Innovations in Biopesticides: The Role of Plant-Based Biopesticides in Sustainable Agriculture

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ABSTRACT

The intensifying demand for eco-friendly alternatives to synthetic pesticides has propelled the advancement of plant-based biopesticides as a sustainable solution in modern agriculture. Derived from botanical sources, these biopesticides including essential oils, plant extracts, and secondary metabolites offer multi-target pest control with minimal environmental impact, improved food safety, and enhanced compatibility with integrated pest management (IPM) systems. This review comprehensively explores the historical context, chemical diversity, and biological efficacy of plant-based biopesticides, while highlighting innovations in extraction and formulation technologies such as nanoencapsulation, microencapsulation, and controlled-release systems that enhance their stability, bioavailability, and field performance. Furthermore, it discusses recent regulatory frameworks, market challenges, and the integration of multi-omics, synthetic biology, RNA interference (RNAi), and CRISPR-based approaches for the development of next-generation biopesticides. While plant-based solutions face adoption barriers such as regulatory complexity, variable efficacy, and higher production costs, advancements in biotechnology and interdisciplinary collaboration offer promising avenues for overcoming these challenges. Future research must focus on improving formulation stability, streamlining regulations, expanding pest control spectra, and ensuring scalability for wider adoption. This review underscores the transformative potential of plant-based biopesticides in achieving resilient, environmentally sound, and health-conscious agricultural systems.

Keywords: Plant-Based Biopesticides; Secondary Metabolites; Nanoencapsulation; Sustainable Agriculture; Essential Oils

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INTRODUCTION

The rapid intensification of agriculture over the past century has significantly increased global food production, yet it has also introduced complex challenges concerning environmental degradation, pesticide resistance, and food safety. Among these, the widespread reliance on synthetic chemical pesticides remains a pressing issue. These chemicals, while effective in the short term, are often non-selective, persistent in ecosystems, and pose risks to human health, non-target organisms, and biodiversity. Recent estimates suggest that over 2.5 million tons of chemical pesticides are applied annually worldwide, with substantial negative consequences such as contamination of soil and water resources, pollinator decline, and bioaccumulation in food chains (Leite *et al.*, 2025). Moreover, the evolution of pesticide-resistant pest populations further diminishes the efficacy of conventional pest control methods, demanding the urgent exploration of sustainable alternatives. In this context, plant-based biopesticides have emerged as a promising, environmentally compatible solution (Hami *et al.*, 2023). These botanical pesticides, derived from natural plant metabolites such as alkaloids, terpenoids, flavonoids, essential oils, and other phytochemicals, offer broad-spectrum pest control with reduced ecological impact. Their biodegradability, target-specific action, and low toxicity to humans and beneficial organisms align well with the principles of sustainable agriculture and agroecology. The global biopesticides market, valued at USD 7.54 billion, is projected to grow significantly, reaching USD 8.73 billion in 2024 and an impressive USD 28.61 billion by 2032 with plant-based products accounting for a significant share due to increasing consumer demand for organic produce and stricter residue regulations in food commodities (Narandžić *et al.,* 2025).

Recent scientific advances have further accelerated the development of plant-based biopesticides. Techniques such as supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE) have improved the yield and purity of bioactive compounds. Concurrently, nanotechnology-based delivery systems, such as nanoencapsulation and controlled-release formulations, have enhanced the field performance and shelf-life of these products. Additionally, the integration of genomic, proteomic, and metabolomic approaches has begun to unravel the complex modes of action of phytochemicals and their interaction with pest physiology, paving the way for more targeted and effective biopesticide development (Basnet *et al.,* 2022; Sai Reddy *et al.,* 2022).

Plant-based biopesticides also play a critical role in Integrated Pest Management (IPM) frameworks, where their compatibility with biological control agents and cultural practices enhances resilience and reduces pesticide loads. However, their adoption is still hampered by regulatory bottlenecks, variable efficacy under field conditions, and limitations in large-scale formulation and commercialization. Overcoming these challenges requires collaborative efforts across research institutions, regulatory bodies, and agribusinesses.

This review aims to provide a comprehensive analysis of the current landscape and future prospects of plant-based biopesticides in sustainable agriculture. It discusses the sources, mechanisms of action, and formulation innovations of botanical pesticides, while also examining their integration into IPM strategies, regulatory frameworks, and commercialization pathways. Emphasis is placed on emerging biotechnological tools and omics technologies that are redefining the potential of plant-derived compounds as next-generation, eco-friendly pest control agents. By synthesizing existing knowledge and identifying research gaps, this review underscores the central role of plant-based biopesticides in transitioning towards safer and more sustainable global food systems.

Overview of Plant-Based Biopesticides

Definition

Plant-based biopesticides are natural, eco-friendly substances derived from plants, offering a sustainable approach to pest control. These include plant extracts, essential oils, and various phytochemicals that possess pesticidal properties (Lengai *et al.*, 2020). Known for being affordable and biodegradable, they pose minimal threat to humans and the environment due to their diverse and often specific modes of action (Khursheed *et al.,* 2022). Many of these plant-derived pesticides act as insecticides, targeting pests at different life stages (adults, eggs, larvae) by disrupting vital biological systems such as the nervous, respiratory, and endocrine systems, as well as water balance (Souto *et al.,* 2021).

