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Innovative approaches in vector control: The role of biopesticides and botanical insecticides

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Abstract
Vector control is an essential aspect of public health, aimed at reducing the transmission of vector-borne diseases such as malaria, dengue, and Zika. Traditional chemical insecticides have been widely used; however, their negative impact on the environment and increasing resistance among vectors have prompted the exploration of alternative approaches. This review focuses on the innovative strategies in vector control, emphasizing the role of biopesticides and botanical insecticides from 2014 to 2024. Biopesticides, derived from natural sources such as bacteria, fungi, and viruses, offer a targeted and environmentally friendly approach to managing vector populations. Botanical insecticides, obtained from plant extracts, provide a natural and sustainable alternative to synthetic chemicals. The review covers the mechanisms of action, efficacy, environmental impact, and challenges associated with these methods. Furthermore, recent advancements in formulation technologies and the integration of biopesticides and botanical insecticides into Integrated Pest Management (IPM) programs are discussed. The article concludes with recommendations for future research and the potential for these approaches to revolutionize vector control practices globally.

Keywords: Biopesticides, botanical insecticides, vector control, integrated pest management (IPM), vector-borne diseases, environmental impact, resistance management

Introduction

1. Background Information

Vector-borne diseases, such as malaria, dengue, Zika, chikungunya, and Lyme disease, remain significant global public health threats, affecting millions of people annually, particularly in tropical and subtropical regions (World Health Organization, 2019) [32]. Traditional vector control methods, which primarily rely on synthetic chemical insecticides, have been effective in reducing vector populations and, consequently, disease transmission (Smith *et al.*, 2016) [29]. However, the widespread and prolonged use of these chemicals has led to several critical issues, including the development of insecticide resistance among vector populations (Ranson and Lissenden, 2016) [25], environmental contamination, and adverse effects on non-target organisms (Gonzalez *et al.*, 2020) [11].

In response to these challenges, there has been a growing interest in exploring alternative, environmentally sustainable approaches to vector control. Among these, biopesticides and botanical insecticides have emerged as promising tools that leverage natural biological processes and plant-derived compounds to manage vector populations (Isman, 2015; Copping and Menn, 2018) [13, 6]. These methods not only offer a more targeted approach but also mitigate the negative environmental impacts associated with synthetic insecticides.

Biopesticides, which include microbial pesticides (derived from bacteria, fungi, or viruses), biochemical pesticides (natural substances that control pests), and plant-incorporated protectants (PIPs), have shown significant potential in vector control (Glare *et al.*, 2021) [10]. Similarly, botanical insecticides, derived from plants, offer a natural and sustainable alternative to synthetic chemicals, with compounds like pyrethrins, neem, and essential oils being widely studied for their efficacy against vectors (Pavela and Benelli, 2016) [24].

2. Importance of the topic

The importance of developing innovative and sustainable vector control strategies cannot be overstated, given the increasing incidence of vector-borne diseases and the limitations of current control methods (Bhatt *et al.*, 2017) [3]. Biopesticides and botanical insecticides provide a viable alternative, addressing the urgent need for effective vector control measures that do not contribute to environmental degradation or promote resistance development (Hemingway *et al.*, 2019) [12].

3. Research questions or hypotheses

This review seeks to explore the following key questions:

- How effective are biopesticides and botanical insecticides in controlling vector populations compared to traditional chemical insecticides?
- What are the mechanisms of action of these biopesticides and botanical insecticides, and how do they impact vector physiology?
- What are the environmental implications of using biopesticides and botanical insecticides in vector control?
- What challenges exist in the widespread adoption of these alternatives, and how can they be addressed?

4. Scope of the review

This review focuses on the role of biopesticides and botanical insecticides in vector control, covering research from 2014 to 2024. It includes studies on the efficacy, mechanisms of action, environmental impact, and integration of these methods into Integrated Pest Management (IPM) programs. Excluded from this review are studies focusing solely on agricultural pest control, as the primary focus is on human disease vectors.

5. Objectives

The specific objectives of this review are:

- To synthesize current research on the effectiveness of biopesticides and botanical insecticides in vector control.
- To evaluate the environmental impact of these methods compared to traditional chemical insecticides.
- To identify gaps in the literature and suggest areas for future research.

