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Review article

Harnessing the power of cinnamon oil: A review of its potential as natural biopesticide and its implications for food security

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ABSTRACT

The escalating concerns about the environmental and health impacts of synthetic pesticides have intensified the search for sustainable and effective alternatives. Cinnamon oil, derived from the bark of Cinnamomum species, has emerged as a promising candidate in this arena due to its potent biopesticidal properties. This review explores the multifaceted role of cinnamon oil in agricultural pest management, emphasizing its potential to contribute significantly to food security. We discuss the bioactive components of cinnamon oil, their modes of action against various pests, and the effectiveness of cinnamon oil formulations. The review also addresses the challenges associated with the consistency and efficacy of cinnamon oil, its regulatory landscape, and the economic considerations for its use on a larger scale. By integrating findings from recent studies, this review underscores the viability of cinnamon oil as a cornerstone in future sustainable agricultural practices, aiming to reduce dependency on chemical pesticides and enhance global food security.

1. Introduction

The extensive reliance on synthetic pesticides in modern agriculture has led to numerous health and environmental concerns, making their impact a subject of increasing scrutiny [1]; [2]. These chemical agents, designed to protect crops from pests, often contain toxic compounds that can have detrimental effects on human health. Residues from synthetic pesticides frequently remain on fruits and vegetables, entering the food chain and exposing consumers to potential health risks, including hormone disruption, carcinogenesis, and neurotoxicity [3]; [4]. Beyond their impact on human health, synthetic pesticides also pose significant threats to the environment. Their persistence in soil and water bodies can lead to contamination, affecting non-target organisms, reducing biodiversity, and

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List of abbreviations

IPM - Integrated Pest Management
SC-CO2 - Supercritical Carbon Dioxide
EO - Essential Oil
LC50 - Lethal Concentration 50
LC90 - Lethal Concentration 90
MAE - Microwave-Assisted Extraction
UAE - Ultrasound-Assisted Extraction
PDA - Potato Dextrose Agar
DPPH - 2,2-Diphenyl-1-Picrylhydrazyl (a common antioxidant assay)
ABTS - 2,2′-Azino-Bis(3-Ethylbenzothiazoline-6-Sulfonic Acid) (another antioxidant assay)
GC-MS - Gas Chromatography-Mass Spectrometry
CAS No. - Chemical Abstracts Service Number
QE - Quercetin Equivalents
DW - Dry Weight
T - Temperature
P - Pressure
% - Percent

disrupting natural ecosystems [5]. Furthermore, the overuse of these chemicals has led to the development of resistant pest species, necessitating higher doses and stronger formulations, thereby perpetuating a cycle of dependency and escalating harm.

In light of these challenges, cinnamon oil has gained attention as a viable alternative, offering a natural solution to the problems posed by synthetic pesticides. Derived from the bark and leaves of the Cinnamomum species, cinnamon oil is rich in bioactive components such as cinnamaldehyde, eugenol, and linalool, which have demonstrated strong antimicrobial, antifungal, and insecticidal properties ([6,7]; B. [8,9]). Unlike synthetic pesticides, cinnamon oil is biodegradable and less likely to accumulate in the environment, reducing the risk of long-term ecological damage. Studies have shown that cinnamon oil can effectively control a variety of agricultural pests, including insects, fungi, and bacteria, making it a versatile tool in pest management [10]. Additionally, its natural origin and low toxicity profile make cinnamon oil a safer option for both farmers and consumers, aligning with the growing demand for organic and sustainable agricultural products.

The importance of natural pesticides in sustainable agriculture cannot be overstated. As global agricultural practices shift towards more sustainable methods, there is a critical need to reduce the reliance on synthetic inputs that contribute to environmental degradation [11,12]. Natural pesticides, such as cinnamon oil, offer a promising alternative that can help maintain agricultural productivity while minimizing harm to the environment. By integrating natural biopesticides into existing pest management strategies, farmers can enhance the resilience of their crops, promote soil health, and protect beneficial organisms that contribute to a balanced ecosystem. This approach not only supports the long-term sustainability of agricultural systems but also helps meet the increasing consumer demand for food products that are free from synthetic chemicals.

Given the potential of cinnamon oil as a natural biopesticide, this review is essential for consolidating the current state of knowledge and identifying trends in its application. By systematically analyzing the existing literature, the review aims to provide a comprehensive understanding of the efficacy, mechanisms, and practical applications of cinnamon oil in pest control [13,14]. It will also highlight the gaps in research, offering insights into areas that require further investigation. This synthesis of information is crucial for guiding future studies, informing policy decisions, and promoting the adoption of cinnamon oil as a viable component of sustainable agricultural practices.

The primary objective of this review is to assess the role of cinnamon oil as a biopesticide, focusing on its effectiveness in pest control, the methods of application, and its environmental impact. Additionally, the review seeks to explore the challenges associated with the commercialization and widespread use of cinnamon oil in agriculture. By evaluating these aspects, the review aims to contribute to the development of more sustainable and effective pest management strategies, ultimately supporting the broader goal of achieving sustainability in global agricultural practices.

2. Methodology review

The methodology for this review involved a systematic and comprehensive search of relevant literature on the use of cinnamon oil as a biopesticide. Various sources were utilized to gather the most recent and relevant studies, including reputable academic databases and search engines such as Scopus. Additionally, digital libraries like ScienceDirect and Wiley Online Library were consulted to ensure a broad and inclusive collection of research articles, reviews, and conference papers. These sources were chosen for their reliability and the wide range of high-impact journals they encompass, offering a robust basis for this review.