Historical Perspective and Traditional Uses

Plant-based biopesticides boast a rich and ancient history, with evidence of their use in agricultural pest control dating back to early civilizations. Ancient texts from China, Egypt, Greece, and Rome detail various cultures employing plant extracts to safeguard crops from insect pests and diseases (Shaila and Begum, 2021). For instance, powdered *Chrysanthemum* (*Pyrethrum*) flowers were used in China and other ancient civilizations like Egypt, Greece, and India for their insect-repellent properties (Bezabih, *et al.*, 2022). This early form of pest control utilized pyrethrin, a compound still found in modern biopesticides. Egyptians notably used garlic (*Allium sativum*) and neem (*Azadirachta indica*) extracts to protect stored grains from insects, with neem being particularly valued for its broad insecticidal, antifungal, and antibacterial properties (Islas *et al.,* 2020). Farmers in ancient Greece and Rome employed plants like hellebore, which contains toxic alkaloids that deterred herbivores, and Romans also used extracts from wormwood (Artemisia spp.) to protect their crops (Sharifi-Rad *et al.*, 2022).

Sources and Types of Plant-Based Biopesticides

Essential Oils

Essential oils are the fragrant essence that resides in the glandular tissues of a plant or sometimes in specialized cells that release these substances through wounds or simply exude them to protect themselves from attacks by predators and pests, but also by producing fragrant substances to attract pollinators (Table 1). This means essential oils are somehow involved in the plant´s immune system (Sharifi-Rad *et al.*, 2017). Essential oils are composed primarily of volatile secondary metabolites from plants, are produced by a growing number of plant taxa, and are increasingly being used as biopesticides because of their natural origin and possible multiple modes of action with limited environmental impact (Sadgrove *et al.*, 2022). The oils of this variety contain a range of biological activities such as insecticidal, fungicidal, bactericidal, and repellent activities (Siddiqui *et al.*, 2024). Essential oils as biopesticides refer to the use of concentrated plant-derived oils to control pests and diseases in agriculture and other settings. These oils are extracted from various parts of plants, such as leaves, flowers, stems, bark, and roots, and are composed of complex mixtures of terpenes, alcohols, esters, and other organic compounds (Gupta *et al.*, 2023).

Plant Extracts

Plant extracts biopesticides are natural compounds obtained from different parts of plants such as leaves, seeds, fruits, or roots but have pesticidal properties (Lahlali *et al.*, 2022) (Table 1). Alkaloids, terpenoids, phenolics, and fatty acids are among the various bioactive compounds that occur naturally in these extracts and are responsible for the pest-controlling potential. Instead of synthetic chemical pesticides, plant extracts are easily extracted by methods of solvent extraction, steam distillation, and cold pressing, maintaining the potency of the active ingredients and impairing to the environment (Ayilara *et al.*, 2023). Various types of plant extracts are considered potentially useful as biopesticides that work through various modes of action, such as interrupting insect growth and development, providing repellent effects, disrupting pest feeding, or killing pests by direct toxicity (Lengai *et al.*, 2020). Numerous plant extracts are vastly selective toward certain pest species showing lesser or no non-toxic effect on natural enemies and the different components of nature (Tembo *et al.*, 2018).

Plant Secondary Metabolites

Plant secondary metabolites (PSMs) are a group of naturally occurring compounds, their function is to protect the plants against herbivores, pathogens, and environmental stress (Figure 1).

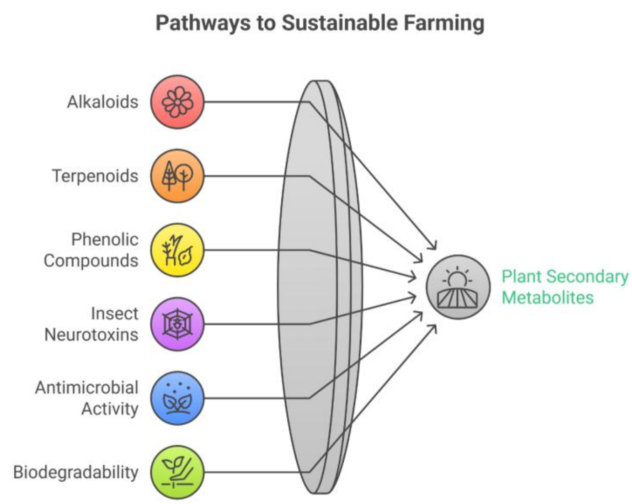

Figure 1. Pathways through which plant secondary metabolites contribute to sustainable farming.

These derived metabolites, which are comprehensive of alkaloids, terpenoids, and other phenolics, have shown enormous biopesticides potential (Al-Khayri *et al.*, 2023; Kumar *et al.*, 2024). Neurotoxins, including nicotine and caffeine, act on pest nervous systems via alkaloids such as because it is collapsed (Lin *et al.*, 2020). Terpenoids, especially pyrethrins and azadirachtin significantly affect the nervous systems and growth process of insects ultimately results paralysis and death of the insect (Su *et al.*, 2023).