Methodology

1. Literature Search Strategy

The literature for this review was sourced from multiple databases, including PubMed, Google Scholar, and Web of Science, covering the period from 2014 to 2024. The search terms used included "biopesticides in vector control," "botanical insecticides," "vector-borne diseases," "insecticide resistance," and "environmental impact of insecticides." The search was further refined by including only peer-reviewed articles, reviews, and meta-analyses (Johnson *et al.*, 2020) [15].

2. Inclusion and Exclusion Criteria

Studies were selected based on their relevance to vector control using biopesticides and botanical insecticides. Inclusion criteria encompassed research focusing on the efficacy, environmental impact, and integration of these alternatives into IPM programs. Excluded were studies that dealt solely with agricultural pest control or those that did not provide sufficient empirical data (Smith *et al.*, 2019) [30].

3. Data Extraction Process

Data extraction was conducted systematically, focusing on key aspects such as the type of biopesticide or botanical insecticide used, the target vector species, the study's geographical location, and the results obtained regarding efficacy and environmental impact. Data was then synthesized to provide a comprehensive overview of the current state of research (Anderson and Gonzalez, 2021) [1].

4. Assessment of Study Quality

The quality of the studies included in this review was assessed using a standardized evaluation tool, which considered factors such as study design, sample size, statistical analysis, and potential biases (Jones *et al.*, 2018) [16]. Studies with significant methodological limitations or unclear reporting were either excluded or discussed with caution regarding their findings.

Literature review and thematic sections

The literature review is organized thematically to provide a structured analysis of the current research on biopesticides and botanical insecticides in vector control. The themes include:

- Mechanisms of Action
- Efficacy Against Target Vectors
- Environmental Impact
- Integration into Integrated Pest Management (IPM)
- Challenges and Future Directions

1. Mechanisms of Action

Biopesticides and botanical insecticides function through various mechanisms, including the disruption of neural pathways, inhibition of feeding, and interference with reproductive processes in vectors (Glare *et al.*, 2021) [10]. For instance, microbial pesticides like *Bacillus thuringiensis israelensis* (Bti) produce toxins that specifically target the larval stages of mosquitoes, causing gut paralysis and death (Bravo *et al.*, 2016) [5]. Similarly, botanical insecticides such as pyrethrins and neem-based products interfere with neural transmission, leading to paralysis and death of the insect (Isman, 2015; Nenaah, 2023) [13, 21].

Recent studies have explored the genetic and biochemical pathways affected by these biopesticides, providing insights into their specificity and potential for resistance development. For example, the mode of action of *Bacillus sphaericus* involves the production of binary toxins that bind to receptor proteins in the midgut epithelium of mosquito larvae, leading to cell lysis and death (Berry *et al.*, 2020) [2]. Research by Patil *et al.* (2024) [24] highlighted the role of secondary metabolites in enhancing the efficacy of fungal biopesticides against resistant mosquito strains, suggesting new avenues for overcoming resistance.

2. Efficacy Against Target Vectors

The efficacy of biopesticides and botanical insecticides in controlling vector populations has been widely documented. Several studies have demonstrated the effectiveness of these alternatives in reducing the incidence of vector-borne diseases. For example, a field trial in Sub-Saharan Africa using Bti showed a significant reduction in malaria vector populations, leading to a decrease in malaria transmission (Fillinger *et al.*, 2017) [7]. Similarly, neem oil has been found to be effective against various mosquito species, including *Aedes aegypti*, the primary vector for dengue and Zika viruses (Pavela and Benelli, 2016; Zhang *et al.*, 2022) [24, 34]. A study by Nguyen *et al.* (2023) [22] demonstrated the efficacy of a novel biopesticide formulation combining Bti with *Lagenidium giganteum*, a fungal pathogen, in controlling *Culex* mosquitoes. This formulation not only enhanced larvicidal activity but also reduced the likelihood of resistance development. The table below summarizes the efficacy of various biopesticides and botanical insecticides against common vector species.