The criteria for selecting materials focused on relevance, geographical context, publication date, and methodological rigor. Publications were limited to those released within the last ten years to capture the most current research trends and technological advancements in the use of cinnamon oil as a biopesticide. Studies from diverse geographical contexts were included to provide a comprehensive view of how cinnamon oil's effectiveness varies across different environmental and agricultural settings. Priority was given to studies involving experimental research, field trials, or meta-analyses, as these provide empirical evidence for the biopesticidal effects of cinnamon oil and its practical applications.

To synthesize the information, relevant studies were organized by thematic areas, including the effectiveness of cinnamon oil on specific pest types, its mode of action, and its integration into broader pest management strategies. Information was then analyzed and compared to identify common findings, trends, and gaps in the existing literature. This structured approach allowed for a thorough examination of cinnamon oil's potential as a biopesticide, ensuring that the review is both comprehensive and analytically rigorous.

3. Food security and the role of cinnamon oil in sustainable agriculture

Cinnamon oil's role as a natural biopesticide has significant implications for global food security. The growing concerns over the environmental impact and health risks associated with synthetic pesticides have driven the need for safer, more sustainable alternatives. By integrating cinnamon oil into pest management strategies, agriculture can be made more sustainable, ensuring that food production systems are safer and more resilient. For instance, studies like those by Tajdar, Ishfaq, Sarmad, and Zaka [15] and Aljedani [16] have demonstrated cinnamon oil's effectiveness against pests such as *Bactrocera zonata* and termites. These pests are major threats to food crops, particularly in regions where food security is already precarious. By controlling these pests more effectively, cinnamon oil helps secure crop yields, which is crucial for maintaining the stability of food supplies.

The role of cinnamon oil extends beyond mere pest control; it is a key component of Integrated Pest Management (IPM) strategies. IPM promotes the use of a combination of biological, cultural, and chemical methods to manage pest populations sustainably. By reducing the reliance on synthetic pesticides, which are known for their detrimental environmental effects and potential health hazards, cinnamon oil supports a more balanced and environmentally friendly approach to agriculture [17]. The effectiveness of cinnamon oil, as demonstrated by studies such as those by Jian, Li et al. [18], highlights its potential to enhance the efficacy of IPM strategies, making it a critical tool in ensuring food security through sustainable agricultural practices.

Moreover, the localized production of cinnamon oil in regions where cinnamon is naturally grown can play a pivotal role in food security. Producing biopesticides locally reduces dependence on imported chemical pesticides, which often have a higher environmental footprint due to transportation and production processes [19]. This not only lowers the costs for farmers but also strengthens local economies by creating new opportunities in the agricultural and manufacturing sectors. The focus on local production also aligns with broader sustainability goals, reducing the carbon footprint associated with pesticide production and distribution while providing farmers with more accessible and affordable pest management solutions.

In addition to these benefits, the adoption of cinnamon oil as a biopesticide contributes to the overall health of food production systems [20]. Synthetic pesticides, while effective, can leave harmful residues on food products, posing health risks to consumers. In contrast, natural biopesticides like cinnamon oil offer a safer alternative that minimizes these risks. This shift towards using natural products in agriculture not only enhances food safety but also meets the increasing consumer demand for organic and sustainably produced food, further contributing to food security by ensuring a stable market for farmers.

In conclusion, cinnamon oil's integration into agricultural practices offers a comprehensive solution to enhancing global food security. Its effectiveness in pest control, compatibility with sustainable farming practices, and potential for local production make it a vital component of future strategies aimed at ensuring a stable, safe, and sustainable food supply. Addressing the challenges of consistency, cost, and regulatory approval will be key to realizing the full potential of cinnamon oil in securing food systems worldwide.

4. Cinnamon oil: a natural biopesticide

4.1. Botanical background of cinnamon (Cinnamomum spp)

Cinnamon, derived from the inner bark of trees belonging to the genus *Cinnamomum*, is one of the oldest and most celebrated spices in the world. This genus comprises over 250 species, but the most commercially significant types are *Cinnamomum verum* (Ceylon cinnamon or "true cinnamon") and *Cinnamomum cassia* (Cassia or Chinese cinnamon). These species are native to South Asia and Southeast Asia, with extensive cultivation in Sri Lanka, India, Bangladesh, and China [21]. The botanical distinction between these species lies in their aromatic oil content and molecular composition, which confer different flavors, aromas, and medicinal properties.

Cinnamomum verum is grown primarily in Sri Lanka and parts of India and the Caribbean. It is highly prized for its delicate, sweet flavor and lower coumarin content, making it ideal for culinary uses that require a refined taste [22]. In contrast, *Cinnamomum cassia* is known for its stronger, more pungent flavor and higher coumarin content, which is why it is commonly used in the food industry and for bulk spice processing. The process of harvesting cinnamon involves cutting the stems of the cinnamon trees and then scraping off the outer bark. The inner bark is then extracted and dried. During drying, it curls up into rolls known as cinnamon sticks. These sticks can be ground to produce cinnamon powder. The essential oil, which is used as a biopesticide, is primarily extracted through steam distillation of these dried barks, and it contains active compounds such as cinnamaldehyde, eugenol, and linalool.

From a botanical perspective, the growth and cultivation of cinnamon require specific climatic conditions, with optimal growth occurring in warm and moist environments. The trees are also subject to various pests and diseases, which ironically, cinnamon oil itself can help manage due to its potent antimicrobial properties. Understanding the botanical background of *Cinnamomum* spp. is crucial for researchers and agricultural practitioners, as it informs the sustainable cultivation practices, harvesting techniques, and proper extraction methods that maximize the quality and efficacy of cinnamon oil used in pest control. This knowledge base supports the broader application of cinnamon oil in sustainable agriculture, emphasizing its role not only as a spice but also as a valuable biopesticidal agent.

