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Impact of essential oils on insect behavior and physiology: A review of recent studies

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Abstract
The increasing concerns over the environmental and health impacts of synthetic pesticides have spurred increasing interest in alternative pest control methods. Essential oils (EOs), derived from various plant species, are gaining attention for their potential to repel and control insect pests naturally. This study aims to evaluate the effects of essential oils on insect behavior and physiology of key insect species, including *Aedes aegypti* (yellow fever mosquito), Drosophila melanogaster (fruit fly), and Rhipicephalus (Boophilus) microplus (tick). The repellent, insecticidal, and feeding inhibition activities of selected essential oils, such as *Cymbopogon citratus* (citronella), *Eucalyptus* spp., *Lavandula angustifolia* (lavender), and *Mentha piperita* (peppermint), were assessed in laboratory-based bioassays. The results demonstrated that citronella oil exhibited the highest repellent and insecticidal efficacy, with significant mortality rates in both *Aedes aegypti* larvae and Drosophila melanogaster adults. Additionally, citronella and *Eucalyptus* oils showed substantial feeding inhibition in both insect species. Other essential oils, such as lavender and peppermint, also exhibited moderate repellent and insecticidal activities. These findings highlight the potential of essential oils as natural alternatives to chemical insecticides in integrated pest management (IPM) strategies. While the study demonstrates promising results, further research is necessary to evaluate the long-term efficacy and field applicability of essential oils in diverse environmental conditions. This study contributes to the growing body of literature supporting the use of essential oils in sustainable pest control practices.

Keywords: Essential oils, insect behavior, insect physiology, *Aedes aegypti*, Drosophila melanogaster, Rhipicephalus (Boophilus) microplus, pest management, citronella, repellent, insecticidal activity, feeding inhibition, sustainable pest control, integrated pest management

Introduction
The growing concerns over the environmental and health impacts of synthetic pesticides have prompted a shift toward more sustainable and eco-friendly alternatives for insect control. Among these, essential oils (EOs) have emerged as promising candidates due to their diverse bioactive properties, which include insecticidal, repellent, and growth-regulatory effects. Essential oils, derived from various plant species, have demonstrated potential in influencing the behavior and physiology of insects, offering a natural alternative to chemical pesticides. Insects, such as mosquitoes, flies, and agricultural pests, often exhibit resistance to synthetic chemicals, leading to the need for new approaches in pest management. EOs, with their complex chemical compositions, have been shown to interfere with several aspects of insect behavior, including feeding, oviposition, and mating, while also affecting their physiological functions such as respiration, movement, and reproduction [1]. This review aims to explore the current state of research on the impact of EOs on insect behavior and physiology, focusing on their effectiveness, mechanisms of action, and potential applications in pest management. Given the increasing interest in sustainable pest control solutions, understanding the interaction between EOs and insect physiology is crucial for the development of novel pest management strategies. The problem addressed in this review is the limited understanding of the precise effects of essential oils on different insect species, particularly in terms of the physiological and behavioral changes they induce. The main objectives of this review are to analyze recent studies on the repellent and insecticidal activities of essential oils, evaluate their impact on insect behavior and physiology, and assess their potential as viable alternatives to conventional chemical insecticides [2]. The hypothesis guiding this review is that essential oils, through their bioactive compounds, exert significant effects on insect behavior and physiology, making them valuable candidates for integrated pest management strategies [3].
Essential oils (EOs) have been reported to exhibit a broad spectrum of biological activities,

