REVIEW ARTICLE
AGROBIOLOGICAL RECORDS
ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

BIOPESTICIDES FOR USE IN AGRICULTURE AND THE HEALTH SECTOR

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ABSTRACT

Biopesticides derived from natural sources such as microorganisms, plants, and biochemicals offer a sustainable alternative to synthetic pesticides by minimizing environmental and health risks. This review explores the types of biopesticides, including microbial, e.g., *Bacillus thuringiensis*, *Beauveria bassiana*, plant-incorporated protectants (PIPs), and botanicals (e.g., neem, pyrethrum), and their applications in agriculture for pest management, soil health enhancement, and integrated pest management (IPM). In the health sector, biopesticides like *B. thuringiensis israelensis* (Bti) are pivotal in vector control for diseases such as malaria and dengue. Despite advantages like biodegradability and target specificity, challenges persist, including low field efficacy, short shelf life, and regulatory hurdles. Recent advances in nano-formulations, genetic engineering, and AI-driven development aim to overcome these limitations. This review underscores the role of biopesticides in achieving sustainable agriculture and public health goals, calling for interdisciplinary collaboration, policy support, and farmer education to scale adoption. By addressing current constraints, biopesticides can significantly reduce reliance on chemical pesticides, aligning with global sustainability agendas.

***Keywords*:** Biopesticides, Sustainable agriculture, Microbial pesticides, Vector control, Integrated Pest Management (IPM)

Article History (ABR-25-059) || Received: 25 Jun 2025 || Revised: 07 Aug 2025 || Accepted: 08 Aug 2025 || Published Online: 09 Aug 2025

1. INTRODUCTION

Biopesticides are increasingly drawing interest among stakeholders seeking eco-friendly, safe and Integrated Crop Management (ICM) compatible strategies for pest control (Zhou et al. 2024a). Despite promising outcomes in various crop systems, especially those involving insecticidal products derived from *Bacillus thuringiensis* (Bt) Berliner biopesticides, have yet to fulfill expectations as dominant players in the pesticide industry (Ortiz and Sansinenea 2022). Currently, traditional biopesticide applications are primarily effective in specialized and niche markets within the agricultural and horticultural sectors. In 1998, the global pesticide industry was valued at nearly US$32 billion, with biopesticides (excluding genetically modified crops) accounting for only about US$350 million or just over 1% of the total market (Marrone 2024). This limited adoption can be attributed to numerous factors such as inconsistent performance in field applications, generally short shelf-life, frequently unsuitable formulations, less favorable economic viability compared to chemical pesticides, and a narrow pest-control spectrum (Guru et al. 2022). Nevertheless, biopesticides are appreciated for their safety to non-target organisms and mammals. Moreover, their environmental compatibility and the relatively simplified registration procedures in the United States potentially set a precedent for future regulatory frameworks in the European Union (Fusar Poli and Fontefrancesco 2024). Farmer adoption of biopesticides could rise in response to the growing demand for organically produced food, which is expanding more rapidly than any other food sector in developed countries. The emergence of more potent biological products with broader activity or improved targeting of key pests, alongside the strategic integration of biopesticides with lower doses of chemical pesticides, may further encourage usage (Baker et al. 2020). Incorporating biopesticides into such integrated programs could help delay or prevent the onset of resistance in pest populations to both chemical pesticides and biopesticide-derived toxins (Chavana

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and Joshi 2024).

Consequently, biopesticides are increasingly being acknowledged as vital tools in crop protection. Critical challenges shaping their future development and acceptance include constrained research and development funding, limited shelf stability, narrow host specificity, which can be beneficial in some cases, and low environmental persistence, which may also be advantageous and variable effectiveness in field conditions (Fenibo et al. 2022). As understanding and experience with biopesticides grow, companies are likely to overcome these hurdles through better selection, formulation and marketing of innovative products for the global market (Ndolo et al. 2019). For developing nations, biopesticides present a distinct opportunity to utilize their indigenous biological resources for pest management. Such initiatives can help conserve foreign exchange, enhance user and consumer safety and safeguard the environment (Fenibo et al. 2022). However, it is essential to ensure that any new biopesticide, whether a microbial agent, secondary metabolite, plant extract, or living organism, undergoes rigorous evaluation to confirm it poses no risk to applicators the environment or end users before being introduced into crop-protection practices (Kumar et al. 2021b). While biopesticides are generally safer for non-target species, their natural origin does not inherently guarantee safety (Kumar et al. 2021b).