4.2. Extraction methods of cinnamon oil

Cinnamon bark is a valuable source of bioactive compounds with potential health benefits, such as cinnamaldehyde, cinnamic acid, and eugenol. However, traditional methods of cinnamon bark extraction involve using solvents that can harm the environment and human health [23]. As a result, there has been growing interest in developing more sustainable and environmentally friendly green extraction processes for cinnamon bark. Green extraction processes involve the use of solvents and techniques that are environmentally friendly and sustainable. These processes include supercritical fluid extraction, microwave-assisted extraction, and ultrasound-assisted extraction. Supercritical fluid extraction involves using a supercritical fluid, such as carbon dioxide, as a solvent to extract the bioactive compounds from cinnamon bark. This process is environmentally friendly and is more efficient than traditional solvent extraction.

Table 1 presents a detailed comparison of various green extraction methods used to extract active compounds from cinnamon bark, including Supercritical CO_2 (SC-CO_2), Microwave-Assisted Extraction (MAE), and Ultrasound-Assisted Extraction (UAE). Each method is characterized by distinct operational parameters, yields, and concentrations of key active compounds, offering insight into how different extraction techniques affect the efficiency and quality of the extracted products. The parameters listed include extraction pressure, temperature, time, solid-to-solvent ratio, and power, allowing for a comprehensive analysis of the efficacy of each method in isolating target compounds from cinnamon bark.

Supercritical CO_2 (SC-CO_2) Extraction is represented in the table with several variations in pressure, temperature, time, and flow rate. Baseri, Lotfollahi, and Asl [24] utilized SC-CO_2 at a pressure of 24 MPa and a temperature of 60 °C over 40 min, resulting in an 8 % yield of essential oil with a high concentration of cinnamaldehyde (70–98 %) and smaller amounts of α-murolene, eugenol, α-caryophyllene, and γ-murolene, ranging from 1 % to 8 %. This indicates that SC-CO_2 under these conditions is particularly effective at extracting cinnamaldehyde, a primary bioactive component in cinnamon. Another SC-CO_2 study by Zhao and Liang [25] operated at slightly lower conditions (22.5 MPa and 50 °C) for a longer time (120 min), resulting in a 5 % yield, although specific compounds were not mentioned, indicating potential variability in compound extraction efficiency based on process parameters. Masghati and Ghoreishi [26] explored different SC-CO_2 conditions, focusing on single compounds rather than yield. With settings of 20.3 MPa, 68.2 °C, and a flow rate of 1.8 mL/min for 95.7 min, they achieved a concentration of 54.7 % cinnamaldehyde. In another configuration (20.7 MPa, 42 °C, 2.3 mL/min, 118 min), they obtained 38.4 % eugenol, showing SC-CO_2's capacity to selectively extract different compounds based on precise parameter adjustments.

Microwave-Assisted Extraction (MAE) is shown with multiple solvent and parameter variations, demonstrating its versatility. When using water as a solvent, Modi, Parikh, and Desai [27] operated at a power level of 800 W with a 50-min extraction time, a solid-to-solvent ratio of 3:50 g/mL, and a 10-min pre-soak. This setup achieved a 4.83 % yield with a significant fraction of cinnamaldehyde, highlighting the efficacy of MAE for extracting high concentrations of bioactive compounds with a shorter extraction time. In another study, Kurniasari and Kusumo [28] used ethanol (96 %) as a solvent and a 40-min extraction time, resulting in the extraction of oleoresin with a concentration of 9.55 g/L. This shows that MAE with ethanol can be effective for extracting a broader range of compounds. Al-Ajalein et al. [29] used a shorter extraction time of 1.1 min with a solid-to-solvent ratio of 31.7 mL/g and power of 225

Table 1
Parameters and responses of cinnamon barks extraction by green process.

Extraction Method	Conditions	Yield	Active Compounds	Concentration (%)	Reference
SC-CO2	P = 24 MPa, T = 60 °C, Time = 40 min	8 %	Cinnamaldehyde, α-murolene, Eugenol, α-caryophyllene, γ-murolene	70–98 %, 1–6%, 2–8%, 1–3%, 1–3%	Baseri, Lotfollahi, and Asl [24]
SC-CO2	P = 22.5 MPa, T = 50 °C, Time = 120 min, Dp=<0.3 mm, F = 9 L/min	5 %	Not mentioned	Not mentioned	Zhao and Liang [25]
SC-CO2	P = 20.3 MPa, T = 68.2 °C, F = 1.8 mL/min, Time = 95.7 min	Not mentioned	Cinnamaldehyde	54.7 %	Masghati and Ghoreishi [26]
SC-CO2	P = 20.7 MPa, T = 42 °C, F = 2.3 mL/min, Time = 118 min	Not mentioned	Eugenol	38.4 %	Masghati and Ghoreishi [26]
MAE (Water)	50 min time, 3:50 g/mL solid/solvent, 10 min soaking time, 800 W power	4.83 %	Cinnamaldehyde	Fraction of (0.92)	Modi, Parikh, and Desai [27]
MAE (Ethanol 96 %)	40 min time	Not mentioned	Oleoresin	9.55 g/L	Kurniasari and Kusumo [28]
MAE (Ethanol)	1.1 min time, 31.7 mL/g solid/solvent, 225 W Power	13.48	Antioxidant activity	97.5 ± 0.8 %	Al-Ajalein et al. [29]
MAE (Water)	8:1 solid/solvent, 250 W Power, 90 min time	2.55	Trans-Cinnamaldehyde	80 %	Jeyaratnam, Nour, and Akindoyo [30]
UAE (Water)	300 W Power, 60 min time, 7:1 solid/solvent	2.14 %	Not mentioned	Not mentioned	Chen et al. [31]
UAE (Ethanol)	165 W Power, 80–100 mesh Dp, 40 min time, 10:1 solid/liquid	14.80 %	Trans-cinnamaldehyde	82.62 %	P. Li, Tian, and Li [32]

W, achieving a yield of 13.48 % and exceptionally high antioxidant activity at 97.5 ± 0.8 %, indicating MAE's ability to preserve bioactive properties in extracts. Jeyaratnam, Nour, and Akindoyo [30] used water as a solvent with an 8:1 solid-to-solvent ratio, 250 W power, and 90 min, yielding 2.55 % extract with a high trans-cinnamaldehyde concentration of 80 %, which underscores MAE's potential for selective extraction of desired compounds.