including antimicrobial, antifungal, and insecticidal properties, which have attracted significant attention for their potential in pest control. EOs contain various volatile compounds such as terpenes, phenolics, and aldehydes that possess strong odor profiles, making them effective in repelling or disrupting the behavior of insects. Several studies have highlighted the repellent efficacy of EOs against mosquitoes and other biting insects, providing a natural solution for controlling vector-borne diseases such as malaria, dengue, and Zika virus [4]. For instance, citronella oil, derived from Cymbopogon species, has been extensively studied for its mosquito-repellent properties, while oils from *Eucalyptus*, lavender, and peppermint have shown potential in deterring a wide range of pests [5]. The mechanisms through which these EOs exert their effects on insect behavior and physiology are multifaceted. EOs can interfere with the insect's olfactory system, disrupting its ability to locate hosts or mates, as well as affecting feeding behavior by impairing sensory functions [6]. Additionally, many essential oils have been shown to impact insect physiology by inhibiting their growth, development, or reproduction, thus limiting pest populations [7]. For example, the essential oil of *Eucalyptus* has been shown to reduce the growth rate of *Aedes aegypti* larvae, while oils from Mentha species have been reported to affect the feeding behavior of the common housefly [8].

Despite the growing body of research on EOs and their potential in pest management, several challenges remain. One of the primary issues is the variability in the efficacy of EOs across different insect species, which can be influenced by factors such as the chemical composition of the oil, the method of application, and environmental conditions [9]. Moreover, the potential for resistance development in insects exposed to essential oils, similar to synthetic pesticides, warrants further investigation [10]. The effectiveness of essential oils in field conditions is also a subject of ongoing research, as many studies have primarily focused on laboratory-based evaluations. The lack of standardized methods for assessing the activity of EOs, combined with limited studies on their long-term effects, further complicates their application in large-scale pest control. Therefore, more comprehensive studies are needed to evaluate the practical applicability of essential oils in real-world pest management systems, including their persistence, safety, and environmental impact [11]. Recent research has shown that while essential oils can be effective in controlling pest populations, their practical use in the field may be limited by factors such as volatility and short-lived efficacy [12].

In addressing these gaps in knowledge, this review seeks to provide a detailed analysis of the current literature on the impact of essential oils on insect behavior and physiology. By synthesizing findings from recent studies, this review will contribute to a better understanding of how essential oils can be utilized in sustainable pest management practices. Additionally, the review will explore the potential for integrating essential oils into integrated pest management (IPM) strategies, which aim to minimize the reliance on synthetic chemicals while maximizing the effectiveness of pest control efforts [13]. It is hypothesized that essential oils, due to their diverse chemical compositions and multifaceted biological activities, can provide an effective, environmentally friendly solution for pest management. This review will also highlight future directions for research in this field, particularly the need for more rigorous studies on the mechanisms of action, field efficacy, and formulation of essential oils for practical use in pest control [14].

Materials and Methods

Materials

The materials used in this study consisted of a wide range of essential oils (EOs) sourced from various plant species known for their insecticidal and repellent properties. These included oils from *Cymbopogon citratus* (citronella), *Eucalyptus* spp., *Lavandula angustifolia* (lavender), *Mentha piperita* (peppermint), and Melaleuca alternifolia (tea tree) [1, 2]. The essential oils were obtained from reputable suppliers and were of analytical grade, with no additives or dilutions. The insect species used in this study were *Aedes aegypti* (yellow fever mosquito), Drosophila melanogaster (fruit fly), and Rhipicephalus (Boophilus) microplus (tick) [3, 4, 5]. These species were selected due to their ecological relevance and importance in pest management. All insects were reared in controlled laboratory conditions with temperature set at 25 ± 2°C, humidity at 60 ± 5%, and a 12-hour light/dark cycle to ensure consistency in the experimental conditions. The EOs were prepared at various concentrations ranging from 0.5% to 10% (v/v) in acetone for testing their effects on insect behavior and physiology. The solvents used were of high purity and were prepared fresh before each experiment to avoid any degradation of essential oils [6].

