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INNOVATIONS IN CROP PROTECTION: BIOPESTICIDES AND MORE

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Abstract:

The increasing global demand for sustainable agricultural practices has driven innovations in crop protection, particularly in the development of bio pesticides and other eco-friendly alternatives. This article explores the recent advancements in crop protection technologies, focusing on the potential of bio pesticides to address pest resistance, reduce environmental impacts, and promote biodiversity. Innovations such as microbial bio pesticides, plant-derived compounds, and genetic techniques are discussed alongside challenges like regulatory hurdles, market adoption, and large-scale implementation. By examining these innovations, this paper highlights the critical role bio pesticides and other emerging technologies play in achieving sustainable agricultural systems.

Keywords: *bio pesticides, crop protection, microbial pesticides, sustainable agriculture, integrated pest management, genetic modification, regulatory challenges, pest resistance, environmental impact, biodiversity.*

INTRODUCTION

Agriculture faces an unprecedented challenge: balancing food production for a growing population with environmental sustainability. Traditional chemical pesticides, while effective, have raised concerns due to their environmental and health impacts, such as biodiversity loss, water contamination, and pest resistance. In response, scientists and agronomists have turned to innovative solutions like bio pesticides, which offer eco-friendly alternatives to conventional chemicals. This article investigates the cutting-edge developments in crop protection, with a particular emphasis on bio pesticides, exploring their mechanisms, benefits, and limitations. It also addresses other promising technologies that complement bio pesticides in integrated pest management (IPM) systems.

Microbial Bio pesticides

Microbial bio pesticides have emerged as an environmentally friendly alternative to synthetic chemical pesticides, playing a crucial role in integrated pest management (IPM). They utilize naturally occurring microorganisms, such as bacteria, fungi, viruses, or protozoans, to control agricultural pests and diseases. Among the most well-known microbial agents are *Bacillus thuringiensis* (Bt) and species of *Trichoderma*, which have demonstrated effectiveness against a wide range of pests. These bio pesticides offer specific advantages such as target specificity, minimal toxicity to non-target organisms, and reduced environmental impact, making them a preferred choice in sustainable agriculture (Gupta & Dikshit, 2010).

Bacillus thuringiensis (Bt) is a bacterium that produces proteinaceous crystals, known as Cry toxins, which are toxic to specific insect pests, particularly lepidopteran larvae (moths and butterflies). When insect larvae ingest Bt spores, the Cry toxins disrupt the insect's midgut cells, causing lysis and eventual death of the pest (Bravo et al., 2011). Bt-based products have been widely used in pest control for crops such as cotton, maize, and vegetables, contributing to reduced chemical pesticide use and improved crop yields. In addition to foliar sprays, genetically modified crops expressing Bt toxins have been developed, further enhancing the efficacy of this bio pesticide (James, 2017).

In contrast to Bt, *Trichoderma* species are fungal bio pesticides that act primarily as antagonists to plant pathogens through mechanisms such as mycoparasitism, competition, and the production of antifungal metabolites (Harman et al., 2004). They are particularly effective against soil-borne pathogens, including *Fusarium* and *Rhizoctonia*, which cause root rot and damping-off diseases in many crops. *Trichoderma* can also promote plant growth by enhancing nutrient uptake and inducing systemic resistance, making them a versatile agent in both pest and disease management (Vinale et al., 2008).

The mode of action of microbial bio pesticides varies depending on the organism. Bacterial bio pesticides like Bt act through the production of toxins that target specific pests, whereas fungal agents like *Trichoderma* use a combination of direct antagonism and indirect plant health benefits to control pathogens. In some cases, microbial bio pesticides can colonize the plant rhizosphere or endophytic spaces, providing long-term protection against pests and diseases (Siddiqui & Shaukat, 2004). This biological control strategy offers a highly specific and sustainable approach, minimizing the development of resistance compared to chemical pesticides.

Application methods for microbial bio pesticides are diverse and tailored to the specific agent and target pest. Bt, for example, is often applied as a foliar spray, while *Trichoderma* may be applied as a soil amendment or seed treatment (Glare et al., 2012). The timing of application is crucial for effectiveness; as microbial agents generally work best when applied during the early stages of pest infestation or disease development. Additionally, environmental factors such as temperature, humidity, and soil pH can influence the efficacy of microbial bio pesticides, making careful monitoring and precision in application essential for successful pest management (Fargues et al., 2002).

