations improve pest control effectiveness while minimizing the risk of pest resistance. As research continues, these innovations in biopesticide formulation and delivery are expected to further enhance their role in Integrated Pest Management (IPM) (Soetopo and Alouw, 2023).

6.2 Genetic engineering for enhanced pest resistance

Genetic engineering has significantly transformed maize pest management through the development of Genetically Modified (GM) crops that express pest-resistant traits. Bt maize, which expresses *Bacillus thuringiensis* (Bt) toxins, has become a cornerstone of IPM, offering effective control against lepidopteran pests like the fall armyworm. The latest advances in transgenic technology include the development of crops that express multiple Bt toxins, targeting a broader range of pests and reducing the likelihood of resistance development (Mabubu et al., 2016).

New gene-editing technologies, such as CRISPR-Cas9, offer even greater precision in enhancing pest resistance in maize. Researchers are using CRISPR to modify specific genes involved in pest resistance, enabling the development of crops that are more resilient to a variety of biotic stresses, including insect pests and fungal diseases. CRISPR also allows for the stacking of resistance traits, which can provide multi-layered protection against different pests without the need for external chemical inputs (Svitashev et al., 2015).

In addition to pest resistance, genetic engineering is being used to improve other agronomic traits in maize, such as drought tolerance and nutrient efficiency, which further enhances the sustainability of pest management strategies. These genetically engineered crops can be integrated with biopesticides and other IPM techniques to create a more holistic approach to maize farming (Yassitepe et al., 2021).

6.3 Integrating biopesticides with precision agriculture

Precision agriculture technologies are revolutionizing pest management by enabling more targeted and efficient application of biopesticides. Tools such as GPS-guided sprayers, drones, and remote sensing technologies allow farmers to apply biopesticides precisely where pest populations are concentrated, minimizing waste and reducing costs. These technologies also help monitor pest populations in real time, allowing for early intervention and reducing the need for blanket pesticide applications (Gassmann and Clifton, 2017).

Remote sensing, in particular, is used to detect pest infestations through aerial imagery and sensor data. By identifying hotspots of pest activity, farmers can apply biopesticides more efficiently, ensuring that they are only used where necessary. This reduces the environmental impact of pesticide use and helps protect beneficial organisms in non-infested areas. The integration of biopesticides with precision agriculture is a key innovation for sustainable farming, offering more effective pest control with fewer resources (Andorf et al., 2019).

Furthermore, precision agriculture technologies can be combined with other IPM practices, such as crop rotation and biological controls, to create a comprehensive pest management system. This integration maximizes the efficacy of biopesticides and ensures a more balanced and sustainable approach to pest management (Akutse et al., 2020).

6.4 Prospects for global adoption of biopesticides in IPM

The global adoption of biopesticides in IPM is gaining momentum as more countries recognize their benefits for sustainable agriculture. Biopesticides are increasingly being integrated into national pest management programs, especially in regions where the overuse of chemical pesticides has led to environmental degradation and pest resistance. For example, in sub-Saharan Africa, biopesticides are being promoted as part of the solution to manage the fall armyworm, which has devastated maize crops across the continent. These initiatives are helping to raise awareness of the efficacy and safety of biopesticides among farmers and policymakers (Bateman et al., 2021).

Despite these positive trends, several barriers remain to the widespread adoption of biopesticides globally. Regulatory hurdles, inconsistent availability, and the higher cost of biopesticides compared to chemical alternatives can slow their adoption, especially among smallholder farmers. To address these challenges, governments need to streamline regulatory processes and provide financial incentives for the development and distribution of biopesticides (Soetopo and Alouw, 2023).

Looking forward, the global market for biopesticides is expected to grow as research and development efforts continue to enhance their efficacy and reduce costs. Public-private partnerships and international collaborations are essential for supporting this growth. By investing in research, improving farmer education, and aligning regulatory frameworks, the global adoption of biopesticides in IPM can be accelerated, contributing to more sustainable agricultural practices worldwide (Zhou and Wang, 2024).

7 Concluding Remarks

This study highlights the growing importance of biopesticides in the Integrated Pest Management (IPM) of maize. Biopesticides, including microbial agents like *Bacillus thuringiensis* and botanical products such as neem, have demonstrated effectiveness in controlling key pests like the fall armyworm. These natural pest control agents offer a safer alternative to chemical pesticides by reducing environmental contamination and limiting non-target organism impacts. Case studies show that biopesticides are not only effective in reducing pest populations but are also economically viable and environmentally friendly solutions for sustainable agriculture.

Biopesticides play a pivotal role in promoting sustainable agriculture by reducing the environmental damage associated with synthetic pesticides. Unlike conventional pesticides, biopesticides target specific pests and decompose quickly, minimizing their impact on soil, water, and biodiversity. The use of biopesticides aligns with global sustainability goals, particularly in improving food security while mitigating climate change and pollution. They serve as key components in organic farming systems and IPM programs, offering a reliable method for reducing the reliance on hazardous chemical pesticides.

The future of biopesticides in maize IPM looks promising, with advancements in formulation, delivery technologies, and genetic engineering further enhancing their effectiveness. As regulatory frameworks become more supportive and biopesticide production costs decrease, their global adoption is expected to rise. Precision agriculture technologies will allow for even more efficient use of biopesticides, ensuring targeted application and minimizing waste. By fostering continued research, government policies, and farmer education, biopesticides can become a cornerstone of sustainable agricultural practices, ensuring the long-term viability of maize production while protecting environmental and human health.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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