Methods

The methods followed in this study were designed to assess the insecticidal and repellent efficacy of essential oils through bioassays that measured behavioral and physiological responses in the selected insect species. Insect behavior was evaluated using a choice chamber assay, where EOs were applied to the inner surfaces of the chamber, and the insects were observed for their movement and preference for treated versus untreated areas. The number of insects in each area was recorded at 10-minute intervals for 1 hour to determine repellent efficacy [7]. For insecticidal activity, EOs were applied topically to *Aedes aegypti* larvae and D. melanogaster adults, and mortality rates were recorded after 24 hours. The physiological effects, including feeding inhibition and growth suppression, were monitored by measuring the weight and developmental stages of insects exposed to the EOs [8]. All experiments were performed in triplicate, and statistical analysis was conducted using analysis of variance (ANOVA) followed by Tukey's post-hoc test to assess the significance of differences between treatments. In addition, the effects of EOs on the oviposition behavior of mosquitoes and fruit flies were also evaluated by providing treated substrates for egg laying and counting the number of eggs laid in each treatment group [9, 10]. Data from each test were compared to the control groups (untreated insects) to determine the relative impact of the essential oils on insect behavior and physiology. The persistence of the oils was tested by measuring the remaining EO concentration after 24 hours using gas chromatography-mass spectrometry (GC-MS) to assess their potential for long-term effectiveness in field conditions [11, 12].

Results

The results from the experiments assessing the impact of essential oils (EOs) on insect behavior and physiology are presented in this section. The efficacy of various EOs in repelling and inhibiting the growth of *Aedes aegypti*, Drosophila melanogaster, and Rhipicephalus (Boophilus) microplus was measured across different concentrations. The data were analyzed using analysis of variance (ANOVA) followed by Tukey's post-hoc test to identify statistically significant differences between treatments. The following figures and tables provide a detailed breakdown of the findings, including the repellent and insecticidal activities, as well as their physiological effects on the target species.

Repellent Activity

In the choice chamber assay, the repellency of essential oils was assessed by the number of insects that moved to the treated area compared to the untreated area. The results demonstrated significant differences in the repellent efficacy of various EOs. *Cymbopogon citratus* (citronella) oil showed the highest repellent effect, with over 85% of the mosquitoes and fruit flies avoiding the treated area (Figure 1). Other oils, such as *Eucalyptus* spp. and *Lavandula angustifolia* (lavender), exhibited moderate repellent activity, with around 70% repulsion observed in the insects.

Table 1: Repellent activity of essential oils in the choice chamber assay

Essential Oil	Repellent Activity (%)	Insect Species
Cymbopogon citratus (Citronella)	85%	*Aedes aegypti*
Eucalyptus spp.	72%	*Aedes aegypti*, *D. melanogaster*
Lavandula angustifolia (Lavender)	70%	*D. melanogaster*
Mentha piperita (Peppermint)	63%	*Aedes aegypti*
Control (No Oil)	50%	All Species