The world's population is growing faster than ever before and is expected to approach 9.7 billion people by the year 2050, with the majority residing in Africa and Asia. This rapid growth has placed immense pressure on agriculture and its associated industries to fulfill the escalating demand for food, necessitating increased inputs for crop cultivation. (Mrabet 2023). Human-induced activities have significantly altered natural ecosystems, resulting in adverse environmental effects, including the conversion of agricultural land for infrastructure, excessive depletion of nutrients, degradation, and pollution of water sources (Akhtar et al. 2021). Therefore, leading to scarcity accumulation of harmful xenobiotics in the soil and a decline in soil quality, fertility and productivity, all contributing to land degradation from soil loss and shifts in climate patterns are major concerns (Biswas et al. 2018). Tackling these issues requires an effective solution, and ensuring food availability, enhancing the efficiency and sustainability of agricultural systems is essential, necessitating the adoption of innovative and advanced methods (Nicolétis et al. 2019). Agricultural productivity can be boosted by methods such as enhancing crop yield through the application of organic amendments like manure and bio-based treatments, including biopesticides, or by mitigating crop losses due to harsh environmental factors, including both biotic and abiotic stresses. Abiotic stress, in particular, can be effectively managed using bioeffectors and biostimulants (Priya et al. 2023).

Crop-specific pesticide usage is significant, with fiber crops consuming in India the application of pesticides varies across agricultural categories, with usage levels reaching 67% in general crops, 50% in fruits, 46% in vegetables, 43% in spices, 28% in oilseed, and 23% in pulses (Reddy et al. 2024). According to the Indian Ministry of Chemicals and Fertilizers, pesticide output increased from 186,000 metric tons in 2014-2015 to 217,000 metric tons by 2018-2019. Data from the Food and Agriculture Organization (FAO) covering the years 2015 to 2018 reveals that Asia was responsible for 52.2% of the World's pesticide consumption, trailed by the Americas at 32.4%, Europe at 11.8%, Africa at 2%, and Oceania at 1.6% (Reddy et al. 2024). Among nations, China reported the highest pesticide application per hectare, followed by the United Kingdom, while India recorded the lowest rate (Sharma et al. 2019). Within India, Jammu and Kashmir topped the list for pesticide usage, followed by Andhra Pradesh. These statistics underscore the critical need for more sustainable pest management solutions, particularly the increased adoption of biopesticides (Reddy et al. 2024). Bio pesticides derived from natural origins are substances used to manage pests and are found in various organisms, including plants, animals, bacteria, cyanobacteria, and microalgae (Mol and Purushothaman 2020). As defined by the U.S Environmental Protection Agency, these products originate from natural sources such as mineral, flora, fauna and microbes. Many biopesticides contain active compounds or genetic elements from these biological agents, offering effective protection against pest-related crop damage (Seiber et al. 2018).

Compared to synthetic chemicals, biopesticides offer several benefits; they are environmentally safe and often exhibit host specificity (Ayilara et al. 2023). Their integration into agrochemical practices can significantly enhance pest management in agriculture (Deguine et al. 2021). Although increasing agricultural productivity is essential for sustainability, it often comes at the cost of environmental health, contributing to excessive water usage, pollution of ecosystems, and the widespread application of agrochemicals on farmland (Zhou et al. 2024b). To promote sustainable farming practices, such as crop rotation, integrated pest management (IPM), biological and mechanical weed suppression, and minimizing pesticide usage, has been recommended (Baker et al. 2020). Nonetheless, conventional farming systems still suffer from considerable crop losses due to factors like pest and pathogen infestations, weed interference, poor soil health, limited nutrient availability and climate-related adversities (Thakur and Uphoff 2017). In this context, the environmental impact of synthetic pesticides, historical background, and the global shift toward sustainable alternatives underscore the importance of biopesticides in modern agriculture (Table

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1).

This review highlights the pivotal contributions of biopesticides in closing the gap between agricultural productivity and the health sectors. By integrating existing developments, challenges and future directions. This paper seeks to inform policymakers, researchers and stakeholders on the game-changing capacities of biopesticides in minimizing the dependence on chemical pesticides while counteracting global food security and public health requirements. This study calls for expediting innovation, multi-disciplinary action and policy adjustments to realize the complete potential of biopesticides as the anchor of sustainable agriculture as well as health sectors.

Table 1: Effects of Biopesticides

Theme	Details	References
Environmental Impact of Synthetic Pesticides	Persistent in the environment, affecting non-target species like beneficial insects, soil microbes, plants and humans.	(Chávez-Dulanto et al. 2021; Chormare and Kumar 2022)
Shift Toward Sustainability	Growing concerns led to the 2030 Agenda for Sustainable Development (UN, 2015) and the Fifth Industrial Revolution, focusing on ethical, sustainable tech.	(Biswas et al. 2018; Mrabet 2023)
Historical Context	The Green Revolution (1970s) increased food production but caused environmental damage through monoculture and chemical use.	(Thakur and Uphoff 2017; Sharma et al. 2019)
European Green Deal & Farm to Fork Strategy	Launched in 2019–2020 to reduce soil, water and air contamination and create a sustainable food system in Europe.	(Baker et al. 2020; Fusar Poli and Fontefrancesco 2024).
Zero-Waste & Circular Economy Initiatives	Emphasis on reducing waste by using agricultural by-products to produce biopesticides, aligned with 3Rs and 5Rs principles.	(Ndolo et al. 2019; Fenibo et al. 2022)
Types of Biopesticides	1. Microbial Agents (e.g., fungi, bacteria); 2. Macrobial Agents (e.g., nematodes, insects); 3. Biochemical Agents (e.g., plant extracts, pheromones).	(Seiber et al. 2018; Mol and Purushothaman 2020)
Plant-Incorporated Protectants (PIPs)	Defined by the U.S. EPA as natural pesticides produced by plants (including via genome editing or seed treatments).	(Deguine et al. 2021; Kumar et al. 2021b)
Terminology Differences	Organizations like IBMA refer to "Biocontrol Agents" (BCAs) instead of biopesticides, classified into macrobial, microbial, natural products and semiochemicals.	(Ortiz and Sansinenea 2022; Zhou et al. 2024a)
Scientific Analysis Scope	Study focused on the term "biopesticide" in Web of Science (1994–2024); excludes broader biological control research, despite its historical roots (since the 1800s).	(Guru et al. 2022; Marrone 2024)
Limitations of the Study	Many key contributions in biocontrol excluded due to narrow keyword focus; broader search terms would yield more comprehensive coverage.	(Ayilara et al. 2023; Reddy et al. 2024)