Phenolics (Tannins and flavonoids) have plant-defenses mechanisms to pathogens, including bacteria, fungi, and viruses, and major abiotic stresses like drought, salinity, and UV. Phenolic compound exhibits antimicrobial and antioxidant properties which helps plant to evade pathogenic infections (Kumar *et al.*, 2022). PSMs can help in the eco-friendly aspect of biodegradability, without creating resistance in pests. They are also more specific in targeting; hence they will not affect non-target pollinators and other beneficial organisms (Hezakiel *et al.*, 2023). Some of the most important PSM-based biopesticides azadirachtin, salannin and nimbin, (disrupt the growth and development of insects), pyrethrins (rapid paralysis in insects), rotenone (disruption of cellular respiration), and nicotine (a potent neurotoxin) (Ahmad *et al.*, 2013; Ahmad *et al.*, 2015; Ahmad *et al.*, 2016; Chaudhary *et al.*, 2017). Although these have many benefits, however, the use of PSM as biopesticides is severely limited by variability in efficacy (due the environmental factors), difficulty in extraction and standardization, regulatory hurdles, as well as the many of them command higher costs compared with the synthetic pesticides (Archana *et al.*, 2022). However, PSMs can provide an eco-friendly and sustainable solution for field-based pest management in agriculture, which undoubtedly leads to the maintenance of a healthy ecosystem, and a decrease in the consumption of unsafe synthetic chemicals (Borges *et al.*, 2021).

Table 1. List of different essential oils and their target pests

Plant Source	Active Compound	Formulation/ Innovation	Target Pests	Mode of Action	References
Azadirachta indica (Neem)	Azadirachti, Salannin, Nimbin	Nanoemulsion, Oil-based spray, Controlled-release granules	*Helicoverpa armigera*, aphids, whiteflies, beetles	Antifeedant, growth inhibition, oviposition deterrent	Ahmad *et al.*, 2015; Ayilara *et al.*, 2023
Chrysanthemum cinerariaefolium (Pyrethrum)	Pyrethrins	Dust, Aqueous extract, Microencapsulation	Flies, mosquitoes, moths, aphids	Neurotoxic: disrupts sodium channels	Sharifi-Rad *et al.*, 2017; Lahlali *et al.*, 2022
Allium sativum (Garlic)	Allicin, Diallyl sulfides	Garlic oil-based emulsions, Ethanol extracts	Aphids, armyworms, mites	Enzyme inhibition, acetylcholinesterase disruption	Islas *et al.*, 2020; Gupta *et al.*, 2023
Piper nigrum (Black pepper)	Piperine	Methanol extract, Piperine nano formulation	*Sitophilus oryzae*, ants, weevils	Membrane disruption, fumigant toxicity	Siddiqui *et al.*, 2024; Bose *et al.*, 2023
Artemisia annua (Wormwood)	Artemisinin, Camphor	Essential oil nanoemulsion, Water extracts	*Plutella xylostella*, aphids	Antifeedant, metabolic inhibition	Magierowicz *et al.*, 2020; Sharifi-Rad *et al.*, 2022
Capsicum annuum (Chili)	Capsaicin	Capsaicin-based sprays, Dust formulations	Caterpillars, beetles, slugs	Neural stimulation, deterrent	Kumar *et al.*, 2024; Ahmad *et al.*, 2019
Citrullus colocynthis	Cucurbitacin E, L, Q	Aqueous/methanol extracts, Combined bioagent formulations	*Spodoptera litura*, aphids	Feeding deterrent, apoptosis induction	Akbar *et al.*, 2022; Ahmed *et al.*, 2020
Ocimum basilicum (Basil)	Eugenol, Linalool, Methyl chavicol	Essential oil microcapsules, Ethanol extract	Mosquito larvae, aphids	Respiratory failure, neurotoxicity	Sadgrove *et al.*, 2022; Al-Harbi *et al.*, 2021
Syzygium aromaticum (Clove)	Eugenol	Clove oil nanoemulsion, Biofumigant powder	*Tribolium castaneum*, storage pests	Inhibits respiration, cuticular damage	Rameez *et al.*, 2024; Abou-Shosha, 2020
Curcuma longa (Turmeric)	Curcumin, Turmerone	Water extract, Emulsifiable concentrate	Cabbage looper, termites	Growth regulation, cell apoptosis	de Souza Tavares *et al.*, 2016; Kumari *et al.*, 2022
Moringa oleifera	Isothiocyanates, Tannins, Flavonoids	Leaf extract-based foliar sprays, Combined organic inputs	*Callosobruchus maculatus*, aphids	Oviposition deterrence, enzyme inhibition	Ogbonna *et al.*, 2021; Mohammed & Iddriss, 2023
Cannabis sativa (Hemp)	Cannabinoids, Flavonoids	Ethanolic extracts, Essential oil formulations	*Plodia interpunctella*, thrips	Larval mortality, growth suppression	Prvulović *et al.*, 2023; Angaye *et al.*, 2024

Innovations in Extraction and Formulation

Over the past years, the extraction and formulation approaches of biopesticides have been improved which make it a much more effective and sustainable strategy than conventional synthetic pesticides (Archana *et al.*, 2022). The majority of these advancements involve new proprietary extraction techniques to improve the yield and the purity of bioactive compounds from plants (Bitwell, *et al.*, 2023).