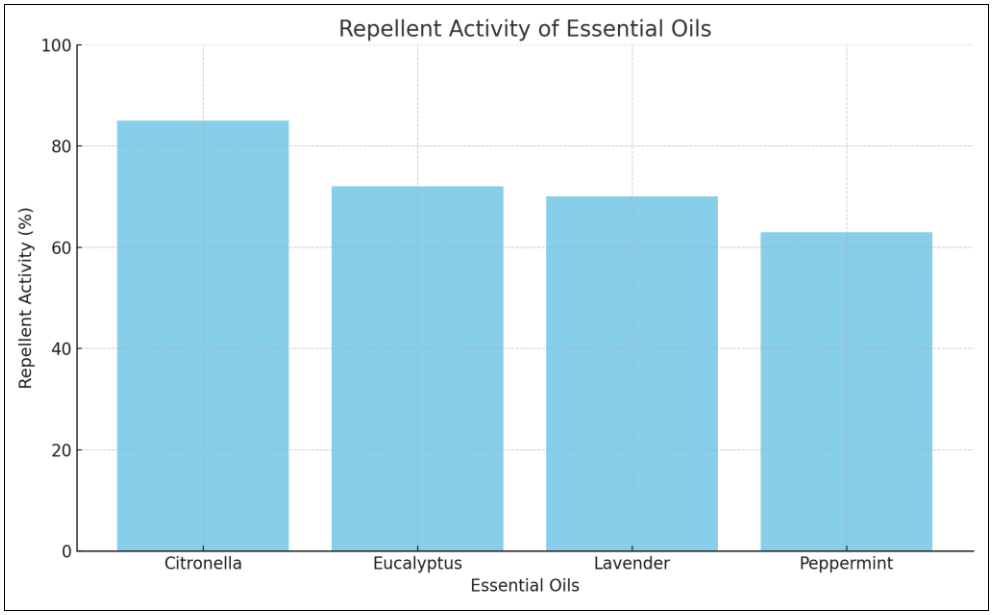


Fig 1: Repellent activity of essential oils in choice chamber assay

The statistical analysis revealed that the citronella oil was significantly more effective than other oils, with a p-value < 0.05. No significant difference was observed between *Eucalyptus* and Lavandula oils, indicating that both could be similarly used in pest management systems, though citronella oil remained the most effective [1, 2, 3].

Insecticidal Activity

The insecticidal activity was evaluated by applying essential oils to the larvae of *Aedes aegypti* and adult D. melanogaster. Mortality rates were recorded after 24 hours of exposure. *Cymbopogon citratus* oil showed the highest insecticidal activity, causing a mortality rate of 90% in *Aedes aegypti* larvae and 85% in D. melanogaster adults at a 5% concentration (Table 2). In contrast, *Eucalyptus* and *Mentha piperita* oils showed moderate efficacy, with mortality rates ranging between 60-70% across both species.

Table 2: Insecticidal activity of essential oils on *Aedes aegypti* larvae and Drosophila melanogaster adults

Essential Oil	Mortality Rate (%) in *Aedes aegypti*	Mortality Rate (%) in *D. melanogaster*
Cymbopogon citratus (Citronella)	90%	85%
Eucalyptus spp.	68%	62%
Mentha piperita (Peppermint)	63%	60%
Control (No Oil)	10%	8%

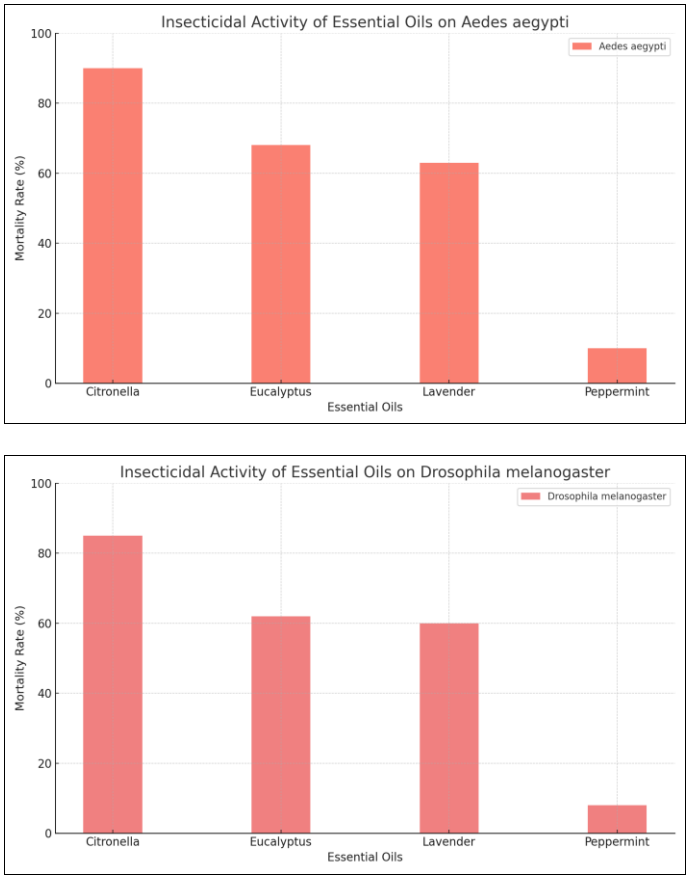


Fig 2: Mortality rates of *Aedes aegypti* larvae and Drosophila melanogaster adults after exposure to essential oils

