Review Article

PLANT-DERIVED PEST CONTROL: MOLECULAR, ECOLOGICAL & TECHNOLOGICAL PERSPECTIVES

ABSTRACT

Aims: To explore and synthesize current knowledge on botanical pest management, emphasizing plant-pest interactions from evolutionary, molecular, and ecological perspectives. This study evaluates plant-based compounds and biotechnological approaches as sustainable alternatives to synthetic pesticides.

Study Design: A comprehensive review of scientific literature on botanical pest management, focusing on interdisciplinary approaches.

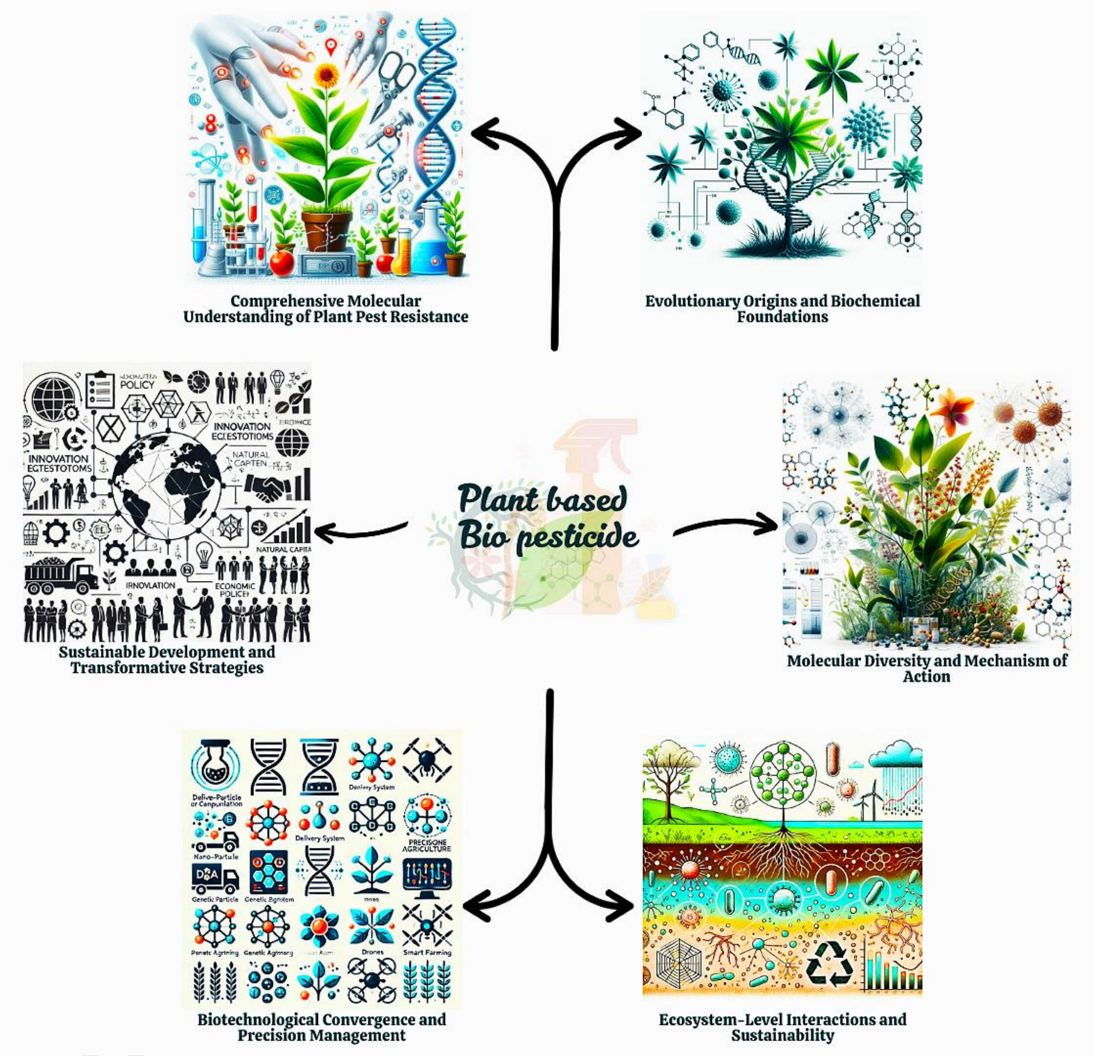
Methodology: The study reviews data on plant chemical defenses, molecular interactions, and biotechnological innovations for sustainable pest control. It analyzes plant-derived compounds' capacity to disrupt pest physiology with minimal ecological impact. Insights from genomics, molecular biology, and ecology are integrated to propose a sustainable pest management framework.