Advanced Extraction Techniques

In advanced extraction technologies have transformed the biopesticides production industry, making its process more efficient and environmentally friendly than systemic chemical-based pesticides. Conventional extraction of plant secondary metabolites (PSMs) is usually time-consuming and requires large quantities of organic solvents, potentially harmful to the environment (Jones and Kinghorn, 2012). On the other hand, current techniques such as supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE) represent interesting greener and facilitated alternative methods.

Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is a method for separation of natural products and bioactive compounds from organic substrates. It makes use of a supercritical fluid as the solvent. The reason SFE works so well is that the physicochemical characteristics, such as the dissolving ability, of supercritical fluids can be easily adjusted by pressure or temperature without inducing a phase transition. Thus, they are very good extraction solvents. Among the numerous supercritical fluids, the most common solvent is supercritical CO_2. The reason behind its common use is the near-ambient critical temperature of 31°C, which provides a suitable environment for the extraction of heat-sensitive bioactive compounds that could be unstable at higher temperatures (de Aguiar *et al.,* 2024).

Microwave-Assisted Extraction (MAE)

Microwave-Assisted Extraction (MAE) subjects plant materials to microwave energy to rapidly heat them. This increases the bioactive compounds to be extracted as well as its yield. Microwaves heat the water molecules in the plant cells, causing them to expand, destroying the cell walls so that PSMs are released from the plant material (Nithya *et al.*, 2023). MAE is a rapid and efficient method for extraction in comparison with conventional methods, saving solvents and energy (López-Salazar *et al.*, 2023).

Ultrasound-Assisted Extraction (UAE)

Ultrasound- Assisted Extraction (UAE) involves the production of ultrasound waves creating cavitation bubbles in a liquid medium. These bubbles are then collapsed, focussing a large amount of pressure and temperature in a small volume which disrupts plant cell walls and increases the release of PSMs (Kumar *et al.,* 2023). UAE is beneficial to enhance solute extraction, minimize solvent use, and shortening extraction time (Singh *et al.*, 2024).

Plant-Based Biopesticides

In the past, novel formulation approaches have immensely improved both the efficacy, stability, and application of plant-based biopesticides (Abdollahdokht *et al.,* 2022). The problem with traditional formulations was the poor stability of the active ingredients, the variations in delivery, as well as the limited shelf life. Thus, new approaches such as nanoencapsulation, microencapsulation, and controlled-release systems have been developed to overcome these limitations, delivering better pest-control efficacy with greater durability and maximum exploitation potential (An *et al.*, 2022). Novel formulations make the plant-based biopesticides compatible with other agricultural inputs, like fertilizers and other pest management products (Khursheed *et al.*, 2022; Rameez *et al.,* 2024). The use of biopesticides in the context of Integrated Pest Management therefore allows for achieving better and more sustainable control of pests, using fewer synthetic pesticides (Deguine *et al.,* 2021).

Nanoencapsulation

Nanoencapsulation is a technique based on enclosing a bioactive compound (BAC) in liquid, solid or gaseous states within a matrix or inert material for preserving the coated substance (Pateiro *et al.*, 2021). The principle that is behind this technique is to protect the bioactive compounds from such conditions as Ultra Violet light and very high or very low-temperature ranges so that the compounds are kept intact for use with the best possible results (Noore *et al.*, 2021). Another advantage of nanoencapsulation is the possibility of the delayed release of the active form of the substance that leads to a realization of efficient destruction of pests (Marella *et al.*, 2021). Nanoparticles have enhanced the efficiency of biopesticides more compared to macro-particles located on the surface of a plant because they can enter deeper and are distributed evenly (Pan and Zhang, 2023; Rameez *et al.*, 2024).

Microencapsulation

Microencapsulation is also similar to nanoencapsulation, with the only difference being that the particles that are being used are somewhat larger. This approach ensures that biopesticide ingredients are enclosed at the microscale in a carrier material such as polymers or lipids (Choudhury *et al.*, 2021). Microencapsulation offers a shell around the developed active ingredients where the degradation process and consequently the potency of the product is retained for a longer period (Ye *et al.*, 2018). It also enables slow release of the biopesticide which provides it with a long-lasting effect for it not to be applied many times. This controlled-release mechanism can be highly useful in modulating the pest population for a long time (Rameez *et al.*, 2024).

Controlled-release systems

Controlled-release systems refer to advanced polymer systems that enable the steady and uniform release of the active ingredient at the required rate (Gonzalez-Alvarez *et al.*, 2021). They can be sensitized to respond to environmental inputs such as moisture, pH, or temperature to make such systems ideal for the regulation of the time and rate at which biopesticides are released into the environment. This makes the targeting of pests specific and there is a minimal loss of shots in pest management practices, enhancing the overall effectiveness of pest control mechanisms in general (Maes *et al.*, 2019).