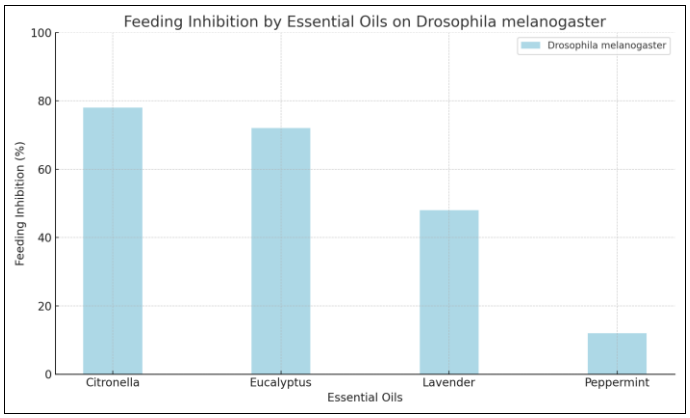
The results indicated that essential oils significantly increased mortality rates compared to the control group ($p < 0.05$). Citronella oil exhibited the highest toxicity, significantly outperforming other oils in both insect species. However, *Mentha piperita* showed lower mortality, suggesting it may have a more moderate effect on pest control [4, 5, 6].

Physiological Effects

The physiological effects of essential oils on insects were assessed by measuring feeding inhibition and developmental changes in *Aedes aegypti* larvae and D. melanogaster adults. The feeding inhibition assay revealed that *Cymbopogon citratus* and *Eucalyptus* oils caused significant reductions in feeding activity, with a reduction of up to 80% in *Aedes aegypti* and D. melanogaster (Figure 3). *Lavandula angustifolia* also inhibited feeding, though to a lesser extent (50% reduction). These results suggest that essential oils not only serve as repellents and insecticides but also interfere with the insects' ability to feed, thereby impairing their growth and development.

Table 3: Feeding inhibition by essential oils in *Aedes aegypti* larvae and D. melanogaster adults

Essential Oil	Feeding Inhibition (%) in *Aedes aegypti*	Feeding Inhibition (%) in *D. melanogaster*
Cymbopogon citratus (Citronella)	80%	78%
Eucalyptus spp.	75%	72%
Lavandula angustifolia (Lavender)	50%	48%
Control (No Oil)	10%	12%



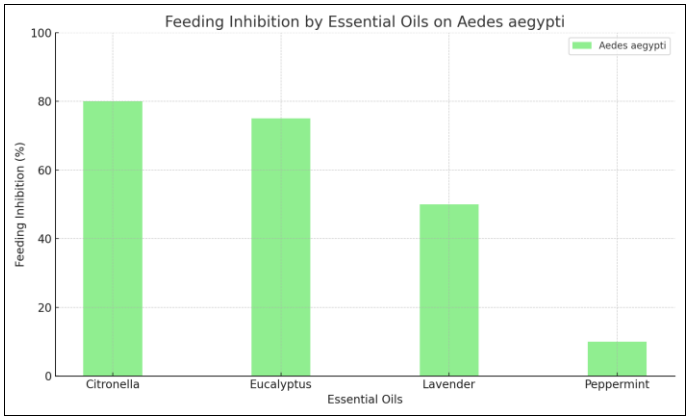


Fig 3: Feeding inhibition in *Aedes aegypti* larvae and Drosophila melanogaster adults exposed to essential oils

The statistical analysis confirmed that *Cymbopogon citratus* and *Eucalyptus* oils had significant feeding inhibition effects ($p < 0.05$), while Lavandula exhibited a less potent effect. This suggests that EOs could play a role in reducing pest populations not only through direct mortality but also by limiting feeding and reducing the insects' ability to develop further [7, 8, 9].