Results: Botanical pesticides demonstrated effectiveness in targeting pest physiological pathways while reducing ecological disturbances. Molecular studies revealed significant interactions between plant-derived compounds and pest systems, supported by advanced biotechnological methods. Genomic and ecological research underscored a balanced approach to enhancing agricultural productivity while minimizing environmental harm.

Conclusion: Botanical pest management is a promising, sustainable alternative to synthetic pesticides. It addresses current agricultural challenges while fostering long-term ecological sustainability. The findings highlight the potential of plant-based strategies to advance precise, eco-friendly pest control methods aligned with global sustainability goals. Further research is essential to validate and expand these solutions across diverse agricultural systems.

KEYWORDS: botanical pesticides, ecological interactions, pest management, plant defense mechanisms, sustainable agriculture,

GRAPHICAL ABSTRACT



1. INTRODUCTION

1.1 Evolution of Plant Chemical Defenses

Over millions of years, plants have developed various chemical defense mechanisms against pests (Huot *et al.,* 2013; Zhu-Salzman *et al.,* 2005). These defenses include constitutive and inducible strategies to protect against pathogens and herbivorous insects (Arnason & Bernards, 2010; Fürstenberg-Hägg *et al.,* 2013). Constitutive defenses consist of preformed barriers, such as cutin and suberin, and biologically active inhibitors always present in plant tissues (Arnason & Bernards, 2010). Inducible defenses activate upon pest attack, involving complex physiological and biochemical processes such as jasmonic acid and salicylic acid pathways, calcium flux, reactive oxygen species burst, and mitogen-activated protein kinase activation (Wang *et al.,* 2023). Plants generate a wide range of bioactive molecules, including antimicrobial, antifeedant, and phototoxic compounds, to counter evolving pest strategies (Arnason & Bernards, 2010; Fürstenberg-Hägg *et al.,* 2013). They have also evolved cost-effective strategies such as producing glandular trichomes, latex, accumulating specific metabolites, and preparing defense pathways in advance for transmission to descendants (Zhou *et al.,* 2022). Some plants engage external organisms or cooperate with relatives for protection, reducing defense costs (Zhou *et al.,* 2022). The evolutionary arms race with pests has led to diverse and redundant defense mechanisms, crucial for slowing pest resistance to host-plant defenses (Arnason & Bernards, 2010; Huot *et al.,* 2013).

1.2 Biochemical Pathways in Plant Resistance

Plant resistance strategies involve intricate biochemical pathways comprising signaling molecules, hormones, and metabolites, leading to defensive compounds and immune responses. Phytohormones, such as salicylic acid, jasmonic acid, ethylene, and abscisic acid, regulate responses to pathogens like Botrytis cinerea (Abuqamar *et al.,* 2017). Salicylic acid, crucial for resistance, is synthesized via the isochorismate and phenylalanine ammonia-lyase pathways (Ding & Ding, 2020). Pipecolic acid, derived from lysine catabolism, enhances defense responses and systemically acquired resistance (Zeier, 2013). Amino acid metabolism, particularly Asp-derived amino acid biosynthesis, affects pathogen resistance, with imbalances in homoserine or threonine levels potentially increasing immunity against oomycetes (Zeier, 2013). Phyto-oxylipins, generated by oxidative transformation of unsaturated fatty acids, contribute to defense mechanisms (Blée, 2002). Understanding these complex biochemical networks is essential for developing enhanced resistance through genetic engineering and breeding (Abuqamar *et al.,* 2017; Jirschitzka *et al.,* 2012).