The use of microbial bio pesticides is gaining traction worldwide as part of sustainable agricultural practices. With the growing concern over pesticide residues, biodiversity loss, and pest resistance to chemical pesticides, microbial agents like Bt and Trichoderma offer an effective and eco-friendly solution. Continued research and development into new strains and formulations will further expand their role in integrated pest management, helping farmers meet the challenges of modern agriculture while reducing environmental impacts (Marrone, 2014).

Plant-Derived Compounds

Botanical pesticides, derived from plants, have been used in agriculture for centuries to protect crops from pests. In recent years, they have gained renewed attention due to growing concerns about the environmental and health risks associated with synthetic chemical pesticides. Among the most widely known botanical pesticides are neem (from *Azadirachta indica*) and pyrethrin (from *Chrysanthemum cinerariifolium*). These plant-derived compounds offer a natural alternative to synthetic pesticides and have been incorporated into integrated pest management (IPM) systems to minimize chemical inputs and their harmful effects on ecosystems (Isman, 2020).

Examples of Botanical Pesticides

Neem oil, extracted from the seeds of the neem tree, is one of the most commonly used botanical pesticides. Its active ingredient, azadirachtin, interferes with the growth and reproduction of insects, reducing pest populations without causing immediate death. Neem is effective against a wide variety of pests, including aphids, whiteflies, and caterpillars, and is also non-toxic to beneficial insects like pollinators (Mordue & Nisbet, 2019). Pyrethrin, derived from chrysanthemum flowers, is another widely used botanical insecticide. It works by disrupting the nervous systems of insects, leading to paralysis and death. Pyrethrins are particularly effective against mosquitoes, flies, and other flying insects (Casida & Durkin, 2013).

Efficacy of Botanical Pesticides

Botanical pesticides, while generally effective, often work slower than synthetic chemical alternatives. Neem, for example, affects pests through hormonal disruption, which may take several days to manifest in reduced pest activity. Pyrethrins, on the other hand, provide rapid knockdown of pests but can degrade quickly when exposed to sunlight (Ware & Whitacre, 2004). Despite these limitations, botanical pesticides are still favored in organic farming and IPM programs due to their lower toxicity levels and minimal environmental persistence. Research has shown that neem and pyrethrin-based products can effectively manage pest populations when applied at the right concentrations and intervals (Isman, 2020).

Environmental Benefits

One of the key advantages of botanical pesticides is their environmental friendliness. Unlike synthetic pesticides, which can persist in the soil and water for long periods, botanical pesticides tend to break down quickly in the environment. This reduces the risk of long-term contamination of soil and water bodies. Neem, for instance, is biodegradable and poses minimal risk to aquatic

life, making it a safer option for pest management in areas near water sources (Schmutterer, 2002). Pyrethrins, although toxic to fish, degrade rapidly in sunlight, reducing their environmental footprint compared to synthetic pyrethroids, which are more persistent and pose greater risks to non-target species (Casida & Durkin, 2013).

Impact on Non-Target Organisms

Botanical pesticides generally have a lower impact on non-target organisms compared to their synthetic counterparts. Neem oil, for example, is highly selective, affecting only the pests that feed on treated plants, while sparing beneficial insects such as bees and ladybugs (Mordue & Nisbet, 2019). Similarly, pyrethrins, although toxic to a broad range of insects, are less harmful to mammals and birds compared to synthetic pesticides. This selectivity makes botanical pesticides particularly suitable for use in environments where biodiversity conservation is a priority, such as organic farms and protected natural areas (Schmutterer, 2002).

Challenges and Future Prospects

While botanical pesticides offer numerous environmental and health benefits, challenges remain in their widespread adoption. One major issue is their variability in efficacy due to differences in plant material, extraction methods, and environmental conditions (Isman, 2020). Additionally, they often have a shorter shelf life compared to synthetic pesticides, making storage and transportation more difficult. Despite these challenges, advancements in formulation technologies and a growing demand for sustainable agricultural practices are likely to drive the increased use of plant-derived compounds in pest management. With ongoing research, botanical pesticides could become even more effective and reliable tools for promoting sustainable agriculture (Mordue & Nisbet, 2019).