2. TYPES OF BIOPESTICIDES

Biopesticides are generally classified into the following categories:

2.1. Microbial Biopesticides

These involve microorganisms such as bacteria, fungi, viruses or protozoa that act against specific pests. For instance, *Bacillus thuringiensis* (Bt) produces toxins that are lethal to certain insect larvae (Valtierra-de-Luis et al. 2020). Microbial organisms show great promise in enhancing food safety and can serve as cost-efficient tools within integrated pest management (IPM) programs. Two entomopathogens that have been independently commercialized as successful biopesticides are *Bacillus thuringiensis* Berliner (Bt) (Adilkhankyzy et al. 2025) and *Beauveria bassiana* (Balsamo) Vuillemin (Bb) both widely recognized for their effectiveness against insect pests (Sayed and Behle 2017). Bt-based biopesticides dominate the global market accounting for over 90% of total biopesticide sales. The commercial success of Bt is attributed to cost-effective mass production through liquid fermentation and its wide pest control range, including major pests in large-scale cropping systems. Furthermore, advancements in genetic engineering have enabled the integration of Bt's insecticidal protein genes into crop genomes broadening its application as a pest control strategy (Anderson et al. 2019). Primarily effective against lepidopteran insects Bt functions as a stomach poison that activates upon ingestion by vulnerable species. However, the emergence of resistance among pest populations feeding on transgenic Bt crops has been reported necessitating affordable and sustainable resistance management approaches to ensure long-term efficacy (Anderson et al. 2019). Similarly, Bb has been developed into biopesticide formulations effective against a broad spectrum of agricultural, horticultural and forest insect pests (Reddy and Chowdary 2021). Most Bb-based products employ infective conidia as the primary active component. Bb operates as a contact insecticide where germinating spores breach the insect cuticle to initiate infection (Wraight et al. 2022). This method allows Bb to effectively target pest species with

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piercing-sucking mouthparts unlike Bt. However, the high cost associated with conidia production via solid substrate fermentation may hinder Bb's market competitiveness relative to Bt (Sala et al. 2019).

Combining different active microbial agents has the potential to enhance pest control efficiency and can also serve as a tactic to delay or manage resistance development (Sheoran et al. 2025). Several investigations into Bt and Bb combinations have revealed synergistic effects leading to increased insect mortality rates. For instance, it was found that a slight synergistic interaction when applying a tank mix of Bt tenebrionis and Bb strain GHA to manage *Leptinotarsa decemlineata* (Colorado potato beetle) in field trials (Smagghe et al. 2023). Laboratory studies by also confirmed this synergism through simultaneous infections of beetle larvae. Other studies reported additive effects for *Musca domestica*, no interaction in corn pest *Ostrinia nubilalis* management and antagonism in *Ostrinia furnacalis* exposed to sublethal Bt Cry1Ac and Bb doses (Sun et al. 2022). Despite promising results, Bt and Bb are seldom formulated into a single biocontrol product. However, a wettable powder combining the two with a 3:1 Bt to Bb ratio, yielding optimal control of *Malacosoma Neustria* (Manohar 2023). These support further investigation into dual-agent products. Progress in fermentation and formulation technologies has enabled the cost-effective production of shelf-stable Bb blastospores, offering an economical alternative to traditional solid substrate methods. Reduced production costs could make the commercial development of combined Bt-Bb formulations more feasible (Ikhwani et al. 2024).

2.2. Plant-Incorporated Protectants (PIPs)

These are pesticidal substances produced by plants that have been genetically modified to express specific genes, such as those from Bt to confer resistance against pests (Nagaraj et al. 2024). Ensuring food security for an expanding global population presents one of the most pressing challenges of this century. Projections indicate that global food production must rise by a minimum of 70% to feed an estimated population exceeding 9 billion by the year 2050 (Giller et al. 2021). One key strategy to boost agricultural productivity involves safeguarding crops through the application of pesticides, a market valued at approximately \$50–60 billion (Yadav et al. 2023). Worldwide, pesticides help mitigate crop losses caused by insects and other pests by nearly 39%. The majority of these chemical agents are low molecular weight (LMW) synthetic organic compounds usually with molecular masses under 500g/mol (0.5kDa) (Faixo et al. 2021). The chemistry, environmental behavior and health implications of these synthetic pesticides have been comprehensively examined (Zhou et al. 2024b).