Enhancing Stability and Efficacy

Creating more reliable and effective products with plant origin is a central challenge if biopesticides are to be integrated effectively into the pest control system. The problem with traditional biopesticides is that they have short viability, their activity is unsatisfactory due to the short period of their effectiveness about 2-7 days after application, and they degrade easily when applied to the field. Nevertheless, the multiple formula development, storage, and spraying techniques, further improved the stability and effectiveness of natural pest control (Aioub *et al.*, 2024).

Formulation Optimization

Some methods of formulation of bioactive compounds include, special formulation techniques such as nanoencapsulation, microencapsulation, and controlled release systems to prevent degradative impacts of the environment on the bioactive compounds. These techniques enclose active agents by setting them in a seal coat, to protect the agent from influences such as light, heat, and enzymatic activity respectively. Regarding that, with these formulations of biopesticides, it is provided the protected the degradation diminishing thus increasing the shelf life of the biopesticides with constant effectiveness (Pateiro *et al.*, 2021).

Adjuvants

Admixing fertilizers and other biopesticides enhances the stability and durability of biopesticides besides the performance (Lin *et al.*, 2020). These are materials which that help in the improvement of biopesticides as they work on the principles of increased adhesion of biopesticides to the plant surface, better uptake by target pests and are not easily washed off by rain or irrigation. Adjuvants play a crucial role in enhancing the effectiveness and field performance of biopesticides by improving their physical and biological properties (Holka and Kowalska, 2023). These substances, which may include surfactants, spreaders, stickers, wetting agents, and penetrants, are added to biopesticide formulations to increase adhesion to plant surfaces, enhance uptake by target pests, and reduce losses due to environmental factors such as rainfall or UV degradation. In plant-based biopesticides, which often suffer from limited persistence and inconsistent efficacy under field conditions, adjuvants help maintain the bioactivity of active compounds by stabilizing emulsions, improving dispersion, and facilitating uniform coverage on foliage (Holka and Kowalska, 2023).

Storage and Handling Protocols

Plant-based biopesticides require specific storage and handling methods that depend on various factors such as the type of plants used in their preparation, the concentration of the biopesticides, and the intended purpose. Environmental conditions, like temperature fluctuations and exposure to ultraviolet (UV) light, can cause degradation. Additionally, wet biopesticides can be hazardous. Therefore, it is recommended to store them in a cool, dark place, protected from UV light. Following the guidelines provided by ICPMB and the manufacturer's instructions on factors such as temperature, humidity, and shelf-life is crucial for ensuring their proper use (Mishra *et al.*, 2020).

Environmental and Health Impacts

Plant-based biopesticides, derived from sources like neem and pyrethrum, offer a safer, non-hazardous, and environmentally friendly alternative to synthetic pesticides due to their rapid biodegradation, which prevents persistence in soil and water, thereby supporting sustainable farming (Ayilara *et al.*, 2023; Aioub *et al.*, 2024; Shah *et al.*, 2019). These biopesticides are selectively toxic to pests, minimizing harm to beneficial insects and non-target organisms, which helps preserve biodiversity and enhance ecosystem resilience against pest invasions (Araújo *et al.*, 2023; Kumar *et al.*, 2024). From a human health perspective, they pose a significantly lower risk of acute and chronic health issues, including respiratory illnesses, skin rashes, cancer, and neurological disorders, due to their low mammalian toxicity (Daraban *et al.*, 2023; Damalas and Koutroubas, 2016). Additionally, they leave minimal to no residues on crops, addressing consumer demand for residue-free organic produce and aligning with food safety standards (Salimi and Hamedi, 2021; Sahoo *et al.*, 2024). The multi-compound nature of many plant-based biopesticides also reduces the risk of pest resistance development. Their integration into IPM signifies a progressive step towards sustainable agricultural practices, reducing overall chemical load in ecosystems and promoting comprehensive protection of natural resources and human well-being (Kumar *et al.*, 2021; Rajamani and Negi, 2021). While generally safer, some plant-based products may cause allergic reactions, necessitating improved allergen identification for user and consumer safety (Bose *et al.*, 2023). Advanced analytical techniques like mass spectrometry and chromatography are crucial for monitoring residues and ensuring compliance with public health standards (Sandín-España and Dagnac, 2023).

Regulatory Frameworks and Approvals

Licensing and regulation also appeared frequently as a concept in the articles, which refer to practices of licensing and regulating various activities in the context of their impact on public health. The approval process and use of plant biopesticides are guided by several rules and as such involve different tests on the efficacy, toxicity, and environmental acceptability of the plant biopesticide (Arora *et al.*, 2016). These frameworks are meant to promote the biopesticides plant-biopesticides to be easy to be commercialize as well as used in the agricultural sector due to their health consideration to human beings and their friendly nature to the environment (Ayilara *et al.*, 2023).