1.3 Genomic insights into plant–pest interactions

Comparative genomic analysis serves as a powerful tool for elucidating the universal principles of plant-pest interactions. Through the utilization of high-throughput sequencing and bioinformatics, conserved genetic mechanisms in plant defense and pest virulence across species are identified. (Sironi *et al.,* 2015; Sturdevant *et al.,* 2010). Studies have shown that genes involved in plant defense and pathogen virulence are highly polymorphic, reflecting the evolutionary arms race between plants and pests (Karasov *et al.,* 2014). This genetic diversity results from complex ecological interactions and selective pressures. Comparative analyses have uncovered common gene expression responses in host cells to various infectious stimuli, indicating some universal defense mechanisms (Diehn & Relman, 2001). However, there is often a disconnect between real-world plant-pest interactions and the simplified models used (Karasov *et al.,* 2014). To address this, integrative approaches combining comparative genomics with transcriptomics, proteomics, and metabolomics are used to assess insect resistance at multiple biological levels (Gado and Alviar, 2022). Novel methods, such as using non-target sequencing reads as phenotyping proxies, show promise for studying natural variation in plant pest resistance efficiently (Galanti *et al.,* 2024). Advances in ecological genomics will likely reveal more universal principles governing plant-pest interactions.

2. MOLECULAR DIVERSITY AND MECHANISM OF ACTION

2.1 Structure and Efficacy of Plant-Derived Pesticides

Plant-derived pesticides have structural features influencing their pest control efficacy. Botanical pesticides contain various active components contributing to diverse action modes and effectiveness (Miresmailli, 2013; Oliveira *et al.,* 2019). These components often synergize to enhance activity and reduce pest resistance (Koul & Walia, 2009; Oliveira *et al.,* 2019). Their chemical structure affects stability, volatility, and release mechanisms, impacting efficacy (Miresmailli, 2013; Oliveira *et al.,* 2019). The release of eugenol and cinnamaldehyde from nanoparticles is temperature-sensitive, affecting bioavailability (Oliveira *et al.,* 2019). Odorant binding proteins (OBPs) in insect sensory organs bind and transport hydrophobic odorant molecules, influencing behaviors like host location, mating, and oviposition (Rana *et al.,* 2024). Botanical pesticide efficacy varies by pest species; tobacco-derived insecticides are more effective against citrus aphids than citrus psyllids (Wuryantini *et al.,* 2021). Volatilization patterns of botanical insect repellents can vary with time and factors like gender, ethnicity, and skin condition (Miresmailli, 2013). Understanding these factors is crucial for developing effective, sustainable botanical pesticides for integrated pest management (Dao *et al.,* 2021; Oliveira *et al.,* 2019; Villaverde *et al.,* 2016).

2.2 Phytochemical Variations in Pest Management

Phytochemical variations significantly affect pest management strategies and integrated pest management (IPM) efficacy. Utilizing phytochemicals through host plant resistance is crucial for IPM, particularly in field crops like maize and alfalfa, where insecticide use is often uneconomical (Horn, 2019). However, extreme temperatures can induce stress in arthropods and host plants, potentially altering their resistance mechanisms (Horn, 2019). Chemical ecology, including pheromones and semiochemicals, offers promising alternatives to broad-spectrum toxicants (Pickett *et al.,* 1997). Phytochemical-based methods can be integrated with host-masking agents, repellents, antifeedants, or oviposition deterrents in a multifaceted approach known as the stimulo-deterrent diversionary strategy (SDDS) to manipulate pest behaviour and reduce conventional pesticide use (Pickett *et al.,* 1997). Incorporating host plant resistance, semiochemicals, and other phytochemical-based methods into IPM programs aligns with public preference for bio-rational pest control alternatives (VanRyckeghem, 2011) and supports the development of innovative and sustainable agricultural practices.