Although synthetic LMW pesticides dominate the market, biopesticides, defined broadly as pest control products derived from natural sources, are becoming increasingly significant (Ndolo et al. 2019). Presently, biopesticides account for around \$3–4 billion of the total pesticide market, representing about 6% of the global share (Marrone 2024). In contrast to synthetic pesticides, which show a compound annual growth rate (CAGR) of 4.8%, biopesticides are expanding at a much faster pace with a CAGR of 14.1% (Sălceanu et al. 2022). By 2050, biopesticides are projected to constitute half of the global pesticide market. Among biopesticide types are plant-incorporated protectants (PIPs), which are genetic traits engineered into crops to provide resistance against insect pests and viral pathogens (Kumar et al. 2021b). Insect-targeting PIPs are due to their widespread application and the development of new variants aimed at controlling insect pests (Iftikhar et al. 2023). These PIPs are consumed alongside plant tissues during pest feeding (Hezakiel et al. 2024). Once ingested, they interfere with insect growth and development or result in pest death (Shahid et al. 2023). Despite the broadening deployment of genetically modified (GM) crops expressing insecticidal PIPs, significant knowledge gaps persist regarding the environmental behavior of these proteins (Rakesh et al. 2023).

2.3. Biochemical Pesticides

These are naturally occurring substances that control pests through non-toxic mechanisms. Examples include insect pheromones that disrupt mating patterns and plant extracts that deter feeding (Mishra et al. 2022). Essential oils (EOs) also referred to as volatile oils, etheric oils, aetheroleum or essences and their bioactivity such as the anticoccidial and growth-promoting effects observed in star anise oil, highlight their therapeutic relevance (Al-Hoshani et al. 2023). These are naturally occurring mixtures of volatile substances produced as secondary metabolites in aromatic plants. These oils are typically obtained via water or steam distillation methods (Akdağ and Öztürk 2019). In general, EOs possess lower densities compared to water. They consist of complex blends containing hundreds of individual constituents which collectively define their physical, chemical and biological characteristics (Bunse et al. 2022). Aromatic plants may also be processed using organic solvents to obtain oleoresins or by supercritical carbon dioxide extraction to yield solvent-free, high-quality extracts (Uwineza and Waśkiewicz 2020). However, solvent extraction is more intricate and labor-intensive than steam distillation. This method produces both volatile essential oils and non-volatile flavor components which find widespread use in the food, agricultural and pharmaceutical sectors (Aziz et al. 2018).

In recent years, there has been a growing global interest, especially in both industrialized and developing nations in exploring botanical insecticides such as essential oils for pest control largely due to the increasing resistance of insect populations to conventional synthetic insecticides (Isman 2020). The prolonged use of synthetic insecticides has led to the accumulation of chemical residues in various environmental compartments including water, soil, air and food posing threats to non-target species, disrupting ecosystems and posing health hazards to humans (Oaya et al. 2019). Consequently, bio-insecticides like EOs have emerged as sustainable alternatives to synthetic pesticides in agriculture and public health (Ladan et al. 2022). The adoption of eco-friendly pest management practices often termed "green pesticides," includes the application of plant-based products such as essential oils and botanical extracts. Green pesticides are defined as naturally derived substances capable of suppressing pest populations and contributing to increased agricultural productivity (Souto et al. 2021). As a result, EOs play a pivotal role in pest management strategies, particularly in the context of organic farming systems worldwide (Chang et al. 2022).

2.4. Botanical Pesticides

Botanical insecticides currently make up around 1% of the global insecticide market and are associated with significantly fewer environmental and health risks compared to their synthetic counterparts (Isman 2020). Globally, approximately 17,500 aromatic plant species thrive in tropical regions and over 3,000 chemical constituents have been identified from them (Riaz et al. 2021b). Out of these, about 300 essential oils are commercially used across industries, animal feed, and pest control (Shahbakht et al. 2024). Prominent plant families known for EO production include Apiaceae, Asteraceae, Combretaceae, Geraniaceae, Gramineae and Lamiaceae as well as Myrtaceae, Meliaceae, Piperaceae, Rutaceae, Verbenaceae and Zingiberaceae (Mohammed et al. 2024). Commercially, essential oils can be produced by angiosperms and gymnosperms, and significant sources are primarily angiosperms due to their greater species diversity and medicinal use in traditional systems (Nomi et al. 2024). Over the past few decades a substantial body of research has examined the insecticidal properties of essential oils and their potential application as biopesticides against key insect pests (Gupta et al. 2023). Recent technological developments have expanded the scope of biopesticides such as RNA Interference (RNAi) technology involves silencing specific genes in pests that are leading to their death or reduced fitness (Fletcher et al. 2020). RNAi-based biopesticides offer high specificity and are less likely to affect non-target species. Bionanopesticides are nanoparticles derived from biological materials that can deliver pesticidal agents more effectively, enhancing stability and targeted delivery while reducing environmental impact (Anjaneyulu et al. 2024).

