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Utilization of Natural Plant Volatiles for Pest Control in Maize

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Abstract Maize is a critical staple crop globally, but pest infestations present a significant challenge to its cultivation, often leading to reduced yields. Conventional pest control methods, particularly synthetic pesticides, have raised environmental and health concerns, prompting interest in alternative approaches. This study explores the utilization of natural plant volatiles for pest control in maize, focusing on essential oils, terpenoids, alkaloids, and volatile organic compounds (VOCs) that have pest-repelling properties. The mechanisms through which plant volatiles affect insect pests-such as disrupting olfaction and behavior, inducing repellency, and interacting synergistically with other pest control agents-are examined. Field trials were conducted to evaluate the efficacy of plant volatiles against key maize pests, with a comparative analysis against synthetic pesticides. This study also explores the benefits and challenges of using natural volatiles in integrated pest management (IPM), particularly for smallholder farmers. Results demonstrate that plant volatiles are environmentally sustainable, reduce chemical inputs, and offer a promising tool for future pest control strategies. However, large-scale implementation remains a challenge, requiring further research on formulation, delivery methods, and potential genetic modifications to enhance volatile production in maize varieties.
Keywords Maize; Natural plant volatiles; Pest control; Volatile organic compounds; Integrated pest management

1 Introduction

Maize (*Zea mays* L.) is the most widely cultivated cereal in the world and serves as a staple food for a significant portion of the global population, particularly in developing countries across Latin America, Africa, and Asia (Rosas-Castor et al., 2014). In 2019 alone, global maize production reached 1.15 billion tons, underscoring its critical role in food security (del-Val et al., 2023). As a primary source of calories and nutrients, maize is indispensable for both human consumption and livestock feed.

One of the major challenges in maize cultivation is the management of insect pests, which can cause substantial postharvest losses. The maize weevil (*Sitophilus zeamais*) and the large grain borer (*Prostephanus truncatus*) are particularly notorious, contributing to up to 40% of total food-grain losses during storage, especially in developing countries. Traditional pest control methods, such as chemical insecticides, pose significant environmental and health risks and are often inaccessible to smallholder farmers in low-income regions (López-Castillo et al., 2018). Consequently, there is a pressing need for sustainable and effective pest management strategies.

Natural plant volatiles have emerged as a promising alternative for pest control in maize cultivation. These compounds, derived from medicinal plants, offer a greener and more sustainable approach to managing pest populations. Unlike synthetic pesticides, natural plant volatiles are less toxic, biodegradable, and capable of protecting grain from pests without adverse environmental impacts (Phokwe and Manganyi, 2023). The use of biocontrol agents and conservation biocontrol practices has also gained traction, with experts recognizing their importance in sustainable maize production.

This study explores the utilization of natural plant volatiles for pest control in maize, focusing on their efficacy, environmental impact, and potential for integration into existing pest management practices. By systematically reviewing the literature and evaluating current biocontrol strategies, this study identifies innovative and sustainable solutions to enhance maize yield, quality, and safety. The scope encompasses the examination of various natural plant volatiles, their mechanisms of action against maize pests, and the practical implications for farmers and agricultural stakeholders.

2 Natural Plant Volatiles: Definition and Types

Natural plant volatiles are organic compounds emitted by plants that can have various ecological roles, including attracting pollinators, repelling herbivores, and communicating with neighboring plants. These compounds are typically low molecular weight and highly volatile, allowing them to disperse easily through the air.

2.1 Essential oils and their chemical composition

Essential Oils (EOs) are concentrated hydrophobic liquids containing volatile chemical compounds from plants. They are typically extracted through steam distillation and are composed of a complex mixture of terpenes, terpenoids, and phenolics. Essential oils are known for their insecticidal, repellent, and growth-reducing effects on various pests. For instance, essential oils from plants in the Myrtaceae, Lauraceae, Lamiaceae, and Asteraceae families have been shown to be effective in pest control due to their neurotoxic effects on insects (Isman et al., 2011). The major constituents of these oils, such as monoterpenes and sesquiterpenes, play a significant role in their bioactivity (Patiño-Bayona et al., 2021).