2.3 Molecular Interactions in Pest Disruption

Molecular interactions disrupting pest physiology involve various mechanisms, where SubCELL, a database of subcellular compartment-specific interactions among DNAs, RNAs, and proteins, facilitates understanding and potential disruption of pest physiology at the molecular level (Zhang *et al.,* 2024), while kairomones mediate host-plant selection and enhance natural enemy effectiveness in biocontrol (Murali-Baskaran *et al.,* 2017). Plants have evolved sophisticated defense mechanisms, including the release of volatile organic compounds (VOCs) that attract natural enemies of pests and facilitate plant-plant communication (Pérez-Hedo *et al.,* 2024), with specific compounds like (Z)-3-hexenyl propanoate activating defense mechanisms in citrus plants (Pérez-Hedo *et al.,* 2024). These defenses involve multiple components: molecular markers for studying pest genetics and population dynamics (Ibrahim *et al.,* 1997), paratransgenesis for modifying bacterial symbiont relationships in heteropteran pests (Prado & Zucchi, 2012), and defense proteins like NBS-LRR that recognize pathogens (Liu *et al.,* 2023). The defense response involves complex signaling cascades, including jasmonic acid and salicylic acid pathways (Ali *et al.,* 2024), while plants must balance resource allocation between growth and defense, influenced by light perception (Breen *et al.,* 2023). Climate change impacts pest physiology and behavior through thermal traits and environmental interactions (Patterson *et al.,* 1999; Terblanche *et al.,* 2015), and lipids serve as important mediators in plant defense signaling cascades (Seth *et al.,* 2023). This comprehensive understanding of plant defense mechanisms is crucial for developing innovative pest management strategies and improving crop resistance (Hasan et al. 2023; Kansman *et al.,* 2023; Li *et al.,* 2023).

3. ECOSYSTEM-LEVEL INTERACTIONS AND SUSTAINABILITY

3.1 Ecological Impact of Botanical Pesticides

Botanical pesticides, derived from plant compounds, are a promising alternative to synthetic pesticides, modulating ecological networks with minimal adverse effects on non-target organisms and the environment (Jyoti, 2024; Ahmed *et al.,* 2022). Targeting specific pests, these pesticides leave minimal residues and possess insecticidal, antifeedant, or repellent properties, making them ideal for organic food production and post-harvest protection (Ahmed *et al.,* 2022). Botanical pesticides are less disruptive to trophic interactions and ecosystems compared to synthetic pesticides, aligning better with integrated pest management strategies (Beringue *et al.,* 2024; Jyoti, 2024). However, their impact on soil microbial biodiversity varies, with some extracts decreasing and others increasing microbial populations (Salamiah & Aidawati, 2022), highlighting the complexity of ecological networks and the need for careful consideration when using these pesticides. Botanical pesticides offer a selective and environmentally friendly approach to pest management, but further research is necessary to fully understand their ecosystem effects and optimize their use in integrated pest management strategies (Jyoti, 2024; Dang *et al.,* 2012).

3.2 Ecosystem Adaptations to Plant-Derived Interventions

Plant-derived interventions trigger long-term ecosystem adaptations through complex species-environment interactions. Changes in specific leaf area (SLA) indicate plant strategies for resource acquisition and environmental adaptation (Liu *et al.,* 2022), influencing ecosystem structure and function. Long-term responses include shifts in species composition, changes in productivity, and alterations in ecosystem services. Short-term losses from plant interventions may be offset by long-term biodiversity and ecosystem health gains (Sun et al. 2012). It is essential to consider both the immediate and long-term effects when evaluating ecosystem responses. Environmental hormesis suggests that mild stressors can enhance plant resilience against stronger stressors (Erofeeva, 2021). Understanding these multilevel adaptations is crucial for predicting ecosystem dynamics and informing management strategies, despite the complexity and slow pace of some processes, necessitating ongoing research and monitoring (Maček *et al.,* 2016).