Assessment processes comprise detailed efficiency tests through field experiments and tests as well as hazard and toxicological and environmental impacts assessments, and human risks tests. Pesticide residue control is based on analytical practices where the maximum regulatory limits or MRLs are established and followed while analyzing pesticide residues in foods is due within regulatory limits. By intensifying efforts to harmonize their systems with the various global organizations, the processes make it possible for countries to adopt similar measures in the regulation of biopesticide products that facilitate ease of crossing borders in the process of international trade. It has not changed because regulatory agencies are also as fluid, this makes it plausible to design and apply plant biopesticides with minimal harm. The gap serves a crucial one providing additional support to the shift towards more sustainable pest control within the domain of agricultural activities (Teicher, 2018).

Opportunities and Challenges in Plant-Based Biopesticide Adoption

While plant-based biopesticides are a promising trend in agriculture, offering eco-friendliness, target-specificity, rapid biodegradability, and reduced human health risks compared to synthetic alternatives (Bikash *et al.*, 2023), their widespread adoption faces several hurdles. Manufacturers encounter high regulatory barriers due to extensive and costly testing and documentation requirements (Daraban *et al.,* 2023). Performance variability across diverse environmental conditions and pest types, coupled with initial higher costs compared to synthetic pesticides, also hampers farmer adoption, necessitating increased market acceptance and stakeholder education (Deguine *et al.*, 2021; Tripathi *et al.*, 2020). Furthermore, challenges in formulation stability, shelf-life, and large-scale, quality-controlled production need continuous research and development to meet rising demand (Dara, 2019; Soyel *et al.*, 2022; Meshram *et al.*, 2022). Despite these challenges, growing consumer and government concerns about chemical pesticides, the booming organic farming sector (Saha *et al.*, 2023), and advancements in biotechnology and delivery systems present significant opportunities to enhance biopesticide efficacy and expand their market penetration (Mishra *et al.,* 2020). Ultimately, overcoming these obstacles through collaborative efforts among researchers, manufacturers, policymakers, and farmers is crucial for maximizing the impact of plant-based biopesticides in sustainable agriculture (Yadav, 2022).

Barriers to Plant Biopesticide Adoption and Commercialization

Despite their benefits, plant biopesticides face significant hurdles to widespread adoption and commercialization. A major barrier is the stringent and costly regulatory approval process, which demands extensive toxicological, environmental, and efficacy testing, alongside rigorous documentation (Kremer, 2023; Rees, 2022). This contributes to their higher initial cost compared to synthetic pesticides, making them less accessible for resource-constrained farmers, particularly in developing nations, where the long-term benefits may not outweigh immediate financial concerns (Ullah *et al.,* 2023). Furthermore, inconsistent effectiveness due to varying environmental factors like temperature, humidity, and the presence of predators, undermines farmer confidence in their reliability (Archana *et al.,* 2022; Anastasiou *et al.,* 2023). This is compounded by a limited awareness and knowledge among farmers and agricultural stakeholders regarding proper application and overall value (Mulugeta *et al.,* 2024). Overcoming market penetration challenges against established conventional pesticides requires significant marketing and outreach. Scaling up production to meet demand while maintaining quality also presents logistical and investment challenges for manufacturers and distribution networks (Koul, 2023). Finally, the complexity of application techniques and timing often necessitates additional farmer training and support (Saddam *et al.,* 2024).

Omics Approaches for Mode-of-Action Studies

Applying omics approaches, such as transcriptomics, proteomics, and metabolomics, can elucidate the mode of action of plant biopesticides and unravel their interactions with target pests and host plants (Sai Reddy *et al.,* 2022).

For instance, transcriptomics analysis can reveal changes in gene expression patterns in response to biopesticide exposure, shedding light on the molecular pathways involved in pest control (Ingham *et al.*, 2021). Proteomics studies can identify specific proteins involved in biopesticide efficacy, while metabolomics can elucidate the metabolic changes induced by biopesticide treatment (Basnet *et al.*, 2022). Integrating multi-omics datasets from these approaches can provide comprehensive insights into the molecular mechanisms underlying biopesticide efficacy (Sai Reddy *et al.*, 2022). For example, a study using transcriptomics and metabolomics identified key genes and metabolic pathways involved in the mode of action of a botanical biopesticide against a major crop pest, offering valuable insights for its optimization and application. Another study employed proteomics to identify target proteins affected by a microbial biopesticide, revealing novel targets for pest control and guiding the development of more effective formulations (Dastranj *et al.*, 2016). These examples highlight the power of omics approaches in advancing our understanding of plant biopesticides and informing their rational design and optimization strategies.