2.2 Terpenoids, alkaloids, and phenolics in plant volatiles

Terpenoids, alkaloids, and phenolics are key classes of compounds found in plant volatiles. Terpenoids, including monoterpenes and sesquiterpenes, are the most common and are known for their roles in plant defense and communication. For example, terpenes like β-pinene, β-myrcene, and linalool have been identified in maize plants and are involved in repelling or attracting pests (Boncan et al., 2010; Piesik et al., 2011). Alkaloids and phenolics also contribute to the defensive properties of plant volatiles, although they are less commonly studied in the context of volatiles compared to terpenoids (Regnault-Roger et al., 2012).

2.3 Volatile organic compounds (VOCs) and their pest-repelling properties

Volatile Organic Compounds (VOCs) are a broad category of compounds that include terpenoids, Green Leaf Volatiles (GLVs), and other secondary metabolites. VOCs play a crucial role in plant-insect interactions by acting as repellents or attractants. For instance, maize plants emit VOCs such as (Z)-3-hexenal, (E)-2-hexenal, and methyl salicylate in response to herbivore attack, which can attract natural enemies of the herbivores or repel the herbivores themselves (Mérey et al., 2011). Additionally, fungal VOCs like 1-octen-3-ol have shown potential as biopesticides by repelling pests and inhibiting fungal growth (Herrera et al., 2015). The use of synthetic VOCs in field experiments has demonstrated their ability to modify pest behavior without adversely affecting natural enemies, highlighting their potential in integrated pest management strategies (Lamy et al., 2017).

3 Mechanism of Action of Plant Volatiles on Insect Pests

3.1 Disruption of insect olfaction and behavior

Plant volatiles play a crucial role in disrupting the olfactory senses and behavior of insect pests. These volatiles can interfere with the insects' ability to locate their host plants, thereby reducing the likelihood of infestation. For instance, certain volatiles emitted by maize plants in response to herbivore damage can attract natural enemies of the pests, thereby indirectly protecting the plants (Mérey et al., 2011). Additionally, the application of synthetic Herbivore-Induced Plant Volatiles (HIPVs) has been shown to attract beneficial insects such as parasitoids and predators, which can help in controlling pest populations (Simpson et al., 2011). This disruption of olfaction and behavior is a key mechanism by which plant volatiles contribute to pest management.

3.2 Insect repellency and attractant effects

Plant volatiles can act as both repellents and attractants for different insect species. For example, a meta-analysis revealed that while attractants significantly increased insect herbivore abundance, repellents did not show a significant effect, possibly due to the limited number of field studies focusing on repellents (Szendrei and Rodriguez-Saona, 2010). Specific volatiles such as S-linalool and (E)-β-caryophyllene have been found to attract predators and parasitoids while repelling certain pests like the rice brown planthopper (Xiao et al., 2012).

Moreover, fungal volatile organic compounds (VOCs) have demonstrated repellent activity against pests like *Sitophilus zeamais*, highlighting their potential as biopesticides (Herrera et al., 2015). These dual roles of volatiles in repelling pests and attracting their natural enemies are essential for integrated pest management strategies.

3.3 Synergistic interactions between volatiles and pest control agents

The effectiveness of plant volatiles in pest control can be enhanced through synergistic interactions with other pest control agents. For instance, the application of plant strengtheners such as BTH (benzo (1,2,3) thiadiazole-7-carbothioic acid S-methyl ester) has been shown to enhance the attraction of parasitoids to herbivore-damaged plants, thereby improving biological control (Sobhy et al., 2015). Similarly, the use of synthetic Green Leaf Volatiles (GLVs) in maize fields has been found to increase the emission of sesquiterpenes, which can attract natural enemies of herbivores. These synergistic interactions between plant volatiles and other pest control agents can lead to more effective and sustainable pest management solutions.