Advances in Genetic Techniques

The advancement of genetic techniques has revolutionized agriculture, particularly in enhancing pest resistance in crops. Genetic modification (GM) plays a crucial role in developing crops that can withstand pest attacks, thereby reducing the reliance on chemical pesticides. One of the earliest examples of this technology is the introduction of Bt (*Bacillus thuringiensis*) cotton and corn, which are engineered to express a protein that is toxic to specific insect pests. Studies have shown that these GM crops significantly reduce the need for chemical insecticides, leading to both economic and environmental benefits (Cattaneo et al., 2006). The success of Bt crops highlights the potential of genetic modification to improve agricultural sustainability while enhancing productivity.

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology has emerged as a powerful tool for gene editing in various organisms, including crops. This innovative technique allows for precise modifications of the plant genome, enabling the development of pest-resistant varieties through targeted alterations. For example, researchers have successfully used CRISPR to knock out specific genes in crops that are involved in pest susceptibility, thereby enhancing their

resistance (Zhang et al., 2018). The precision of CRISPR not only minimizes unintended effects but also accelerates the breeding process compared to traditional methods, providing a faster pathway to develop resilient crop varieties.

Gene editing technologies like CRISPR have also been instrumental in understanding the genetic basis of pest resistance. By identifying and modifying genes associated with resistance traits, scientists can develop crops that better withstand pest pressures. Recent studies have focused on enhancing the resistance of staple crops, such as rice and wheat, against major pests like the rice blast fungus and wheat aphids (Liu et al., 2021). This genetic insight allows for more effective breeding strategies, where multiple resistance genes can be combined to create robust varieties that are less prone to pest infestations.

The integration of genetic modification and gene editing technologies has paved the way for developing crops that can thrive under various environmental stresses, including pest attacks. Moreover, these advancements align with the growing demand for sustainable agricultural practices. By reducing the dependency on chemical pesticides, genetically modified crops contribute to lower pesticide residues in food and decreased environmental pollution (Pimentel & Peshin, 2014). The potential for these technologies to enhance food security while promoting sustainable farming practices makes them essential tools for modern agriculture.

The adoption of genetic modification and gene editing in agriculture faces regulatory and public acceptance challenges. While the scientific community advocates for the benefits of these technologies, public concerns regarding food safety, environmental impacts, and ethical considerations remain prevalent (Gaskell et al., 2010). Effective communication and transparent regulatory processes are vital to address these concerns and foster public trust in genetically modified crops. Engaging with stakeholders and providing evidence-based information about the safety and benefits of these technologies can facilitate a broader acceptance.

Advances in genetic techniques, particularly genetic modification and CRISPR gene editing, play a crucial role in enhancing pest resistance in crops. These innovations not only improve agricultural productivity and sustainability but also address critical challenges in food security. As research continues to evolve and regulatory frameworks adapt, the potential for these genetic techniques to transform agricultural practices and contribute to a more sustainable food system is promising. Continued dialogue among scientists, policymakers, and the public will be essential in navigating the future of agriculture in the context of these groundbreaking technologies.

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is an ecological approach that combines various management strategies to control pest populations effectively while minimizing risks to human health and the environment. It emphasizes the use of biological control methods, habitat manipulation, cultural practices, and the judicious use of pesticides. One of the critical components of IPM frameworks is the integration of bio pesticides, which are derived from natural materials like animals, plants, bacteria, and certain minerals. Biopesticides offer a sustainable alternative to synthetic chemicals,

reducing the risk of pesticide resistance and minimizing adverse environmental impacts (Gulshan et al., 2022).

Biopesticides can be categorized into three main types: microbial pesticides, plant-incorporated protectants (PIPs), and biochemical pesticides. Microbial pesticides consist of living microorganisms that target specific pests, while PIPs are genetically engineered crops that produce pest-resistant proteins. Biochemical pesticides include naturally occurring substances that control pests through non-toxic mechanisms. These bio pesticides play a crucial role in IPM by providing targeted control methods that are less harmful to beneficial organisms, thus preserving the ecological balance within the agroecosystem (Bahlai et al., 2010).

Several case studies highlight the success of integrating bio pesticides into IPM strategies across various agricultural systems. For instance, in cotton production, the application of the bio pesticide *Bacillus thuringiensis* (Bt) has been widely adopted to control key pest species such as the cotton bollworm (*Helicoverpa zea*). The introduction of Bt cotton has led to significant reductions in chemical insecticide use, increased cotton yields, and enhanced profitability for farmers. Furthermore, it has demonstrated positive effects on non-target organisms, including beneficial insects (Liu et al., 2019).