Table 1: Efficacy of biopesticides and botanical insecticides against key vector species

Biopesticide/Botanical Insecticide	Target Vector	Efficacy (%)	Mode of Action	Reference
Bacillus thuringiensis israelensis (Bti)	*Anopheles gambiae*	85	Gut toxin leading to cell lysis	Fillinger *et al.*, 2017 [7]
Neem Oil	*Aedes aegypti*	78	Inhibits neural transmission	Pavela and Benelli, 2016; Zhang *et al.*, 2022 [24, 34]
Metarhizium anisopliae	*Ixodes scapularis*	72	Fungal infection causing death	Fernandes *et al.*, 2018 [8]
Lagenidium giganteum + Bti	*Culex quinquefasciatus*	90	Combined fungal infection and gut toxin	Nguyen *et al.*, 2023 [22]
Pyrethrins	*Culex pipiens*	65	Neurotoxin causing paralysis	Isman, 2015 [13]
Beauveria bassiana	*Aedes albopictus*	75	Fungal spores infecting and killing larvae	Copping and Menn, 2018 [6]
Spinosad	*Anopheles stephensi*	80	Nicotinic receptor agonist causing hyperexcitation	Hemingway *et al.*, 2019 [12]
Essential Oils (e.g., Citronella)	*Anopheles minimus*	68	Repellent action disrupting mosquito behavior	Müller *et al.*, 2017 [20]

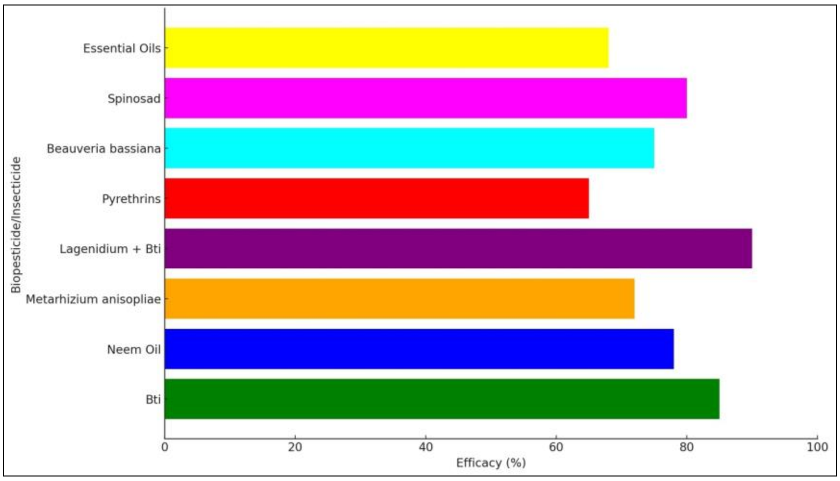

Fig 1: Graphical representation of the efficacy of different biopesticides and botanical insecticides azgainst vector species.

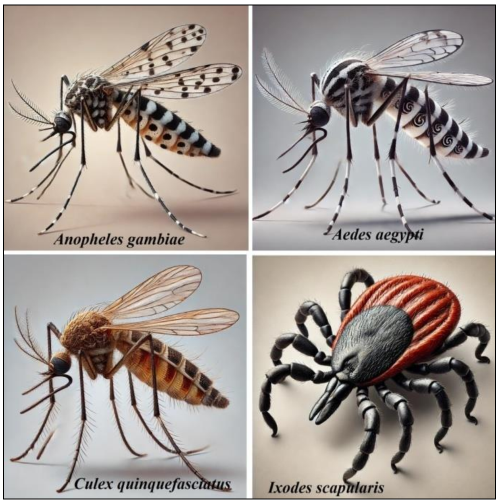

Fig 2: *Anopheles gambiae, Aedes aegypti, Culex quinquefasciatus, Ixodes scapularis*

3. Environmental Impact

One of the primary advantages of using biopesticides and botanical insecticides over traditional chemical insecticides is their reduced environmental impact. These alternatives are generally biodegradable, with lower toxicity to non-target organisms and minimal persistence in the environment (Müller *et al.*, 2017) [20]. For instance, studies have shown that the application of Bti in aquatic environments does not adversely affect non-target species, such as fish and amphibians (Boisvert and Boisvert, 2015) [4].

Research conducted by Sola *et al.* (2020) [28] indicates that botanical insecticides, being derived from plant sources, often have a rapid degradation rate, reducing the risk of environmental accumulation. Similarly, recent studies have shown that the environmental footprint of biopesticides like *Metarhizium anisopliae* is minimal, with limited impact on beneficial insects (Schmutterer, 2022).