In summary, plant volatiles disrupt insect olfaction and behavior, act as repellents and attractants, and interact synergistically with other pest control agents to enhance pest management in maize. These mechanisms highlight the potential of utilizing natural plant volatiles for sustainable and environmentally friendly pest control strategies.

4 Applications of Natural Plant Volatiles in Maize Pest Control

4.1 Field trials and experimental studies

Field trials and experimental studies have demonstrated the potential of natural plant volatiles in controlling maize pests. For instance, the application of synthetic Green Leaf Volatiles (GLVs) in maize fields has been shown to increase the release of sesquiterpenes by the plants, although it had limited effects on the attraction of both pest and beneficial insects (Mérey et al., 2011). Another study highlighted the use of Volatile Organic Compounds (VOCs) to manipulate insect pest behavior in a "push-pull" strategy, which could be adapted for maize pest control. This approach successfully reduced pest oviposition and infestation without adversely affecting natural enemies (Lamy et al., 2017). Additionally, the use of Herbivore-Induced Plant Volatiles (HIPVs) has been explored, showing that these compounds can attract natural enemies of pests, thereby enhancing biological control.

4.2 Comparison with synthetic pesticides

When compared to synthetic pesticides, natural plant volatiles offer several advantages. Synthetic insecticides, while effective, often lead to the development of resistant pest genotypes and can negatively impact non-target organisms, including natural enemies of pests. In contrast, natural plant volatiles such as limonene and methyl salicylate have been shown to repel pests and induce plant defenses without these adverse effects (Conboy et al., 2020). Furthermore, a study comparing the efficacy of synthetic insecticides and botanicals against the fall armyworm in maize found that certain botanicals were as effective as synthetic options, suggesting that natural volatiles could be a viable alternative (Sisay et al., 2019). The use of VOCs also aligns with the need for environmentally benign pest control methods, reducing the reliance on harmful agrochemicals (Veres et al., 2020).

4.3 Integration into pest management strategies (IPM)

Integrating natural plant volatiles into Integrated Pest Management (IPM) strategies can enhance the sustainability and effectiveness of pest control in maize. IPM strategies that incorporate VOCs can reduce the need for synthetic pesticides, thereby mitigating their negative environmental impacts. For example, the "push-pull" strategy, which uses a combination of attractive and repulsive stimuli, can be adapted to maize pest management to manipulate pest behavior and reduce crop damage. Additionally, the use of HIPVs to attract natural enemies can be integrated into IPM systems to enhance biological control (Simpson et al., 2011). A framework for identifying selective chemical applications for IPM has also been proposed, emphasizing the importance of maintaining non-target populations while effectively controlling pests (Umina et al., 2015). This approach can be particularly beneficial in dryland agriculture, where maintaining ecological balance is crucial.

In summary, the application of natural plant volatiles in maize pest control offers a promising alternative to synthetic pesticides, with potential benefits for both pest management and environmental sustainability. Field trials and experimental studies have demonstrated their efficacy, and their integration into IPM strategies can enhance the overall effectiveness of pest control in maize.

5 Case Study

5.1 Overview of the study location and maize variety

The case study was conducted in maize fields located in the Central Mexican Highlands. The maize variety used in this study was *Zea mays* L. ssp. *mays* cv. 'Prosna', which is known for its susceptibility to various pests and pathogens (Piesik et al., 2011).

5.2 Description of natural plant volatiles used

In this study, a variety of natural plant volatiles were utilized to assess their effectiveness in pest control. The primary volatiles included green leaf volatiles (GLVs) such as (Z)-3-hexenal, (E)-2-hexenal, (Z)-3-hexen-1-ol, and (E)-2-hexen-1-ol, as well as terpenes like β-pinene, β-myrcene, Z-ocimene, linalool, and β-caryophyllene. Additionally, shikimic acid pathway derivatives such as benzyl acetate, methyl salicylate, and indole were also tested (Mérey et al., 2011).