3.3 Botanical Pesticides as Selective Pressures

Botanical pesticides can function as selective pressure mechanisms in agriculture, providing targeted pest management compared to synthetic pesticides. These plant-derived compounds possess specific modes of action that affect pests while minimizing harm to beneficial organisms (Dao *et al.,* 2021). Their diverse mechanisms can target insect physiology, including the nervous system, resulting in loss of coordination, paralysis, and mortality (Gupta et al. 2024). This specificity enables precise pest control while preserving natural enemies and pollinators (Ndakidemi *et al.,* 2016; Samanta *et al.,* 2023). Neem seed extract demonstrated comparable effectiveness to synthetic emamectin benzoate in controlling lepidopteran pests on tomatoes, while proving more cost-effective (Akhter *et al.,* 2023). Carlina oxide isolated from Carlina acaulis roots exhibited selective toxicity against the spider mite *Tetranychus urticae* without harming its natural predator *Neoseiulus californicus* (Rizzo *et al.,* 2023). Despite being less harmful to non-target organisms, botanical pesticides can adversely affect beneficial insects if improperly utilized (Ndakidemi *et al.,* 2016; Samanta *et al.,* 2023). This can result in pest resurgence and secondary outbreaks. Consequently, their use should be optimized within integrated pest management programs, with appropriate dosages and selective application, to maintain ecological equilibrium (Gupta *et al.,* 2024; Ndakidemi *et al.,* 2016).

4. BIOTECHNOLOGICAL CONVERGENCE AND PRECISION MANAGEMENT

4.1 Biotechnology in Optimizing Plant-Based Pesticides

Biotechnological techniques, such as genetic engineering, CRISPR-Cas9, and RNA interference, optimize plant-based pesticides by enhancing pesticidal compound production, modifying plants to express insecticidal proteins, and specifically targeting pests while sparing non-target organisms (Sharma *et al.,* 2024). Plant essential oils serve as broad-spectrum, low-toxicity biopesticides, and biotechnology refines their extraction, formulation, and delivery, with nanotechnology enhancing the stability and efficacy of nano-encapsulated essential oils (Mwamburi, 2022; Villarreal *et al.,* 2023). Bioassay-directed isolation, chemical characterization, combinatorial chemistry, and high-throughput screening accelerate the discovery, optimization, and production of novel plant-based pesticides and their synthetic derivatives (Gonzalez-Coloma *et al.,* 2010). These methods improve the efficacy, specificity, and environmental safety of plant-based pesticides, addressing traditional biopesticide limitations while maintaining eco-friendly benefits (Bilgrami & Khan, 2022; Wend *et al.,* 2024).

4.2 Innovative Delivery Technologies for Botanical Pesticides

Innovative delivery technologies have greatly improved the effectiveness of botanical pesticides, thereby addressing the challenges in agriculture and pest management. Microencapsulation enhances the formulation of plant essential oil active ingredients, enabling the development of new products (Paluch *et al.,* 2011). This method addresses stability issues and other limitations that have hindered the large-scale use of botanical pesticides (Dao *et al.,* 2021). Nano-encapsulation ensures precise pesticide delivery to plant tissues, increases effectiveness, and reduces chemical usage (Mmbando, 2024). The integration of nanotechnology with botanical pesticides has led to the development of efficient formulations that overcome degradation, instability, and volatilization (Oliveira *et al.,* 2018). This amalgamation represents a sustainable agricultural approach, optimizing resource use and minimizing environmental impact. Ultimately, technologies such as microencapsulation, nano-encapsulation, and other nanotechnology-based methods are vital for enhancing botanical pesticide efficiency and improving stability, delivery precision, and overall efficacy. Ongoing research in this field promises more sustainable and effective pest management solutions for agriculture.

4.3 Precision Agriculture in Botanical Pest Management

Precision agriculture (PA) integrates advanced botanical pest management for sustainable crop protection, utilizing PA's technological capabilities with eco-friendly pest control methods for targeted pest management. Technologies like GPS, remote sensing, and data analytics enhance botanical pest strategies (Balaji *et al.,* 2024; Tangkesalu *et al.,* 2023). Drones with multispectral sensors detect early pest infestations or plant stress, enabling timely botanical pesticide application (Aldosari, 2024; Gundreddy *et al.,* 2024). This precision reduces pesticide use, minimizes environmental impacts, and supports sustainability (Kayastha *et al.,* 2024; Sharma, 2023). AI and machine learning analyze complex datasets, including soil, weather, and pest data, to optimize pest control strategies (Aldosari, 2024; Divyajyothi *et al.,* 2024). These technologies predict pest outbreaks and tailor botanical pesticide interventions. Integrating advanced botanical pest strategies with PA offers sustainable crop protection, combining precision with ecological benefits for effective management and reduced environmental impacts (Khan, 2024; Khokhar *et al.,* 2024). Challenges like technology access and farmer training must be addressed for widespread adoption (Anand *et al.,* 2023; Sharma, 2023).