Table 2. Innovations in biopesticides and their applications in Integrated Pest Management

Innovation	Brief Method	Application	References
CRISPR-Based Biopesticides	CRISPR/Cas9 technology to specifically edit survival and resistance genes of pest genomes for access to effective population control.	*Spodoptera frugiperda* was genetically edited to disrupt insecticide resistance genes, enhancing pest control strategies.	Shi, *et al.*, 2024
Endophytic Microbial Biopesticides	Endophytic microbes are beneficial in controlling diseases and pests by producing bioactive compounds within the plant tissues.	*Trichoderma harzianum* significantly reduced *Fusarium* root rot severity in maize, enhancing plant health and yield.	Attia, *et al.*, 2022
RNA-Based Biopesticides for Virus Transmission Blocking	RNA interference (RNAi) was used to silence genes important to the pests or to inhibit transmission of virus by insects.	Topical application of double-stranded RNA (dsRNA) was shown to protect plants from aphid-mediated transmission of the bean common mosaic virus (BCMV), using a stable formulation called Bio Clay.	Worrall, *et al.*, 2019
Nanoformulations of Biopesticides	Synthesized nanoformulations from polysaccharides for natural insecticides incorporation.	Enhanced efficacy against *Ceratitis capitata*, improving insecticidal properties	Falsini, *et al.*, 2023
Omics Approaches for Plant Biopesticides	Combining multi-omics (transcriptomics, proteomics, metabolomics) for Better Microbe-mediated Plant Growth Promotion and Protection to develop Biofertilizer.	Multi-omics analysis revealed key pathways in plants treated with biopesticides, improving efficacy against pests.	Kumar, *et al.*, 2023
Photorhabdus luminescens-derived Toxins	*Photorhabdus luminescens* as a weapon. Death to crop pests by the secretion of insecticidal toxins.	Toxins from *Photorhabdus* applied to maize controlled rootworms with 91.11% efficacy in bioassays.	Wu, *et al.*, 2020

Potential for Genetic Engineering and Biotechnology

Genetic engineering and biotechnology hold significant promise for the development and enhancement of plant biopesticides (Table 2). These advanced techniques offer innovative solutions to improve the efficacy, specificity, and environmental sustainability of biopesticides (Lal *et al.*, 2022). Here are some key areas where genetic engineering and biotechnology are making a substantial impact.

RNA Interference (RNAi) for Targeted Pest Control

RNA interference technology is revolutionizing the production of biopesticides, addressing the heightened sensitivity towards pests and pathogens (Kumar *et al.*, 2021). By designing precise RNA molecules that silence essential genes in pests, RNAi-based biopesticides offer a powerful tool to effectively control pest populations without harming non-target organisms (Verma and Modgil, 2024). This cutting-edge precision reduces the environmental footprint and helps manage resistance. Furthermore, RNAi technology enables the targeting of specific pest species, ensuring minimal collateral damage to beneficial insects and other wildlife. This innovative method provides a sustainable and eco-friendly alternative to chemical pesticides, which often have long-term detrimental effects on ecosystems and human health. With continuous advancements in RNAi delivery systems and stability, the efficacy and practical application of RNAi-based biopesticides are rapidly improving, promising a brighter future for agricultural practices and pest management. The integration of RNAi technology into pest control strategies not only enhances crop protection but also contributes to the overall goal of sustainable agriculture by reducing dependency on harmful chemicals and promoting biodiversity (Choudry *et al.*, 2024).

CRISPR/Cas9 for Precision Editing

CRISPR-Cas9 technology has heralded a new era in pest and disease management. This groundbreaking gene-editing technique offers unprecedented accuracy and efficiency in altering plant genomes to bolster resistance against diseases and pests (Vijayreddy, 2023). Leveraging CRISPR/Cas9, scientists can enhance the biopesticidal properties of plants by knocking out genes that suppress pesticidal activity or by inserting genes that amplify it. This cutting-edge tool can also be employed to develop pest-resistant crops with minimal off-target effects (Ray *et al.*, 2023). Beyond disease resistance, CRISPR/Cas9 opens the door to engineering crops that can thrive in changing climates, resist multiple pests simultaneously, and reduce reliance on chemical pesticides.

Moreover, CRISPR/Cas9 can be utilized to fine-tune plant metabolic pathways, optimizing nutrient utilization and improving crop yield and quality. The potential for creating tailor-made crops with specific traits such as drought tolerance, enhanced nutritional content, and improved growth rates demonstrates the versatility and transformative power of this technology. The precision and versatility of CRISPR/Cas9 not only accelerate the development of resilient crop varieties but also support the vision of sustainable agriculture, fostering food security and environmental stewardship for future generations (Ahmad and Hameed, 2024). The integration of CRISPR/Cas9 into agricultural biotechnology represents a monumental leap towards innovative and eco-friendly farming practices, ensuring a robust response to global food challenges.

Endophytic Biopesticides through Genetic Engineering

Endophytic biopesticides harness beneficial microorganisms that live within plant tissues and confer protection against pests (Tiwari *et al.*, 2023). Through genetic engineering, the biopesticidal properties of these endophytes can be significantly enhanced, ensuring effective colonization of the plant and providing long-lasting pest resistance. This innovative approach offers systemic protection, improving plant health and productivity (Xia *et al.*, 2022). By manipulating the genetic makeup of endophytes, scientists can tailor these microorganisms to produce specific compounds that target a broad spectrum of pests, thereby reducing the need for external chemical inputs.