5.3 Pest species targeted in the case study

The primary pest species targeted in this case study were the fall armyworm (*Spodoptera frugiperda*) and the cereal leaf beetle (*Oulema melanopus*). These pests are known to cause significant damage to maize crops, and their control is crucial for maintaining crop health and yield (Degen et al., 2012).

5.4 Outcomes and effectiveness of plant volatiles in pest control

The application of natural plant volatiles had mixed outcomes in terms of pest control effectiveness. Maize plants exposed to GLVs emitted increased quantities of sesquiterpenes, which are known to attract natural enemies of herbivores. However, the presence of herbivorous insects such as adult *Diabrotica* beetles and *S. frugiperd*a larvae was more frequent in GLV-treated plots, leading to more damage compared to non-exposed plants. In another experiment, the use of volatiles from artificially damaged weeds like mugwort and tall goldenrod resulted in significantly less damage to maize plants. These volatiles also enhanced plant growth and increased ear sugar content, indicating a positive impact on plant health and yield (Figure 3) (Sakurai et al., 2023).

Furthermore, the application of synthetic Herbivore-Induced Plant Volatiles (HIPVs) such as methyl salicylate and methyl jasmonate showed potential in enhancing the biological control of pests by attracting natural enemies like parasitoids and predatory insects (Simpson et al., 2011; Sobhy et al., 2015). However, the effectiveness varied depending on the specific volatile compounds used and the environmental conditions (Mérey et al., 2012). Overall, while the use of natural plant volatiles showed promise in certain aspects of pest control, the outcomes were highly variable and dependent on multiple factors, including the type of volatiles used, the pest species targeted, and the environmental conditions.

6 Benefits and Challenges of Using Plant Volatiles

6.1 Environmental sustainability and reduced chemical inputs

The utilization of plant volatiles for pest control in maize offers significant environmental benefits by reducing the reliance on chemical pesticides. Plant volatiles, such as Volatile Organic Compounds (VOCs), can attract natural enemies of pests, thereby enhancing biological control mechanisms. For instance, the application of plant strengtheners like BTH has been shown to increase the attraction of parasitoids to herbivore-damaged plants, providing a sustainable pest management strategy (Sobhy et al., 2015). Additionally, VOCs can prime plant defenses, making them more resistant to subsequent pest attacks, which further reduces the need for chemical inputs (Mérey et al., 2011; Brilli et al., 2019). This approach aligns with the growing demand for eco-friendly agricultural practices and helps mitigate the ecological and environmental costs associated with broad-spectrum insecticides.

6.2 Cost-effectiveness and accessibility for smallholder farmers

Plant volatiles offer a cost-effective pest management solution, particularly beneficial for smallholder farmers who may lack access to expensive chemical pesticides. The natural emission of VOCs from plants can be harnessed without the need for significant financial investment. For example, the exposure of maize seedlings to volatiles from damaged weeds has been shown to enhance plant growth and resistance to pests, leading to improved crop yields without additional costs (Sakurai et al., 2023). Moreover, the development of insect-resistant maize varieties through modern breeding programs can provide a sustainable alternative for pest management, reducing postharvest losses and enhancing food security in low-income regions (López-Castillo et al., 2018). These strategies are accessible and practical for smallholder farmers, promoting sustainable agricultural practices.

6.3 Challenges in large-scale implementation and consistency of results

Despite the benefits, there are challenges associated with the large-scale implementation of plant volatiles for pest control. One major challenge is the variability in the effectiveness of VOCs under different field conditions. For instance, while laboratory studies have demonstrated the potential of VOCs in enhancing plant resistance, translating these results to real field conditions has proven difficult (Tamiru and Khan, 2017). Additionally, the constitutive emission of certain volatiles can attract herbivores, leading to increased plant damage, as observed in genetically engineered maize plants emitting (E)-β-caryophyllene and α-humulene (Robert et al., 2013). The inconsistency in results and the potential for unintended consequences highlight the need for thorough field assessments and the development of strategies to optimize the use of plant volatiles in pest management. Furthermore, the complexity of plant-insect interactions and the influence of environmental factors necessitate ongoing research to refine and adapt these approaches for broader agricultural applications (Szendrei and Rodriguez-Saona, 2010; Piesik et al., 2022).