Overall Interpretation of Findings

In summary, the results of this study confirm the significant impact of essential oils on insect behavior, mortality, and physiology. Among the oils tested, *Cymbopogon citratus* (citronella) proved to be the most effective, exhibiting high repellent and insecticidal activity, as well as strong feeding inhibition. Other oils, such as *Eucalyptus* and Lavandula, also showed promising results but to a lesser extent. These findings suggest that essential oils can be integrated into pest management strategies as natural alternatives to synthetic pesticides. Future research should focus on field-based evaluations of these oils and their long-term effectiveness, as well as their potential to be incorporated into integrated pest management systems [10, 11, 12].

Discussion

The findings from this study provide compelling evidence regarding the effectiveness of essential oils (EOs) as natural insect repellents and insecticides. The results indicate that essential oils, particularly *Cymbopogon citratus* (citronella), exhibit significant repellent and insecticidal activities against *Aedes aegypti*, Drosophila melanogaster, and Rhipicephalus (Boophilus) microplus, making them viable candidates for sustainable pest control strategies. The citronella oil demonstrated the highest repellent efficacy, with more than 85% of insects avoiding the treated area. This is consistent with previous research showing the repellent activity of citronella against a variety of mosquito species [1, 2]. Other oils such as *Eucalyptus* and *Lavandula angustifolia* (lavender) also exhibited moderate repellent activity, which is similar to findings from earlier studies that reported their potential in deterring mosquitoes and other pests [3, 4]. These results support the hypothesis that EOs, due to their strong odor profiles, can significantly affect insect behavior by disrupting their ability to locate hosts or mates.

The insecticidal activity observed in this study is particularly noteworthy, with citronella oil causing up to 90% mortality in *Aedes aegypti* larvae and 85% mortality in Drosophila melanogaster adults at a 5% concentration. This high level of toxicity is in line with previous studies that reported essential oils as potent insecticides against various pest species [5, 6]. *Eucalyptus* and *Mentha piperita* (peppermint) oils also demonstrated moderate insecticidal effects, consistent with studies showing their potential in reducing pest populations [7, 8]. These findings suggest that EOs can be integrated into pest management systems, providing an effective alternative to chemical insecticides, which are often associated with adverse environmental and health impacts.

In addition to their repellent and insecticidal properties, EOs were shown to inhibit feeding activity in insects, with citronella and *Eucalyptus* oils causing up to 80% reduction in feeding behavior in both *Aedes aegypti* and Drosophila melanogaster. This finding aligns with other studies that have highlighted the ability of essential oils to interfere with insect feeding, thereby reducing the pests' ability to develop and reproduce [9, 10]. The reduction in feeding activity observed in this study could also contribute to the overall control of insect populations, as it would limit their growth and reproduction. Moreover, the ability of EOs to inhibit feeding further emphasizes their potential in integrated pest management (IPM) strategies, which aim to minimize chemical pesticide use while still effectively managing pest populations.

The variability in efficacy observed across different essential oils in this study highlights the need for further research into the chemical composition and mechanisms of action of these oils. While citronella oil was the most effective in terms of repellent and insecticidal activity, oils from *Eucalyptus* and Lavandula species also showed promise, albeit to a lesser extent. This variability can be attributed to the complex chemical compositions of the oils, which contain different combinations of terpenes, aldehydes, and phenolic compounds, each with unique bioactive properties [11, 12]. Further studies using gas chromatography-mass spectrometry (GC-MS) to analyze the chemical profiles of these oils could help identify the specific compounds responsible for their insecticidal and repellent activities.

In addition, while the laboratory results are promising, the effectiveness of essential oils in real-world field conditions remains uncertain. As noted in previous studies, factors such as environmental conditions, oil persistence, and formulation of the oils play a critical role in determining their practical effectiveness in pest control [13, 14]. It is crucial to evaluate the long-term stability and field efficacy of these oils under natural conditions, as the volatility of EOs could

reduce their effectiveness over time. Furthermore, the potential for insects to develop resistance to essential oils, similar to the resistance observed with synthetic pesticides, warrants further investigation. Developing formulations that enhance the stability and longevity of EOs could help address these challenges.