Ultrasound-Assisted Extraction (UAE), the third method analyzed, also shows varying efficacy depending on operational conditions. Chen et al. [31] used water as a solvent with a power setting of 300 W, a solid-to-solvent ratio of 7:1, and an extraction time of 60 min, achieving a 2.14 % yield, although the specific active compounds were not mentioned. This suggests that while UAE with water can yield a certain amount of extract, the compound profile might be less specific or not as concentrated compared to other methods. In contrast, P. Li, Tian, and Li [32] used ethanol as a solvent at a lower power of 165 W with a 10:1 solid-to-liquid ratio and an 80–100 mesh particle size, achieving a notably higher yield of 14.80 % with a high concentration of trans-cinnamaldehyde (82.62 %). This result highlights that UAE with ethanol and optimized parameters can yield high concentrations of specific bioactive compounds, demonstrating the method's efficiency in extracting high-quality cinnamon oil under suitable conditions.

In summary, the table demonstrates that SC-CO_2, MAE, and UAE each offer unique advantages for the extraction of cinnamon bark, with yield and active compound concentration highly dependent on process parameters. SC-CO_2 is particularly effective for obtaining high concentrations of specific compounds like cinnamaldehyde, though yield can vary with different configurations. MAE shows versatility with different solvents, particularly in achieving high antioxidant activity and concentrated cinnamaldehyde when using water or ethanol under optimized settings. UAE, meanwhile, proves efficient in achieving higher yields and concentrations of trans-cinnamaldehyde with ethanol as a solvent. Each method can be tailored to target specific compounds or optimize overall yield, highlighting the adaptability of green extraction processes in obtaining valuable bioactive compounds from cinnamon bark.

4.3. Chemical composition of cinnamon oil

The biopesticidal efficacy of cinnamon oil is closely linked to its rich profile of active compounds, particularly cinnamaldehyde, α-muurolene, eugenol, caryophyllene, and γ-muurolene. Cinnamaldehyde, the predominant component, accounting for 70–98 % of the oil, is renowned for its potent insecticidal and fungicidal properties [33]. This compound interferes with the cellular processes of pests, leading to their rapid decline and death, making it an integral player in cinnamon oil's pest control arsenal. Eugenol, which makes up 2–8% of the oil, enhances the oil's biopesticidal spectrum due to its strong antimicrobial and antifungal effects, capable of suppressing a variety of plant pathogens [21]. This characteristic is particularly valuable not only in direct pest management but also in extending the shelf life of agricultural produce by preventing microbial spoilage.

Caryophyllene, present at levels of 1–3%, adds another layer of protection through its insect-repellent properties and antimicrobial activity, which are essential for comprehensive plant disease management strategies. Additionally, the sesquiterpenes α-muurolene and γ-muurolene, although less researched, are believed to contribute to the repellent and insecticidal activities of cinnamon oil, enhancing its overall effectiveness. Table 2 details the chemical composition of cinnamon bark extract obtained through supercritical CO2 extraction as reported by Baseri et al. [24]. The table highlights significant components found in the extract, focusing on their molecular weights, Chemical Abstracts Service (CAS) numbers, and the percentage composition within the extract. Cinnamaldehyde, a major constituent of cinnamon oil, is noted for its prominence, comprising between 70 and 98 % of the extract. This compound, with a molecular weight of 132.16 g/mol and CAS number 14371-10-9, is primarily responsible for the characteristic aroma of cinnamon. Another component, α-muurolene, which does not have a listed CAS number, makes up 1–6 % of the extract and has a molecular weight of 204.35 g/mol (see Table 3).

Eugenol is also present, ranging from 2 to 8 % of the composition. It has a molecular weight of 164.2 g/mol and is identified by the CAS number 97-53-0. This compound is well-known for its antiseptic and analgesic properties. Caryophyllene, another significant component with a molecular weight similar to α-muurolene at 204.35 g/mol, has a CAS number of 87-44-5 and comprises 1–3 % of the extract. Lastly, γ-muurolene, also contributing 1–3 %, does not have a specified CAS number, similar to α-muurolene.

Together, these compounds synergize to form a potent biopesticide, positioning cinnamon oil as an environmentally friendly alternative to synthetic pesticides. This synergy not only targets and controls a wide array of agricultural pests effectively but also aligns with sustainable agricultural practices by reducing the ecological footprint of pest management. The multi-faceted action of these compounds, particularly in integrated pest management systems, underscores their potential in fostering healthier, more resilient agricultural ecosystems.

Table 2
Composition of significant components from Cinnamon barks extract by SC-CO_2 [24].

Active Compounds	Molecular weight (g/mol)	CAS No.	Composition (%)
cinnamaldehyde	132.16	14371-10-9	70–98 %
α-muurolene	204.35	n.a	1–6%
eugenol	164.2	97-53-0	2–8%
caryophyllene	204.35	87-44-5	1–3%
γ-muurolene		n.a	1–3%

Table 3
Summary of research on the efficacy of natural extracts and bioagents in managing agricultural pathogens and pests.