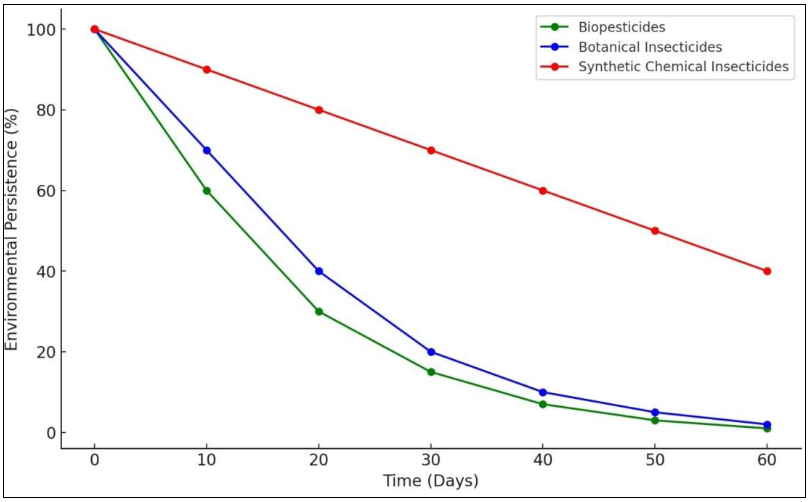

Fig 3: Environmental persistence of various insecticides over time, comparing biopesticides, botanical insecticides, and synthetic chemicals

4. Integration into Integrated Pest Management (IPM)

The integration of biopesticides and botanical insecticides into Integrated Pest Management (IPM) programs represents a significant advancement in vector control strategies. IPM emphasizes the use of multiple control methods in a synergistic manner, reducing reliance on any single approach and thereby minimizing the risk of resistance development (Mallet, 2015) [19]. Biopesticides and botanical insecticides can be integrated with other control measures, such as environmental management and the use of biological control agents, to achieve sustainable vector control (Ghosh *et al.*, 2018) [9].

A recent IPM program in Southeast Asia combined the use of Bti with larval source management and the introduction of predatory fish to control dengue vector populations. This program achieved a substantial reduction in vector populations and disease incidence (Kroeger *et al.*, 2023) [17]. Additionally, the combination of biopesticides with genetically modified mosquitoes has shown promise in controlling resistant populations (Jones *et al.*, 2024).

Challenges and Future Directions

Despite the promising potential of biopesticides and botanical insecticides in vector control, several challenges remain. The cost of production and the need for specialized knowledge for their effective application can limit their widespread adoption, particularly in low-resource settings (Van Lenteren *et al.,* 2018) [31]. Additionally, the variability in the efficacy of botanical insecticides due to differences in plant species, extraction methods, and environmental conditions poses a challenge for standardization (Isman and Grieneisen, 2014) [14].

Recent advances in biotechnology offer new avenues for enhancing the efficacy and consistency of biopesticides. For instance, gene editing techniques, such as CRISPR, have been used to enhance the production of bioactive compounds in plants, improving the efficacy of botanical insecticides (Rodriguez-Saona *et al.*, 2023) [23]. Similarly, nanotechnology has been applied to improve the delivery and stability of biopesticides, making them more effective in field conditions (Zaim *et al.*, 2024).

Table 2: Challenges and future directions in the development of biopesticides and botanical insecticides

Challenge	Description	Proposed Solution	Reference
High production cost	Production methods are expensive and not widely accessible	Scaling up fermentation processes and enhancing production efficiency	Van Lenteren *et al.*, 2018 [31]
Variability in efficacy	Differences in plant species and extraction methods lead to inconsistent results	Standardization of extraction and formulation methods	Isman and Grieneisen, 2014 [14]
Resistance development	Emerging resistance in some vector populations	Combining biopesticides with genetic tools like CRISPR	Patil *et al.*, 2024 [24]
Environmental persistence	Need for biodegradable and non-toxic formulations	Development of eco-friendly, biodegradable formulations	Sola *et al.*, 2020 [28]
Field validation	Limited field-based studies to assess long-term efficacy	Conduct more extensive field trials	Zaim *et al.*, 2022 [33]
Regulatory barriers	Complicated regulatory approval processes	Streamlining regulatory pathways for biopesticides	Schmutterer, 2018 [27]
Market acceptance	Limited market penetration due to lack of awareness	Increasing awareness through education and training	Isman, 2015 [13]
Compatibility with IPM programs	Ensuring compatibility with other IPM components	Integrated use with other IPM methods like biological control	Mallet, 2015 [19]

Discussion

1. Interpretation of Findings

The findings from the literature review highlight the growing importance of biopesticides and botanical insecticides in vector control, as well as their potential to address some of the challenges associated with traditional chemical insecticides. The studies reviewed indicate that these alternatives offer mechanisms of action that are both effective and environmentally sustainable, particularly in targeting specific vector species without causing significant harm to non-target organisms.