3. APPLICATIONS OF BIOPESTICIDES

3.1. In Agriculture

Farmers have successfully enhanced crop yields on limited cultivable land by employing technological innovations, refined agricultural methodologies and effective pest control strategies (Shah and Wu 2019). However, the excessive and improper use of chemical inputs presents a major obstacle to achieving sustainable agricultural development (Pretty 2018). The rise of resistance among various pest and vector species, coupled with environmental pollution concerns and the escalating costs of synthetic insecticides, has highlighted the limitations of relying solely on chemical-based pest control (Wilson et al. 2020). Pesticides, both organic and inorganic, are utilized to eliminate or inhibit harmful organisms to safeguard crops. While prolonged pesticide use may protect plants, it can also cause damage (Pathak et al. 2022).

Resistance mechanisms in pest populations are often mediated by genetic factors, particularly among gram-negative and gram-positive bacteria. For instance, contamination by Aspergillus species in crops producing harmful mycotoxins can occur during various stages, including cultivation, harvesting or storage (Kumar et al. 2021a). Given these concerns, microbial insecticides are gaining popularity as ecologically safer alternatives to traditional chemical pesticides (Ayilara et al. 2023). Rising awareness regarding biodiversity loss and species endangerment is intensifying the demand for increased food production while reducing dependency on chemical interventions (Abudulai et al. 2022). These environmental concerns have accelerated the transition toward organic farming and encouraged the use of biopesticides among growers (Sarwar et al. 2021; Adnan et al. 2025).

In India (Fig. 1), biopesticides constitute around 5% of the pesticide market with more than 15 microbial species and nearly 970 formulations registered under the Central Insecticides Board and Registration Committee (Kumar et al. 2019). Globally, member nations of the OECD have approved various microbial and plant-based biopesticides (Fig. 1) and over 1,000 formulations are currently in circulation (Kumar et al. 2021b). Prominent botanical biopesticides include extracts from neem (Azadirachta indica), sabadilla (*Schoenocaulon officinale*), pyrethrum (*Tanacetum cinerariifolium*), cotton, tobacco (*Nicotiana tabacum*) and ryania (*Ryania speciosa*) while microbial agents like Trichoderma, Bacillus, Pseudomonas and Beauveria species are commercially deployed (Chowdhury et al. 2024). Microbial-based biopesticides are valuable for the development of innovative pest control agents that are effective in safeguarding both agriculture and public health (Mukanga et al. 2024). Substantial

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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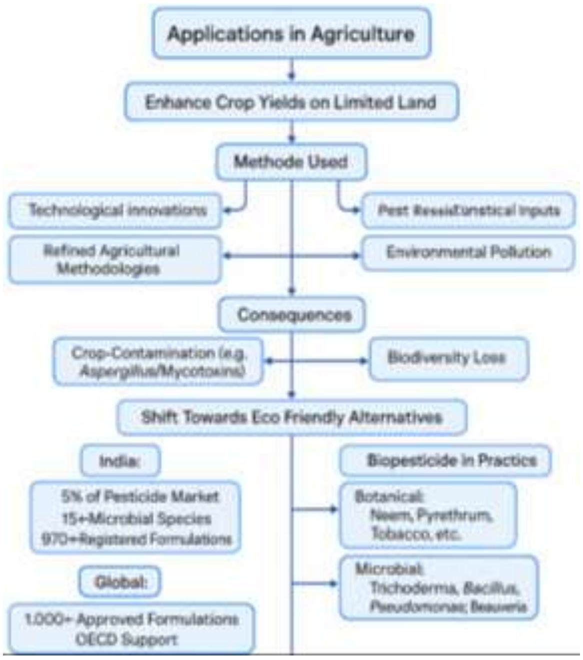

Fig. 1: Biopesticides application in agriculture: Methods, consequences, and eco-friendly alternatives.

progress has been made using *Bacillus thuringiensis, Bacillus sphaericus* and *Entomopathogenic fungi* (Vermelho et al. 2024).