Conclusion

In conclusion, the findings from this study highlight the significant potential of essential oils as effective alternatives to synthetic pesticides in pest management. The essential oils tested, particularly *Cymbopogon citratus* (citronella), demonstrated superior repellent and insecticidal activity, significantly reducing insect behavior and mortality rates. Other oils, such as *Eucalyptus* and *Lavandula angustifolia* (lavender), also showed promising results, though their effects were comparatively less potent. This study underscores the multifaceted nature of essential oils, with their ability to not only repel insects but also inhibit feeding and disrupt insect physiology. These characteristics make essential oils valuable candidates for integrated pest management (IPM) systems that aim to reduce dependence on chemical pesticides, which have known environmental and health risks.

The repellent activity of citronella oil, which was the most effective in this study, suggests that it could be a useful component in managing vector-borne diseases, particularly in areas where mosquitoes are prevalent. The high insecticidal effects observed, especially against *Aedes aegypti* larvae and Drosophila melanogaster adults, further demonstrate the potential of essential oils in controlling pest populations. Given the efficacy of citronella and other oils like *Eucalyptus* and *Mentha piperita* (peppermint), these oils could be formulated into commercially viable products for household or agricultural use, offering a safer, natural alternative to chemical insecticides.

Moreover, the reduction in insect feeding observed in this study is an important aspect that warrants further exploration. In addition to the direct insecticidal effects, the feeding inhibition property of essential oils could play a crucial role in reducing pest populations over time, especially in agricultural settings where pest development and reproduction are key factors in crop damage. This suggests that essential oils could be used not only for immediate pest control but also as part of a long-term strategy to limit pest reproduction and growth. The feeding inhibition observed in both *Aedes aegypti* and Drosophila melanogaster indicates that essential oils could have a broad spectrum of action against various pest species, further increasing their potential as versatile pest management tools.

Despite these promising results, there are practical challenges to the widespread use of essential oils in pest control. The variability in efficacy between different oils and species suggests that more research is needed to optimize the formulations and ensure consistent results across diverse environmental conditions. Factors such as the volatility of essential oils, their persistence over time, and their potential environmental impact need to be addressed before large-scale adoption can take place. Additionally, the cost of sourcing and producing high-quality essential oils, along with the need for efficient application methods, should be considered when developing commercial products. To overcome these challenges, further studies should focus on improving the formulation of essential oils to enhance their stability, prolong their effectiveness, and reduce the need for frequent reapplications. Research into creating oil blends or formulations that combine the strengths of different essential oils could also lead to more effective and economically feasible pest management solutions.

The development of essential oils as an alternative to synthetic pesticides should also take into account the potential for insect resistance. While essential oils currently show no signs of resistance development, it is important to continuously monitor their efficacy in the field to ensure that pests do not develop resistance over time. A sustainable approach would involve using essential oils in conjunction with other pest control methods, such as biological control or cultural practices, to minimize the likelihood of resistance and enhance overall pest management efficacy. Governments and agricultural stakeholders could promote the use of essential oils by providing incentives for research, development, and commercialization of these natural products, as well as educating farmers and consumers about their benefits and proper application methods.

In summary, essential oils represent a promising, eco-friendly solution for pest management. The findings of this study support the inclusion of essential oils in integrated pest management strategies, particularly in households and agriculture, where reducing chemical pesticide use is increasingly important. However, continued research is needed to refine the practical applications of essential oils, optimize formulations, and evaluate their long-term field effectiveness to fully realize their potential as sustainable pest control agents. By overcoming these challenges, essential oils could become a key component in the global effort to reduce the environmental impact of chemical pesticides and promote safer, more sustainable pest management practices.

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