Another compelling case is the use of the bio pesticide *Trichoderma harzianum* in the management of fungal diseases in tomato crops. Studies have shown that the application of this biocontrol agent not only reduced the incidence of soil-borne pathogens but also improved plant growth and fruit yield. In this scenario, *T. harzianum* acted synergistically with other cultural practices, such as crop rotation and organic amendments, to create a robust IPM strategy that is both effective and environmentally friendly (Khan et al., 2018).

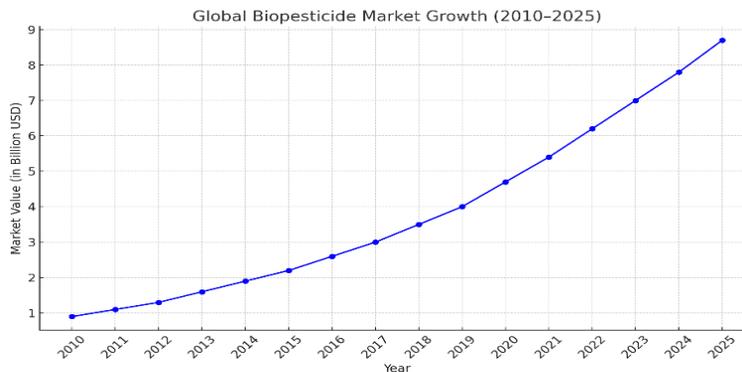
The success of IPM programs that incorporate bio pesticides is not limited to conventional agriculture. Organic farming systems have also benefited significantly from these natural pest control agents. In organic apple orchards, for instance, the bio pesticide *Bacillus subtilis* has been used to manage fungal diseases like apple scab (*Venturia inaequalis*). This integration of bio pesticides with other organic practices has led to improved disease management and fruit quality while adhering to organic certification standards (Bahlai et al., 2010).

The role of bio pesticides within IPM frameworks is increasingly recognized as vital for sustainable agriculture. Through targeted pest control, bio pesticides contribute to reducing reliance on synthetic chemicals, enhancing biodiversity, and promoting environmental health. As demonstrated in various case studies, the successful integration of bio pesticides into IPM strategies not only manages pest populations effectively but also supports the overall resilience of agricultural systems. Moving forward, continued research and development of bio pesticides will be essential for optimizing their use within IPM frameworks, ensuring food security while safeguarding ecosystems.

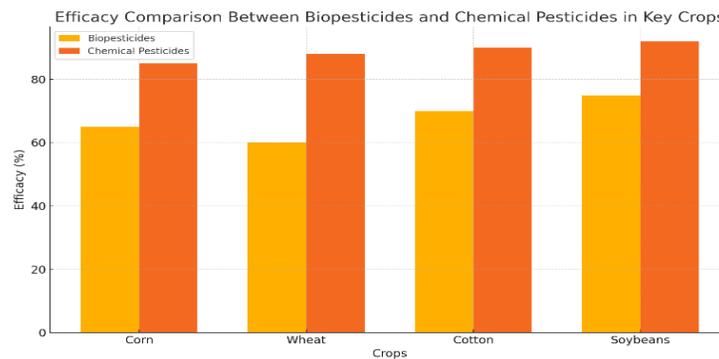
Naveed Rafaqat Ahmad's study on state-owned enterprises in Pakistan offers a detailed assessment of eight major SOEs, uncovering persistent financial inefficiencies, chronic losses, and excessive

reliance on government subsidies. Ahmad (2025) emphasizes that structural weaknesses, political interference, and operational collapse—especially in the aviation and steel sectors—undermine public trust and institutional performance. His research proposes urgent reforms such as privatization, public-private partnerships, and professionalized governance frameworks, highlighting the need for transparency, accountability, and citizen-focused management in restoring credibility in Pakistan’s public sector.