The global production of biopesticides is expanding rapidly reaching approximately 3,000 tonnes annually. In India, the use of biopesticides has risen by 23% contrasting with a mere 2% increase in the application of chemical pesticides (Fig. 1; Chakraborty et al. 2023). The global biopesticide market, valued at USD 5.5 billion in 2022 is projected to double to USD 11.3 billion by 2027. This growing demand has spurred industry interest, demonstrated by companies like AgraQuest (USA) and Prophyta GmbH (Germany) now part of Bayer Crop Science (Hezakiel et al. 2024). Additionally, Monsanto and Novozymes have established the BioAg Alliance to explore new microbial solutions for sustainable farming. With their integration into Integrated Pest Management (IPM) strategies, biopesticides have gained substantial momentum within Indian agriculture (Fenibo et al. 2022). The bioactive ingredients found in plants include diverse classes of compounds such as phenols, quinones, alkaloids, steroids, terpenes, alcohols, and saponins (Abegaz and Kinfe 2019). Different plant families contain unique antimicrobial components, which may include essential oil constituents like α- and β-phillandrene, limonene, camphor, linalool, β-caryophyllene, and linalyl acetate, depending on the species (Saeed and Alkheraije 2023). Examples include parasitoid wasps, beetles, lacewings, predatory bugs, and ladybird beetles, which are effective in controlling pests like *Helicoverpa armigera* (bollworm) in major crops such as cotton (Riaz et al. 2021a). Another category of biopesticides includes compost teas, liquid filtrates derived from compost extracts, which are similarly utilized for their pest and disease control properties (Garg and Rakshit 2024).

Pathogens, insects and weeds present a major threat to global food security and sustainable agriculture as they contribute significantly to reduced crop yields worldwide (Grace et al. 2019). The losses attributed to pest infestations could equate to the amount of food required to nourish nearly one billion people, making pest control a vital element of food security strategies (Botha et al. 2020). To address this issue without relying on the costly and often harmful effects of synthetic pesticides, alternative pest management methods must be adopted (Souto et al. 2021).

3.2. Applications in the Health Sector

Ensuring a steady supply of nutritious and safe food is a fundamental goal of any advanced and organized society (Alegbeleye et al. 2022; Rahman 2023). From a quantitative perspective, achieving large-scale food production often relies on the application of various agrochemicals, including synthetic fertilizers, growth regulators, herbicides, insecticides, fungicides, nematicides, bactericides and antiviral agents (Singh et al. 2021). While these substances support the cultivation of high-yield food crops they also pose significant risks to human and animal health as well as to beneficial insects potentially leading to serious illnesses and physiological disorders (Chávez-Dulanto et al. 2021). In light of these drawbacks, biopesticides present a sustainable alternative, offering significant ecological and health advantages over synthetic pesticides (Table 2).

Research by Damgaard has documented the presence of pesticide residues in human breast milk, highlighting the extent of chemical contamination through food and further elaborated on the adverse health outcomes linked to pesticide exposure including an increased risk of various cancers affecting multiple organs and tissues (Blackburn and Green 2022). Moreover, these toxic chemicals persist in the environment accumulating in ecosystems. Wildlife including animals, birds and insect face dangers such as metabolic disruptions or even death when they ingest contaminated food or inhale polluted air (Chormare and Kumar 2022).

Mosquito control remains a critical public health priority as mosquitoes are vectors of several life-threatening diseases including malaria, filariasis, dengue fever, yellow fever, West Nile virus and chikungunya (Parihar et al. 2020). These illnesses pose significant health risks and contribute to economic strain in countries where they are endemic. Their global spread is accelerating due to factors such as increased international travel, urban development and climate change (Baker et al. 2024). The most effective strategy for lowering disease transmission is through

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

targeting mosquito populations primarily by applying insecticides to their breeding habitats (Rani et al. 2023). Since the 1950s, the widespread use of chemical insecticides has raised major concerns, including toxicity to non-target organisms and the emergence of resistance in mosquito populations (Araújo et al. 2023). A safer and environmentally friendly alternative involves using toxins produced by *Bacillus thuringiensis* subsp. *israelensis* (Bti), which are sprayed over mosquito breeding sites (Margalith and Ben-Dov 2000). Currently, Bti is regarded as the most effective biocontrol agent for managing mosquito populations. Its toxins are considered non-hazardous to humans and other non-target species, exhibit low environmental persistence and importantly have not yet led to any reported resistance among mosquito populations (Sabbahi et al. 2022).