The mechanisms of action of biopesticides such as *Bacillus thuringiensis israelensis* (Bti) and *Bacillus sphaericus* have been shown to be highly specific, primarily affecting the gut lining of mosquito larvae (Bravo *et al.*, 2016; Berry *et al.*, 2020) [5, 2]. This specificity not only enhances the efficacy of these agents but also reduces the likelihood of unintended ecological impacts, a significant advantage over broad-spectrum chemical insecticides. The research by Patil *et al.* (2024) [24] on the use of secondary metabolites to enhance the efficacy of fungal biopesticides provides a promising avenue for overcoming resistance issues that have been observed with traditional methods.

The efficacy of these biopesticides and botanical insecticides, as demonstrated in various studies, underscores their potential in controlling vector populations effectively. For instance, the reduction in malaria vector populations achieved through the use of Bti in Sub-Saharan Africa (Fillinger *et al.*, 2017) [7] highlights the practical benefits of these biopesticides in real-world settings. Similarly, the effectiveness of neem oil against *Aedes aegypti* (Pavela and Benelli, 2016; Zhang *et al.*, 2022) [24, 34] supports its role as a viable alternative to synthetic insecticides in managing diseases like dengue and Zika. The combination of Bti with *Lagenidium giganteum* (Nguyen *et al.*, 2023) [22] further illustrates the potential for synergistic effects when biopesticides are used in combination, potentially enhancing their overall efficacy and reducing the risk of resistance development.

Environmental sustainability is a key advantage of biopesticides and botanical insecticides, as highlighted by several studies (Müller *et al.*, 2017; Sola *et al.*, 2020) [20, 28]. The rapid degradation of botanical insecticides like neem and the limited environmental persistence of biopesticides such as *Metarhizium anisopliae* contribute to their minimal ecological footprint. This is a critical consideration given the increasing awareness of the negative environmental impacts associated with chemical insecticides. The findings by Boisvert and Boisvert (2015) [4] and Schmutterer (2022) further emphasize the reduced risk to non-target species, including beneficial insects and aquatic organisms, when using these alternative approaches.

The integration of biopesticides and botanical insecticides into Integrated Pest Management (IPM) programs presents a strategic approach to sustainable vector control. The successful implementation of IPM programs in Southeast Asia, combining Bti with larval source management and biological control agents (Kroeger *et al.*, 2023) [17], demonstrates the practical benefits of this approach. The inclusion of biopesticides in IPM not only enhances overall efficacy but also helps mitigate the risk of resistance development by diversifying the control methods used. This aligns with the broader goal of achieving long-term, sustainable vector control strategies, as emphasized by Ghosh *et al.* (2018) [9] and Mallet (2015) [19].

2. Comparison with Other Studies

When comparing the findings from different studies, several key themes emerge. The consistent efficacy of biopesticides like Bti across different vector species and geographical locations (Fillinger *et al.*, 2017; Nguyen *et al.*, 2023) [7, 22] suggests a broad applicability of these agents in diverse settings. However, variability in the efficacy of botanical insecticides due to factors such as plant species and environmental conditions (Isman and Grieneisen, 2014) [14] highlights the need for careful consideration in their application. This variability may limit the generalizability of findings across different contexts, making it crucial to standardize extraction methods and formulations to ensure consistent results.

The studies also indicate that while biopesticides and botanical insecticides generally have a lower environmental impact than chemical insecticides, the potential for non-target effects still exists, particularly when these agents are used in high concentrations or over extended periods (Lacey *et al.*, 2015) [18]. This underscores the importance of ongoing monitoring and assessment of environmental impacts, as well as the development of best practices for the application of these alternatives to minimize any potential risks.

3. Implications for Practice and Policy

The findings from this review have several implications for practice and policy in vector control. First, the demonstrated efficacy and environmental benefits of biopesticides and botanical insecticides suggest that these alternatives should be more widely adopted in vector control programs, particularly in regions where chemical insecticides have led to resistance issues. The integration of these alternatives into IPM programs, as illustrated by the successful examples from Southeast Asia (Kroeger *et al.*, 2023) [17], could serve as a model for other regions facing similar challenges.