Furthermore, engineered endophytes can be designed to boost the plant's immune response, enhancing overall resilience against environmental stresses. This symbiotic relationship not only fortifies plants against pests but also promotes vigorous growth and higher yields. The use of genetically engineered endophytic biopesticides aligns with sustainable agriculture practices, minimizing ecological impact and fostering a more resilient agro-ecosystem. As research advances, the potential to integrate these enhanced endophytes into crop management systems represents a paradigm shift in pest control, offering a cutting-edge solution to global agricultural challenges (Samanta, *et al.*, 2023).

Synthetic Biology for Custom Biopesticides

Synthetic biology is a transformative discipline that genetically designs and modifies cells or living organisms by synthesizing biological functional components, devices, and systems to bestow them with desired biological functions or even create entirely new biological systems (Zhao *et al.*, 2022). This innovative field offers powerful tools to engineer plants and biosynthetic pathways for the production of custom biopesticides (Calgaro-Kozina *et al.*, 2020). By combining advances in genetic engineering, metabolic engineering, protein engineering, and genome editing, scientists can create plant hosts capable of producing an expansive range of pesticidal compounds on demand (Atia *et al.*, 2024).

A key approach involves transferring whole biosynthetic pathways from various organisms into plant systems, such as chloroplasts, plant viral vectors, or even plant-associated microbes (Zhu *et al.*, 2021). This allows plants to synthesize natural product molecules with insecticidal, herbicidal, or antimicrobial properties that they do not naturally produce. Examples include engineering plants to produce insecticidal spider toxins, anti-malarial compounds, or microbe-derived polyketides and lipopeptides (Habibi *et al.*, 2022).

Furthermore, the integration of synthetic biology with other emerging technologies, such as machine learning and big data analytics, can accelerate the discovery and optimization of new biopesticidal compounds. Predictive modeling and high-throughput screening can identify novel biosynthetic pathways and regulatory elements, streamlining the development process and enabling rapid deployment of custom biopesticides tailored to specific agricultural needs.

In addition, synthetic biology allows for the creation of "smart" biopesticides that can respond to environmental cues or pest attacks. These dynamic systems can activate or increase the production of pesticidal compounds only when needed, reducing the overall metabolic burden on the plant and preventing unnecessary exposure to non-target organisms. For instance, plants could be engineered to upregulate biopesticide production in response to specific pest-associated molecular patterns (PAMPs), ensuring a timely and efficient defense response (Henry, *et al.*, 2012).

The application of synthetic biology in agriculture also opens the door to sustainable and scalable production methods for biopesticides. Plant-based bioreactors and engineered microbial factories can produce large quantities of biopesticidal compounds with high purity and consistency. This reduces the dependency on chemical synthesis and allows for more environmentally friendly manufacturing processes (Wu, *et al.*, 2023).

Collaboration and Multidisciplinary Approaches

The development and implementation of plant biopesticides benefit significantly from collaboration and multidisciplinary approaches. Integrating expertise from fields such as botany, chemistry, microbiology, ecology, and agricultural science creates a robust framework for designing effective and environmentally friendly pest management solutions (Tiwari, 2024). By fostering cross-disciplinary teamwork, experts can explore a diverse array of plant compounds, elucidate their mechanisms of action, and evaluate their ecological impacts comprehensively. This collective effort not only enhances the efficacy and safety of biopesticides but also contributes to sustainable agriculture by addressing the multifaceted challenges of pest resistance and environmental conservation (Kumar *et al.*, 2021).

Future Directions and Research Needs

To better exploit the virtues of plant-based biopesticides in sustainable agriculture, upcoming research needs to cover a number of key domains. As a first priority, improvement of consistency and efficacy is essential. This involves a greater appreciation of how environmental factors (temperature, humidity, UV radiation) influence biopesticide performance, which should result in more stable formulations with better shelf-life, perhaps by means of novel encapsulation, nano-delivery systems, or controlled-release technology. Second, simplification of the regulatory process is key; studies must guide more streamlined and less expensive testing regimes for biopesticide registration, lowering producers' cost burdens and time-to-market. Third, increasing the spectrum of activity is essential. Although most biopesticides are quite specific, work should seek out new plant chemicals or blends with wider activity against more pests and diseases, and perhaps utilize improved screening methods, metabolomics, and genomics to discover new active ingredients and maximize synergy. Fourth, enhancing production scalability and affordability is necessary for mass market uptake; this entails development of more effective and sustainable large-scale extraction and manufacturing techniques, possibly through optimized plant cultivation or through synthetic biology technologies to derive essential active ingredients. Lastly, successful integration of biopesticides into IPM programs necessitates additional research to determine the best timing for their application, compatibility with other biological control means and agroecological practices, and decision-support tools for farmers. It involves research on pest resistance management strategies under an IPM context to assure effective long-term use of these useful tools. By meeting these research demands, we are able to maximize the potential of plant biopesticides in shaping a more sustainable and resilient future for agriculture.

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AUTHOR'S CONTRIBUTION

Shaizee wrote original manuscript, Arshi Siddiqui and Salman Ahmad check and revise the final version of manuscript and guide the co-authors in writing, Uzma Afaq and Shaizee collected the data from the sources.

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