Table 2: Advantages of Biopesticides

Aspect	Synthetic Pesticides	Biopesticides	References
Historical Use	Used since ancient times for pest control and crop improvement	Emerged as an alternative to address concerns associated with synthetic pesticides.	(Singh et al. 2021; Blackburn and Green 2022)
Composition	Chemical compounds with carriers like polymers	Derived from natural sources: plants, microbes and biological agents.	(Sabbahi et al. 2022; Perumal et al. 2024)
Types	Herbicides, algicides, fungicides, miticides, bactericides, rodenticides, termiticides, insecticides, molluscicides, nematicides.	Phyto pesticides microbial pesticides nano-biopesticides	(Perumal et al. 2024)
Classification Basis	By pest type or active ingredients (e.g., organochlorines, dichlorvos, diazinon, diamide, chlorpyrifos).	By source: plant-based, microbe-based or biologically derived nanoparticles.	(Sabbahi et al. 2022; Perumal et al. 2024)
Benefits	Enhances crop yield and productivity.	Cost-effective, environmentally friendly, target-specific, sustainable, residue-free, no GHG emissions	(Chávez-Dulanto et al. 2021)
Environmental Impact	Damages soil biodiversity, wildlife, aquatic life, and plants	Environmentally sustainable; minimal to no negative impact.	(Baker et al. 2024; Chormare and Kumar 2022)
Soil Impact	Makes soil brittle, reduces respiration and earthworm activity	Promotes soil health by avoiding disruption of beneficial microorganisms.	(Baker et al. 2024; Chormare and
Animal and Human Health Impact	Reduces animal immunity, fertility, and offspring quality; bioaccumulates leading to diseases like cancer, kidney disease, rashes, diabetes	Lower health risks; safer for humans and animals	Kumar 2022)
Water Impact	Contaminates water bodies, causes aquatic life death, bioaccumulation	Biodegradable; reduces risk of water contamination	
Mechanism of Action	Broad-spectrum chemical action.	Inhibits/destructs plasma membranes and protein synthesis in pests and pathogens.	(Yadav et al. 2022; Gupta et al. 2023)
Specific Advantages	Immediate and effective against a wide range of pests.	Specific action, no chemical residues, enhanced delivery (nano-biopesticides) and no impact on greenhouse gas levels	(Adetuyi et al. 2024; Vishnu et al. 2024)

The incidence rose significantly in 2022 with 76,467 cases, up from 36,120 cases in 2021. The dengue virus is transmitted by mosquitoes belonging to the *Aedes* genus, primarily *Aedes aegypti* which is considered the principal vector (Das et al. 2018). This mosquito species poses a considerable threat to public health due to its ability to spread nearly 30 known arboviruses, including four critical ones: dengue (DENVs), chikungunya (CHIKV), Zika (ZIKV) and yellow fever (YFV). *Aedes aegypti* thrives in human environments, exhibits a preference for feeding on humans (anthropophilic) and commonly breeds in artificial containers (Facchinelli et al. 2023). In the absence of a universally effective vaccine or antiviral treatment, controlling the mosquito population remains the primary method to curb disease transmission (Wilson et al. 2020). This involves eliminating breeding habitats and applying chemical insecticides. The widespread distribution and diverse nature of breeding sites, coupled with growing insecticide resistance in *Ae. Aegypti* populations and adverse effects on non-target organisms have significantly diminished the effectiveness of conventional control strategies. This has led to an increased focus on exploring alternative mosquito control approaches (Dusfour et al. 2019).

Several innovative vector control solutions are under development, including the use of plant-derived insecticides, genetically modified organisms and entomopathogenic microbes (Civolani et al. 2025). While botanical insecticides have shown promise in experimental settings, their rapid degradation under field conditions and limited biomass availability for sustained production pose significant challenges to their commercialization. Genetically engineered vectors, though proven effective in some applications, remain costly and raise complex social, political, and ethical concerns (Abbas et al. 2023).

In contrast, the use of entomopathogenic organism's microbes that target insect hosts is gaining attention as an

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eco-friendly vector control strategy. These biological agents including fungi, viruses and bacteria offer an environmentally responsible alternative to synthetic chemicals (Perumal et al. 2024).

4. RECENT ADVANCES AND STRATEGIES: LIMITATIONS AND CHALLENGES OF BIOPESTICIDES

Despite their environmental benefits, biopesticides face several limitations that have hindered their widespread adoption in agriculture and public health. One of the most significant challenges is their low efficacy and slow mode of action compared to synthetic pesticides (Ayilara et al. 2023). Chemical pesticides often provide rapid knockdown of pests, whereas biopesticides, particularly microbial agents, require time to infect, colonize, or disrupt pest physiology (Agboola et al. 2022). For example, *Beauveria bassiana,* a fungal biopesticide, may take days to kill insect hosts, allowing crop damage to continue in the interim (Ayilara et al. 2023). This delay discourages farmers who prioritize immediate pest control, especially during severe infestations (Samal et al. 2023). Botanical-based biopesticides, especially those derived from plant essential oils (PEOs) have gained substantial scientific validation (Giunti et al. 2023). The introduction and integration of advanced technologies mark a new chapter in this domain. Recent advancements have led to the innovation of novel formulations for plant-derived biopesticides (Gupta et al. 2023). Traditional delivery forms such as emulsions, suspensions, dusts, powders, granules, wettable powders, and water-dispersible granules are gradually being replaced by these advanced technologies (Akoijam et al. 2024). These contemporary formulations offer enhanced shelf-life, improved stability and increased consumer safety, making them more advantageous compared to their conventional counterparts. Despite the proven bioactivities of PEOs highlighted in earlier sections, their industrial applications remain restricted by issues like poor solubility, limited bioavailability, and high volatility (Ubeyitogullari et al. 2022). To counter these limitations, researchers have proposed encapsulating PEOs within chemical matrices, enabling controlled and sustained release. Particularly promising are nano- and micro-formulations where the plant's active ingredients are embedded into supportive matrices to yield stable emulsions (Yadav et al. 2022).