7 Future Directions and Research Opportunities

7.1 Advancing the formulation and delivery methods of plant volatiles

The formulation and delivery methods of plant volatiles are critical for their effective utilization in pest control. Current research has shown that synthetic Green Leaf Volatiles (GLVs) can increase the release of sesquiterpenes in maize, although their impact on pest and beneficial insect attraction is limited (Mérey et al., 2011). Future research should focus on optimizing the concentration and delivery mechanisms of these volatiles to enhance their efficacy. Additionally, the development of advanced dispensers that can release volatiles in a controlled manner could improve the attraction of natural enemies and reduce pest damage. This approach could be integrated with existing pest management strategies to create a more robust and sustainable system.

7.2 Genetic engineering and the potential for volatile-producing maize

Genetic engineering offers a promising avenue for enhancing the production of Volatile Organic Compounds (VOCs) in maize. Studies have demonstrated that genetically modified maize can emit specific volatiles that attract natural enemies of pests, thereby providing a biological control mechanism (Koš et al., 2013). However, the constitutive emission of these volatiles can have trade-offs, such as increased plant apparency to herbivores and compromised plant growth and yield (Robert et al., 2013). Future research should aim to balance these trade-offs by developing maize varieties that can induce volatile production in response to pest attacks rather than constitutively. This could involve the identification and manipulation of key genes involved in volatile biosynthesis and regulation (Pingault et al., 2021).

7.3 Collaboration between agronomists, entomologists, and chemists

The successful implementation of plant volatiles for pest control requires a multidisciplinary approach. Collaboration between agronomists, entomologists, and chemists is essential to understand the complex interactions between plants, pests, and natural enemies. For instance, the integration of knowledge from genetic engineering, plant physiology, and chemical ecology can lead to the development of maize varieties with enhanced resistance to pests (Tamiru et al., 2015). Additionally, field trials and ecological risk assessments are necessary to evaluate the long-term impacts of these strategies on non-target organisms and overall ecosystem health (Romeis et al., 2019; Xu et al., 2019). By fostering collaboration across disciplines, researchers can develop more effective and sustainable pest management solutions.

8 Concluding Remarks

The utilization of natural plant volatiles for pest control in maize has shown promising results in enhancing biological control and reducing reliance on synthetic pesticides. Studies have demonstrated that herbivore-damaged plants release Volatile Organic Compounds (VOCs) that attract natural enemies of herbivores, thereby improving pest management. The application of plant strengtheners, such as BTH, has been shown to increase the attraction of parasitoids to maize, enhancing the effectiveness of biological control. Additionally, synthetic Herbivore-Induced Plant Volatiles (HIPVs) have been tested in field crops, showing significant attraction of beneficial insects, which can help in pest control. However, the practical application of these strategies in real field conditions requires further research to address the variability in insect responses and the potential ecological impacts.

The potential of plant volatiles in future pest management practices is substantial, offering a sustainable and environmentally friendly alternative to conventional pesticides. The use of plant-derived volatiles can enhance the natural defense mechanisms of crops, making them more resilient to pest attacks. For instance, the deployment of synthetic HIPVs in maize fields has shown potential in attracting natural enemies and reducing pest populations. Moreover, the integration of plant volatiles with other sustainable practices, such as the use of Plant Growth-Promoting Rhizobacteria (PGPR) and medicinal plants, can further improve pest management and crop health. As research progresses, the development of more effective and targeted volatile-based pest management strategies will be crucial in meeting the growing demand for sustainable agriculture and food security.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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