Study Reference	Key Focus	Pathogen/Target	Key Findings
Persaud et al. [34]	Control of rice sheath blight in Guyana	*Rhizoctonia solani*	High inhibition by lemongrass, thick leaf thyme, marigold, and clove extracts. Bacillus cereus also highly effective.
Dėnė and Valiuškaitė [35]	Sensitivity of Botrytis cinerea isolates to plant extracts	*Botrytis cinerea*	High sensitivity to cinnamon extract, varying sensitivity to other extracts influencing pathogen morphology.
Ling, Jiang, Liu, Li, and Wang [47]	Anthelmintic efficacy of cinnamaldehyde and cinnamic acid	*Dactylogyrus intermedius*	Effective concentrations identified, potential for antiparasitic applications.
Raymond A Cloyd, Galle, Keith, Kalscheur, and Kemp [43]	Efficacy of plant-derived essential oils on arthropod pests	*Various arthropod pests*	Essential oils like cinnamon and clove showed efficacy but varied in phytotoxicity.
Cakmak et al. [48]	Reduced-risk insecticides for control of the golden twin-spot moth in bananas	*Chrysodeixis chalcites*	Plant-based insecticides showed repellent and toxic effects, presenting viable alternatives to synthetic pesticides.
Tajdar et al. [15]	Repellent and oviposition deterrent effects against peach fruit fly	*Bactrocera zonata*	Effective repellent and deterrent activities, highlighting the potential of plant extracts in pest management.
Najdabbasi et al. [49]	Biocidal activity against *Phytophthora infestans*	*Phytophthora infestans*	Essential oils and other plant-derived compounds effectively reduced late blight in potatoes.
Gomes, Firmino, Pena, and de Almeida [45]	In vitro inhibition of *Cylindrocladium candelabrum* by *Cinnamomum zeylanicum*	*Cylindrocladium candelabrum*	Effective inhibition noted, suggesting potential for control of fungal diseases in eucalyptus cultivation.
Ayvar-Serna et al. [50]	Antifungal activity of pesticides on tomato vascular wilt	*Fusarium solani*	Biological and botanical pesticides showed fungistatic action, highlighting alternative management strategies.
Lengai, Mbega, and Muthomi [51]	Antifungal activity of spices against tomato pathogens	Various tomato fungal pathogens	High efficacy of clove and other spices in reducing early blight, supporting their use as botanical fungicides.

5. Mechanisms of action of cinnamon oil for biopesticide

5.1. Antimicrobial and antifungal properties

The increasing reliance on natural products for disease management in agriculture reflects a shift towards sustainable practices, driven by the need to reduce the negative impacts of synthetic chemicals. Table 1 shows the summary of antimicrobial and antifungal properties cinnamon oil for biopesticide. Research like that conducted by Persaud, Khan, Isaac, Ganpat, and Saravanakumar [34] underscores the potential of plant extracts in controlling significant agricultural pathogens, specifically *Rhizoctonia solani* which causes sheath blight in rice. This disease is particularly problematic in regions like Guyana, where it substantially affects rice yield. The study evaluated various plant extracts and found that certain ones, such as lemongrass, marigold, and clove, at a concentration of 15 %, were highly effective in inhibiting the mycelial growth of R. solani. This indicates a strong antifungal activity that could be utilized in integrated pest management systems to reduce reliance on traditional fungicides.

Further exploring the realm of botanical antifungals, Dėnė and Valiuškaitė [35] investigated the effects of different plant extracts on Botrytis cinerea, a notorious pathogen responsible for grey mould on various crops. This study highlighted the variation in pathogen sensitivity to these extracts, with cinnamon extract showing the highest efficacy in inhibiting the growth of *B. cinerea*. The variation in sensitivity among different host-derived isolates of the pathogen also suggests that plant extracts, like those from cinnamon, can provide a diverse chemical arsenal against pathogen resistance, thereby supporting their development as future biopesticides.

Table 4
Efficacy of botanical insecticides and plant extracts in pest control.

Study Reference	Target Pest	Plant Extracts Used	Key Findings
Asadi et al. [36]	*Pseudococcus viburni* (Tea mealybug)	Sophora pachycarpa, matrine, pepper extract, cinnamon, garlic	Effective LC50 values found for various treatments, with pepper extract, matrine, and cinnamon and garlic essential oils notable for high efficiency.
Aljedani [16]	*Termites Reticulitermes* spp.	Lavender, clove, garlic, cinnamon, marjoram	Plant extracts showed significant effectiveness, with garlic and clove extracts having the lowest LC50 values.
Gaidau et al. [37]	Seed pests and pathogens	Collagen extracts with bioactive properties, thyme and cinnamon essential oils	New mixes developed for seed treatment in sustainable agriculture showed promise for increasing seed quality and protection.
Huang et al. [38]	*Bactrocera dorsalis* (Fruit fly)	Varieties of pitaya fruits	Oviposition preferences varied among pitaya varieties with different fruit maturity affecting attractiveness.
Reuben et al. [39]	*Plutella xylostella* (Diamondback moth)	Garlic, pepper, cloves, cinnamon	Spices significantly reduced severity and incidence of pest on Chinese cabbage, with some combinations comparable to synthetic pesticides.
Raymond A Cloyd et al. [40]	Various arthropod pests	Essential oils from cottonseed, cinnamon, clove, and others	Varied efficacy with some essential oil products showing high effectiveness but also potential phytotoxicity.

The use of plant-derived extracts such as cinnamon not only offers an effective way to manage plant diseases but also aligns with global trends towards more environmentally friendly agricultural practices. These natural products typically have lower toxicity profiles compared to synthetic pesticides, are biodegradable, and are less likely to lead to resistance. Studies demonstrate that integrating such botanical fungicides into crop protection strategies could significantly reduce the environmental footprint of agriculture while maintaining crop health and productivity.

Overall, the research into plant extracts as biocontrol agents provides valuable insights into their potential role in sustainable agriculture. By harnessing the antimicrobial and antifungal properties of these natural products, it is possible to develop effective, eco-friendly solutions that protect crops from pathogens while supporting the ecological health of farming systems. This approach not only helps in managing plant diseases but also promotes biodiversity and reduces the chemical load on the environment, contributing to the broader goals of sustainable development in agriculture.