5. SUSTAINABLE DEVELOPMENT AND TRANSFORMATIVE STRATEGIES

5.1 Botanical Pest Management and Sustainability Goals

Botanical pest management supports global sustainability by providing eco-friendly alternatives to conventional pesticides, aligning with United Nations Sustainable Development Goals (SDGs) on food security, environmental protection, and sustainable production. Plant-based pesticides in grain storage offer sustainable pest control with low non-target toxicity and compatibility with integrated pest management (Jyoti, 2024), promoting Responsible Consumption and Production (SDG 12). Biologically based pest management strategies, including plant defense mechanisms, enhance sustainable integrated pest management programs (Chidawanyika *et al.,* 2012), contributing to SDG 2 (Zero Hunger) by ensuring food security and reducing environmental impacts. Botanical gardens, like the University of British Columbia Botanical Garden, advance sustainable pest management and contribute to 12 of the 17 SDGs through ex situ plant conservation, sustainability education, and community engagement (Lopez-Villalobos *et al.,* 2022). These institutions serve as crucial research and education centers for sustainable pest management, essential for achieving the SDGs and ensuring long-term ecological and economic sustainability in agriculture, particularly as climate change affects pest dynamics.

5.2 Economic Valuation of Ecological Pest Management

Economic models valuing ecological pest management services reflect the complex dynamics of agricultural ecosystems and market forces. Microeconomic models estimate the value of natural enemy species richness for biological pest control by analyzing market outcomes affected by crop yield changes, supply shifts, and price elasticities (Letourneau *et al.,* 2015). Dynamic bioeconomic optimization models integrate pest and predator dynamics, crop growth, yield damage functions, and managerial decisions to determine optimal insecticide use while considering natural pest control (Zhang & Swinton, 2009). Market forces and technological substitutes can significantly affect ecosystem service valuations over time, even with constant ecosystem functions. For instance, the pest control value provided by Mexican free-tailed bats declined by 79% over 18 years due to Bt cotton adoption, falling cotton prices, and reduced cotton acreage (López-Hoffman *et al.,* 2014). Effective economic models must integrate ecological processes, market dynamics, and management decisions. Economic surplus models (Zhang *et al.,* 2018), benefit-transfer approaches (Wiederholt *et al.,* 2016), and expert-based models (Riggi *et al.,* 2024) have also been used. However, challenges in capturing these systems' complexity require further interdisciplinary collaboration for more comprehensive valuation methods (Naranjo *et al.,* 2015).

5.3 Policy Support for Botanical Pest Control

Policy frameworks are crucial for advancing innovative botanical pest control technologies within Integrated Pest Management (IPM) and sustainable agriculture. Supportive pest management policies are vital for promoting IPM and botanical alternatives (Munyua, 2006). Government backing is essential for the broad adoption of alternative pest management. Policy frameworks can tackle issues like formulation complexities, limited chemical data, and regulatory barriers hindering plant-based pesticides in grain storage (Jyoti, 2024). Despite benefits such as low toxicity to non-target organisms and IPM compatibility, botanical pest control technologies face social and psychological adoption barriers (Jyoti, 2024; Munyua, 2006). Therefore, policies should foster technological innovation and address social adoption aspects. Effective policies should emphasize regulatory support, training, and collaborative research to overcome botanical pest control challenges (Jyoti, 2024; Quiroz *et al.,* 2019). Integrating these solutions into storage practices and agriculture can enhance food security and reduce the risks of synthetic pesticides. Furthermore, policies should encourage participatory approaches and knowledge exchange among stakeholders to facilitate changes in pest management practices (Munyua, 2006; Zhou *et al.,* 2024).