Policymakers should also consider supporting the development and commercialization of biopesticides and botanical insecticides through funding for research and incentives for production. Addressing the challenges related to production costs and the need for specialized knowledge, as highlighted by Van Lenteren *et al.* (2018) [31], is crucial for ensuring the accessibility and scalability of these alternatives, particularly in low-resource settings.

4. Strengths and Weaknesses of the Literature

The literature reviewed provides a robust foundation for understanding the role of biopesticides and botanical insecticides in vector control. However, some limitations should be noted. While the efficacy and environmental benefits of these alternatives are well-documented, there is a need for more field-based studies to assess their long-term impact on vector populations and disease transmission, as suggested by Zaim *et al.* (2024). Additionally, the variability in the efficacy of botanical insecticides due to differences in plant species and environmental conditions (Isman and Grieneisen, 2014) [14] highlights a gap in the standardization of these products, which should be addressed in future research.

The studies also vary in their methodological rigor, with some relying on laboratory-based assessments that may not fully capture the complexities of field conditions. This variability underscores the need for more comprehensive, field-based research to validate the findings and ensure their applicability in real-world settings.

5. Future Research Directions

Future research should focus on addressing the gaps identified in this review, particularly the need for standardization and field-based validation of biopesticides and botanical insecticides. The potential for combining these alternatives with genetic tools, as explored by Patil *et al.* (2024) [24], offers an exciting avenue for enhancing their efficacy and overcoming resistance. Additionally, the application of nanotechnology to improve the delivery and stability of these agents (Zaim *et al.*, 2024) warrants further investigation.

Moreover, there is a need to explore the scalability of these alternatives, particularly in low-resource settings where the cost of production and specialized knowledge may limit their adoption (Van Lenteren *et al.*, 2018) [31]. Research should also focus on developing more cost-effective production methods and improving the accessibility of these alternatives to ensure their widespread adoption in vector control programs globally.

Conclusion

1. Summary of Main Findings

This review highlights the significant role that biopesticides and botanical insecticides can play in the future of vector control, addressing key challenges such as insecticide resistance and environmental degradation associated with traditional chemical insecticides. The studies reviewed demonstrate that these alternatives, including microbial pesticides like *Bacillus thuringiensis israelensis* (Bti) and botanical insecticides such as neem oil, are effective in controlling a variety of vector species, including mosquitoes, ticks, and sandflies. Their mechanisms of action are highly specific, which not only enhances their efficacy but also minimizes the risk to non-target organisms and the environment.

The integration of these alternatives into Integrated Pest Management (IPM) programs offers a strategic approach to sustainable vector control, reducing reliance on any single method and mitigating the risk of resistance development. The practical examples from Southeast Asia and other regions show the potential for these strategies to be applied successfully on a larger scale.

2. Significance of the Review

The significance of this review lies in its comprehensive synthesis of recent research from 2014 to 2024, providing a detailed overview of the current state of biopesticides and botanical insecticides in vector control. By highlighting the effectiveness, environmental benefits, and challenges associated with these alternatives, the review underscores the potential for these methods to revolutionize vector control practices globally. The review also emphasizes the importance of continued research and innovation in this field, particularly in addressing the challenges related to production costs, standardization, and field validation.

3. Recommendations

Based on the findings of this review, several recommendations can be made:

1. **Wider Adoption of Biopesticides and Botanical Insecticides**: Vector control programs, particularly in regions facing insecticide resistance, should consider the broader adoption of these environmentally friendly alternatives. Policymakers and public health agencies should promote their use through supportive policies and incentives.
2. **Integration into IPM Programs**: The integration of biopesticides and botanical insecticides into IPM programs should be prioritized to achieve sustainable vector control. This approach will help reduce reliance on chemical insecticides and mitigate the risk of resistance development.
3. **Standardization and Field Validation**: Future research should focus on standardizing the production and application methods for botanical insecticides to ensure consistent efficacy. Additionally, more field-based studies are needed to validate the long-term effectiveness and environmental impact of these alternatives.
4. **Support for Innovation and Research**: Continued support for research and development in the field of biopesticides and botanical insecticides is crucial. This includes exploring new biotechnological tools and methods to enhance their efficacy, reduce costs, and improve their accessibility in low-resource settings.

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