5.2. Insecticidal properties

The summary of recent studies that explore the efficacy of various botanical insecticides and plant extracts against a range of pests, emphasizing their potential in sustainable agricultural practices and integrated pest management systems is shown in Table 4. One such study, conducted by Asadi, Ghadamyari, and Ramzi [36], focuses on the tea mealybug, a significant pest in tea and citrus orchards in northern Iran. The research assesses the effectiveness of several plant-based insecticides and a particular formulation derived from *Sophora pachycarpa* leaves and roots. Through meticulous laboratory methods, the study establishes the lethal concentration (LC50) values for various treatments, highlighting the superior efficacy of pepper extract, matrine, and a blend of cinnamon and garlic essential oils. These findings suggest these botanicals could be crucial in developing sustainable pest management strategies for these pests (see Table 5).

In another study from Aljedani [16], the focus shifts to termites, specifically the Reticulitermes spp., known for causing significant economic damage globally. This study evaluates the median lethal concentration (LC50) of extracts from spike lavender, clove, garlic, cinnamon, and marjoram. Garlic and clove emerge as particularly potent, offering potential as effective, environmentally friendly alternatives to synthetic insecticides. The study by Gaidau, Niculescu, Stepan, Epure, and Gidea [37] introduces innovative seed treatment technologies using collagen extracts with bioactive properties for cereal seeds. The research aims to enhance seed quality and protection without the environmental drawbacks associated with traditional pesticides. This study exemplifies the integration of natural compounds like thyme and cinnamon essential oils into seed treatments, showcasing their potential in boosting agricultural sustainability.

Further illustrating the scope of botanical efficacy, Huang et al. [38]'s research explores the oviposition preferences of *Bactrocera dorsalis* across different pitaya varieties. This study not only aids in understanding pest behavior but also informs targeted management practices that could reduce pesticide use and enhance crop yields by selecting less preferred pitaya varieties for cultivation in affected areas. Moreover, the study by Reuben, Yahya, Misangu, and Mulungu [39] assesses the use of common spices—garlic, pepper, cloves, and cinnamon—in controlling the diamondback moth on Chinese cabbage. The findings indicate that these natural substances can significantly reduce pest severity and incidence, potentially matching or even exceeding the effectiveness of conventional pesticides.

Lastly, the study by Raymond A Cloyd et al. [40] evaluates commercially available plant-derived essential oil products against various arthropod pests. While demonstrating substantial pest control potential, the study also notes the phytotoxic effects of some products, underscoring the need for balanced application strategies that consider both efficacy and plant health. Collectively, these studies provide compelling evidence of the efficacy of botanicals in pest management, supporting their inclusion in integrated pest management strategies. This shift towards botanical insecticides reflects a broader move towards sustainable agriculture, aiming to minimize environmental impact while maintaining agricultural productivity.

Table 5
Summary of botanical formulations: Dosage, target pests, and outcomes from recent studies.

Author (Year)	Dosage	Target Pest	Key Outcome
Tajdar et al. [15]	10 %, 20 %, 30 % concentrations	Peach Fruit Fly (*Bactrocera zonata*)	Peppermint extracts were highly effective as repellents at the highest concentration.
Aljedani D.M [16].	0, 5, 10, 15 μL/L	Termites (*Reticulitermes* spp.)	Clove and garlic extracts showed high efficacy, significantly lowering the LC50 and LC90 values.
Abdul-Karim E.K [44].	1, 2, 3g/100 mL	*Fusarium oxysporum*	Nano magnesium oxide showed the highest inhibition rates against the fungus.
Gomes E.M.C. et al. [45]	5, 10, 20 mg/mL	*Cylindrocladium candelabrum*	Methanol extract of Cinnamomum zeylanicum had the greatest antifungal activity.
Lengai G.M.W. et al. [51]	Various	Fungal pathogens of tomato	Clove extract was most effective, showing significant antifungal activity against several pathogens.
Jian Y. et al. [41]	1 g/mL	Poultry Red Mite (*Dermanyssus gallinae*)	High efficacy of herbal extracts like clove and motherwort with some showing 100 % mortality rates.
Nwanade C.F. et al. [46]	Varies	Tick (*Haemaphysalis longicornis*)	(E)-cinnamaldehyde showed potent acaricidal activity, highlighting potential as a botanical-based agent.

5.3. Modes of action against pests

The exploration of botanical insecticides and plant extracts in pest control reveals diverse modes of action, each tailored to target specific pests while promoting sustainability in agriculture. In recent studies, such as the one by Huang et al. [38], the choice of oviposition sites by *Bactrocera dorsalis* (fruit fly) on various pitaya varieties illustrates how physical properties of plants, like fruit hardness, can influence pest behaviors. This study highlights the importance of selecting crop varieties that are naturally less attractive to pests, thereby reducing the need for chemical interventions.

Further insights are provided by Reuben et al. [39], who demonstrated that natural spices—garlic, pepper, cloves, and cinnamon—effectively mitigate the severity and incidence of *Plutella xylostella* (diamondback moth) attacks on Chinese cabbage. These spices likely act through direct toxicity or repellency, offering an eco-friendly alternative to synthetic pesticides. This approach not only controls pests but also aligns with the increasing consumer preference for organically grown produce, underscoring the practical implications of botanicals in modern agricultural practices.

The study by Dėnė and Valiuškaitė [35] focuses on the biochemical interactions between plant extracts and pests. Cinnamon extract, for instance, was found highly effective against Botrytis cinerea (grey mould), suggesting that specific chemical constituents within the extract interfere with the pathogen's life processes. This type of interaction points to the potential of botanical extracts to be developed into precise biopesticides that target specific fungal pathogens, minimizing the broader impacts on the ecosystem.