6. ADVANCED MOLECULAR DECODING OF PLANT DEFENCE MECHANISMS

6.1 Secondary Metabolites in Chemical Defence

Plant secondary metabolites are vital for chemical defense against biotic and abiotic stresses (Dhruv *et al.,* 2022). These compounds defend against pathogens and herbivory and play a key role in plant ecological interactions (Gani *et al.,* 2020). They enable plants to swiftly detect and respond to herbivore attacks under changing conditions (Divekar *et al.,* 2022). Secondary metabolites directly poison insect pests, trigger anti-xenosis, and indirectly protect plants by recruiting herbivorous enemies (Divekar et al. 2022). Recent evidence indicates that some secondary metabolites also regulate immune responses, such as callose deposition and programmed cell death, beyond serving as antibiotics (Piasecka *et al.,* 2015). Plant secondary metabolites act via multiple pathways, including direct toxicity, anti-xenosis, indirect protection, and immune regulation. Their diverse nature and ability to accumulate in various tissues at different growth stages make them essential for plant defense (Dhruv *et al.,* 2022; Divekar *et al.,* 2022).

6.2 Molecular Interactions in Pest Disruption

Selective pest control exploits neuropeptide-receptor interactions, endocrine disruption, and charge-based molecular recognition to disrupt essential insect processes (Nachman *et al.,* 1993; Tebourbi *et al.,* 2011; Gelmi *et al.,* 2012). Peptide mimetics designed as agonists or antagonists can disrupt pest survival, while pesticides acting as endocrine disruptors affect hormone secretion or receptor binding, impacting reproduction and development (Nachman *et al.,* 1993; Tebourbi *et al.,* 2011). Pesticides can also disrupt biochemical processes or generate reactive oxygen species, causing toxicity (Tebourbi *et al.,* 2011). Thiabendazole (TBZ) exemplifies selective targeting by disrupting a specific human β-tubulin isotype (TUBB8), affecting endothelial cell microtubules and angiogenesis (Garge *et al.,* 2020). Understanding molecular mechanisms of pesticide action is crucial for developing selective and sustainable pest control strategies while minimizing unintended effects on non-target organisms (Garge *et al.,* 2020).

6.3 Ethnobotanical Insights into Pest Management

Ethnobotanical knowledge can uncover hidden pest management strategies, as several studies have shown. Indigenous communities have preserved effective, eco-friendly, and cost-efficient pest control practices using local plant materials and animal by-products (Meena *et al.,* 2021). Modern agricultural extension officers often overlook sustainable alternatives to chemical pesticides. In the Thulamela municipality, a study found that 71% of extension officers relied on chemical methods, with only 3.2% being aware of biological control using natural enemies (Thovhogi *et al.,* 2022). Farmers in the state of Andhra Pradesh, India have traditionally used leaves of *Vitex negundo*, locally known as "nirgundi," to protect stored grains from pests. Research has confirmed the efficacy of V. negundo extracts against several storage pests, highlighting the scientific basis of this traditional practice (Hebbalkar *et al.,* 1992). This gap between traditional and modern practices highlights the potential of ethnobotanical knowledge to achieve the Sustainable Development Goals (SDGs) for sustainable agriculture and environmental conservation (Kumar *et al.,* 2021; Kumar, 2021). To harness this potential, better documentation, validation, and integration of traditional knowledge with modern science are needed (Reyes-García *et al.,* 2007).

7. CONCLUSION

Botanical pest management represents a comprehensive approach to sustainable agriculture that integrates the biochemical, molecular, and ecological mechanisms of plant defense. Exploiting plant-derived compounds with specific molecular interactions and targeted modes of action provides an environmentally sensitive alternative to synthetic pesticides. This approach leverages complex plant defense mechanisms, biotechnological innovations, and precise intervention strategies to disrupt pest physiological processes while minimizing ecological disruption. These methods demonstrate significant potential for developing more sustainable and ecologically balanced pest management systems that align with global agricultural sustainability objectives.

CONSENT - NOT APPLICABLE

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