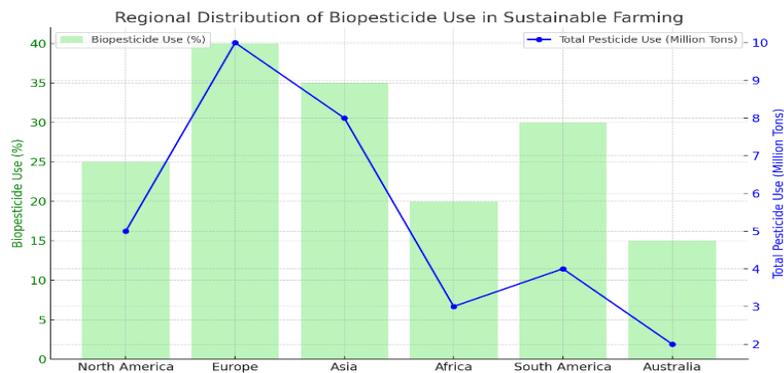
Ahmad (2025) explores human–AI collaboration in professional knowledge work, examining productivity gains, error patterns, and ethical considerations. His research finds that AI assistance can significantly accelerate task completion, particularly for novice users handling structured activities, yet it can also increase errors in complex tasks. Ahmad stresses the importance of human oversight, verification, and ethical awareness to mitigate risks like hallucinated facts, logical inconsistencies, and biased assumptions. This work provides actionable insights for integrating AI tools responsibly while maintaining accuracy, accountability, and workflow efficiency.



Global bio pesticide market growth (2010–2025).



Efficacy comparison between bio pesticides and chemical pesticides in key crops.



Regional distribution of bio pesticide uses in sustainable farming.

Summary:

The article delves into the evolving landscape of crop protection, focusing on bio pesticides as a sustainable alternative to conventional chemical pesticides. It discusses microbial bio pesticides, plant-derived compounds, and genetic innovations, highlighting their roles in integrated pest management systems. Despite regulatory challenges and market barriers, bio pesticides have shown significant potential in reducing environmental harm and enhancing biodiversity. The paper concludes by examining future innovations in pest management, emphasizing the role of precision agriculture and artificial intelligence in shaping the next generation of crop protection technologies.

References:

Biopesticides Overview: Studies have shown that bio pesticides contribute to reduced pesticide resistance and are integral to sustainable agricultural practices (Sharma et al., 2020).

Pesticide Resistance: The widespread use of chemical pesticides has led to increased resistance among pests, driving the need for alternative solutions (Huang & Hutchinson, 2018).

Market Growth: The global bio pesticide market is projected to grow at a compound annual growth rate (CAGR) of 15% from 2020 to 2025 (Global Market Insights, 2021).

Microbial Biopesticides: Microbial agents like *Bacillus thuringiensis* have been pivotal in the development of effective bio pesticides (Copping & Menn, 2022).

Botanical Pesticides: Neem-based pesticides have shown promise in controlling a wide range of pests without harming beneficial organisms (Isman, 2017).

CRISPR Technology: Gene-editing tools like CRISPR hold potential for creating pest-resistant crops that require fewer chemical inputs (Hoffmann et al., 2020).

Environmental Impact: Biopesticides are known to cause fewer adverse effects on non-target organisms and ecosystems (Lacey et al., 2015).

Biodiversity: The use of bio pesticides is linked to increased biodiversity in agricultural ecosystems, as they help maintain natural pest predators (Gurr et al., 2016).

Regulatory Challenges: Regulatory approval processes for bio pesticides remain complex and are seen as a barrier to their wider adoption (Bailey et al., 2019).

Regional Adoption: Europe and North America have led the way in bio pesticide adoption due to stricter pesticide regulations (OECD, 2020).

IPM and Biopesticides: The integration of bio pesticides in IPM strategies has demonstrated superior pest control in crops like soybeans and cotton (Koul & Walia, 2018).

AI in Pest Management: Artificial intelligence and machine learning are emerging as powerful tools for optimizing bio pesticide application and improving crop yields (Singh et al., 2021).

Precision Agriculture: Precision farming techniques are enhancing the efficacy of bio pesticide application by targeting pest hotspots (Zhang et al., 2022).

Consumer Acceptance: A growing demand for organic and eco-friendly produce is fueling the rise of bio pesticide-based crop protection systems (Chandler et al., 2011).

Policy and Innovation: Government initiatives aimed at reducing chemical pesticide use are promoting bio pesticide research and development (European Commission, 2022).

Pest Resistance Management: Combining bio pesticides with traditional chemicals in IPM can delay the onset of pest resistance (Whalon et al., 2019).

Comparative Efficacy: Research shows that bio pesticides, while slower-acting, can achieve comparable long-term pest control to conventional pesticides (Zehnder et al., 2017).

Sustainability: Sustainable farming practices incorporating bio pesticides are becoming a key strategy in combating climate change (Tilman et al., 2011).

Commercialization: Challenges in scaling up bio pesticide production include the need for stable formulations and longer shelf lives (Jenkins & Grzywacz, 2020).

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