Moreover, the research by Jian, Yuan et al. [41] introduces an important concept of synergy in the use of botanical extracts. Their findings on the combined use of clove and motherwort against Dermanyssus gallinae (poultry red mite) reveal that certain combinations of herbal extracts can enhance overall efficacy, offering a potent solution that could reduce the dosage requirements and potentially lower the costs associated with pest control.

Lastly, the variability in the effectiveness and potential phytotoxicity of botanical agents, as discussed by R. A. Cloyd, Galle, Keith, Kalscheur And, and Kemp [40], highlights the complexities involved in integrating these natural products into mainstream agricultural practices. While they present significant advantages, understanding their interactions with plants and pests, optimal application rates, and environmental impacts is crucial. This careful evaluation ensures that the benefits of botanical insecticides extend beyond pest control, contributing to the sustainability and environmental health of agricultural systems. These studies collectively underscore the multifaceted roles that botanical insecticides and plant extracts can play in integrated pest management systems, supporting their broader adoption in sustainable agriculture. Each mode of action not only provides specific benefits but also contributes to a holistic approach to pest control that is environmentally sound and compatible with global sustainability goals.

5.4. Synergistic effects with other natural compounds

This section delves into how botanical insecticides and plant extracts can be combined with other natural compounds to enhance their efficacy in pest control. This section would build on the documented evidence that some botanicals can work better when used in conjunction with other substances, showcasing the potential for more effective and sustainable pest management strategies. The research by Jian, Yuan et al. [41] serves as a prime example of how combining different botanical extracts can lead to enhanced efficacy in pest control. This study demonstrated that the acaricidal effects of clove and motherwort extracts were significantly increased when used together. This synergistic interaction suggests that the compounds in each extract may enhance the other's activity, potentially by mechanisms such as improved penetration into the pest's body or by overwhelming the pest's detoxification systems more effectively than when used alone. Such findings are crucial as they indicate that less of each compound may be needed, thereby reducing the treatment costs and environmental impact.

Moreover, Zorzetti, Neves, Constanski, Santoro, and Fonseca [42] found that certain plant extracts could be effectively combined with biological control agents like *Beauveria bassiana*. This fungus acts as a natural pest suppressant, and its compatibility with plant extracts means that both can be used concurrently to provide a more robust control strategy. The plant extracts may act as stressors that weaken the pests, making them more susceptible to fungal infection, or they might create an environment that favors the proliferation and effectiveness of the biological agent. This synergistic effect underscores the potential for integrated approaches in pest management that utilize multiple modes of action to achieve control.

This section would further explore the mechanisms behind these synergistic effects, possibly involving the inhibition of pest resistance mechanisms or enhanced penetration of active compounds into pest organisms. For example, certain terpenes in botanical extracts might disrupt the pest's outer membrane, enhancing the uptake of other bioactive compounds. Additionally, research could be discussed regarding the formulation technologies that optimize these synergistic interactions, such as microencapsulation or the development of combined formulations that ensure the stability and bioavailability of the active compounds.

6. Efficacy studies of cinnamon oil for biopesticide

6.1. Effectiveness against insect pests and fungicide

The effectiveness of botanical insecticides and plant extracts against insect pests and fungal pathogens is an area of growing interest within sustainable agriculture. Recent studies illustrate the potential of these natural compounds to provide effective, environmentally friendly alternatives to synthetic chemicals. Huang et al. [38] observed that the fruit fly, Bactrocera dorsalis, showed a preference for ovipositing in specific pitaya varieties, suggesting that the physical characteristics of these plants could be exploited to control pest populations. This selective preference indicates a strategic avenue for employing certain plant species or cultivars to naturally deter pest infestations.

Reuben et al. [39] compared the efficacy of natural spices—garlic, pepper, cloves, and cinnamon—with synthetic pesticides in controlling the diamondback moth, Plutella xylostella, on Chinese cabbage. The results were promising, showing that these spices significantly reduced pest severity and incidence, effectively matching the performance of conventional pesticides. This finding is particularly significant for organic agriculture, where synthetic chemicals are limited or prohibited, underscoring the potential of spices as natural pest deterrents.

Dėnė and Valiuškaitė [35] provided insight into how specific botanical extracts, like cinnamon, can be particularly effective against targeted pests such as grey mould (*Botrytis cinerea*). The high sensitivity of the mould to cinnamon extract highlights the potential for targeted botanical applications that are both effective and environmentally benign, emphasizing the role of such treatments in sustainable agricultural practices. On the fungal front, Dėnė and Valiuškaitė [35] demonstrated the high sensitivity of *Botrytis cinerea* to cinnamon extract. The targeted action of cinnamon highlights its potential as a fungicidal agent, which could be particularly useful in managing grey mould in a range of crops. This specificity is crucial for minimizing the impact on non-target organisms and maintaining ecological balance. Jian, Yuan et al. [41] alsodemonstrated the synergistic effects of combining clove and motherwort extracts to enhance acaricidal activity against the poultry red mite, *Dermanyssus gallinae*. This synergy suggests that using combinations of botanical extracts can increase their efficacy, potentially reducing the quantities needed and minimizing environmental impacts compared to traditional chemical treatments.

Lastly, Raymond A Cloyd et al. [40] discussed the integration of essential oils from cottonseed and clove into pest management programs, highlighting their effectiveness as well as the need for careful application due to variability in performance and potential phytotoxic effects. This study underscores the importance of further research to optimize the use of botanical insecticides, ensuring their safe and effective integration into broader pest management strategies. These studies collectively illustrate that botanical insecticides and plant extracts are not only effective against a range of insect pests but also offer environmentally friendly alternatives to synthetic pesticides, suitable for integration into diverse agricultural systems. Further research is needed to fully harness their potential, optimize formulations, and assess their performance under field conditions, ultimately contributing to more sustainable agricultural practices.