Nanoemulsions, due to their kinetic stability and minimal volatility, outperform microemulsions by requiring fewer amounts of surfactants. They also offer controlled release mechanisms and show potent bioherbicidal, biofungicidal, and bioinsecticidal effects (Adetuyi et al. 2024). Since PEOs are hydrophobic, large volumes of harmful solvents are often required for dissolution. To address this, solvent-free nanoencapsulation techniques are emerging as groundbreaking developments (Ayyaril et al. 2023). Various polymeric carriers have been engineered for PEO encapsulation, enabling prolonged and regulated release during storage and application (Yammine et al. 2024). Techniques employed for preparing encapsulated particles include emulsification, coacervation using gelatin or gum arabic, spray drying with maltodextrin, cyclodextrin complexation, ionic gelation using chitosan, nanoprecipitation with poly DL-lactide-co-glycolide (PLGA) and film hydration (Gupta et al. 2023). For instance, observed improved cytotoxic activity and controlled release in chitosan- or lipid-encapsulated plant extracts against Sf9 insect cells compared to conventional pesticides. Similarly, nanostructured lipid carriers containing Palmarosa PEO demonstrated antifungal efficacy against *Aspergillus nomius* in both laboratory and real food conditions (e.g., pre-contaminated Brazil nuts) (Uchida et al. 2021). Nanoemulsions of *Satureja hortensis* PEO showed herbicidal action by disrupting plant membranes and physiological functions (Kaur et al. 2024). Emulsion size and durability are strongly influenced by the source plant, such as *Artemisia* species, whose nano-emulsions retained stability for 28 weeks using a 3:1 oil-to-surfactant ratio (Uchida et al. 2021). Innovative formulations combining pure PEOs or their key constituents with other components are increasingly popular. For instance, azadirachtin exhibited enhanced insecticidal activity when delivered in neem oil rather than alone (Sarmah et al. 2025). These nanoformulations, whether composed of pure PEOs or their isolates, show promising potential as next-generation biopesticides (Vishnu et al. 2024).

5. FUTURE PERSPECTIVE

To enhance product quality and sales, it is essential to provide technical support and training to producers. Increased communication between users, researchers, and the industry during the early stages of biopesticide development is crucial to accelerating research in this area (Marrone 2024). The government should continue to enforce strict regulations on conventional chemical pesticides, creating a significant opportunity for the marketing of biopesticides. This would help bridge the gap in availability while making biopesticides more affordable (Fenibo et al. 2022). To encourage the adoption of these eco-friendly solutions, developing countries should be empowered to build their capacity in biopesticide manufacturing and utilization (Diiro et al. 2020). Incorporating biopesticides into mainstream agriculture requires a deeper understanding of their mechanisms of action to broaden their pest control spectrum (Vijayreddy et al. 2025). Improving their field performance, delivery systems, shelf life, production cost, availability, and increasing farmer awareness, along with simplifying registration and regulatory

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processes, will facilitate their wider adoption (De Jonge et al. 2025). Future advancements in biopesticides will likely stem from research into pest genomes and their natural predators. Researchers are employing molecular technologies to understand the evolution of natural microbial enemies and pinpoint the molecular factors behind their pathogenicity (Chiquito-Contreras et al. 2024). Further ecological studies on disease dynamics within insect populations are essential. Ecological studies are needed to understand the impact of environmental factors on pest disease outbreaks to improve pest control efforts (Blank 2025).

6. CONCLUSION

Biopesticides represent a transformative tool for sustainable pest management in agriculture and public health, offering eco-friendly alternatives to synthetic chemicals. While their benefits such as environmental safety, target specificity and compatibility with organic farming, are well-documented, challenges like inconsistent field performance, high production costs and limited farmer adoption hinder widespread use. Advances in nanotechnology, microbial strain optimization and policy frameworks are critical to enhancing their efficacy and scalability. Future efforts must prioritize interdisciplinary research, public-private partnerships and farmer awareness to integrate biopesticides into mainstream practices. By addressing these barriers, biopesticides can play a pivotal role in reducing agrochemical dependency, safeguarding ecosystems and mitigating vector-borne diseases, supporting global food security and health sustainability.

DECLARATIONS

Funding: This research received no external funding.

Acknowledgement: The authors would like to extend their sincere appreciation to MNS University of Agriculture, Multan, Pakistan.

Conflict of interest: The authors declare that they have no conflict of interest.

Data Availability: All the data collected is inside the article.

Ethics Statement: Not applicable.

Author’s Contribution: SM and MM conceived and designed the project. BM, WA and AY contributed to the literature search and drafting of the manuscript. NH and MA assisted in organizing content and editing. ZAN supervised the work and provided critical revisions.

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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Citation: Muhyuddin S, Nomi ZA, Maryam B, Mobashar M, Yaseen A, Noor-e-Hira, Maria Aziz M and Ahmed W, 2025. Biopesticides for use in agriculture and the health sector. Agrobiological Records 21: 37-50. https://doi.org/10.47278/journal.abr/2025.032