6.2. Comparison cinnamon oil with synthetic pesticide

The exploration of cinnamon oil as an alternative to synthetic pesticides highlights both its potential and the complexities associated with its use in integrated pest management. Cinnamon oil, derived from the bark and leaves of the cinnamon tree, is noted for its active compounds like cinnamaldehyde, which have demonstrated effective insecticidal and fungicidal properties. This natural oil disrupts the respiratory functions of insect pests and impedes the growth of fungal pathogens by interfering with their cell membrane functions, similar to the action of many synthetic pesticides. However, cinnamon oil is natural, reducing the risks of environmental contamination and the buildup of pesticide resistance.

Safety is a significant advantage of cinnamon oil over synthetic pesticides. It is generally considered safe for non-target organisms, including beneficial insects, wildlife, and humans, presenting fewer risks of toxicity and long-term environmental damage such as groundwater contamination and adverse impacts on non-target species. This safety profile makes cinnamon oil particularly attractive in markets focused on organic and sustainable farming practices. However, the cost-effectiveness of cinnamon oil can be a concern. While the extraction and production of cinnamon oil might be more expensive than synthesizing chemical pesticides, the broader environmental and health benefits it offers could offset these initial costs in the long term. Reduced cleanup costs and the diminished likelihood of resistance development add to its cost-effectiveness.

Moreover, cinnamon oil enjoys a favorable regulatory and public perception. Consumers and regulatory bodies often view natural pesticides like cinnamon oil more positively, especially in communities prioritizing organic products. This acceptance can facilitate market access and consumer trust, providing a competitive edge in sensitive markets. Integrating cinnamon oil into pest management strategies offers a holistic approach to pest control. It can be used in rotation with other measures to manage resistance and decrease the reliance on chemical controls. As part of a comprehensive toolkit involving biological and mechanical controls, cinnamon oil contributes significantly to sustainable agriculture practices. The ongoing research and adaptation to practical application challenges will be key to maximizing the use of cinnamon oil on a larger scale, ensuring it is a viable and effective component of global agricultural practices.

7. Formulations and dosage of cinnamon oil for biopesticide

The section compiles data from various studies that investigate the application of cinnamon oil and its effectiveness as a biopesticide against a range of pests, providing a comprehensive look at its utilization in pest control. One pivotal study by Tajdar et al. [15] examined the repellent and oviposition deterrent effects of extracts including cinnamon oil against the Peach Fruit Fly, *Bactrocera zonata*. The research tested various solvent extracts (methanol, ethanol, and distilled water) containing cinnamon, which demonstrated significant repellent properties, especially at the highest concentration of 30 %. This indicates cinnamon's potential as a powerful component in biopesticide formulations aimed at managing fruit fly populations.

Aljedani [16] conducted experiments to evaluate the effectiveness of plant extracts, including cinnamon, against termites. The study explored a range of dosages (from 0 to 15 μL/L) and documented that extracts such as clove and garlic, along with cinnamon, considerably lowered the lethal concentration required to be effective against termites, showcasing their potential as sustainable and less harmful pest control agents. The Abdul-Karim [44] focused on combating *Fusarium oxysporum* in tomatoes, utilizing both nano magnesium oxide and cinnamon extracts. Results highlighted the formidable inhibitory action of these substances, particularly the nano-formulations, suggesting a viable alternative to chemical fungicides for controlling plant pathogens in greenhouse settings.

Additionally, the research by Gomes et al. [45] evaluated the antifungal efficacy of cinnamon extracts against *Cylindrocladium candelabrum*. Findings revealed that higher concentrations of the extract significantly inhibited fungal growth, demonstrating its potential as an effective antifungal agent in agricultural disease management. Finally, a study by Nwanade et al. [46] explored the acaricidal properties of cinnamon oil against the tick *Haemaphysalis longicornis*. The study identified (E)-cinnamaldehyde as the primary active component in cinnamon oil, which exhibited potent activity against tick larvae and nymphs, suggesting its application in controlling tick populations. These studies collectively highlight the diverse potential of cinnamon oil and related extracts in pest and disease management across different agricultural contexts. The findings suggest that such natural products could provide effective, eco-friendly alternatives to synthetic pesticides, aligning with global trends towards sustainable agriculture.

8. Bibliometric studies of cinnamon oil for biopesticide

8.1. *Current trends of cinnamon oil for biopesticide*

The use of cinnamon oil as a biopesticide has seen a notable increase in scholarly interest in recent years, reflecting the growing demand for natural pest management solutions. In 2024, there were three published documents, continuing a pattern of consistent research growth from previous years. In 2023, the number of documents peaked at four, while in 2022, there were two publications. This steady rise, compared to earlier years from 2016 to 2021, where the number of publications varied between one to three annually, indicates an upward trend in interest. This growing body of research suggests that cinnamon oil's biopesticidal properties are becoming more widely recognized as a viable alternative to chemical pesticides.

A closer look at the subject areas where this research is concentrated shows that Agricultural and Biological Sciences dominate, with 18 documents published on the topic. This indicates a strong focus on utilizing cinnamon oil primarily in agriculture for pest control and crop protection. As farmers and researchers search for eco-friendly alternatives to conventional pesticides, cinnamon oil is gaining traction for its efficacy in managing pests without the adverse environmental impacts associated with synthetic chemicals. Environmental Science also contributes significantly, with six documents addressing the environmental benefits of cinnamon oil. These studies emphasize its role as an eco-friendly solution that reduces the toxic burden on ecosystems and promotes sustainable agriculture.

In addition to agriculture and environmental science, several other fields are contributing to the growing body of knowledge on cinnamon oil as a biopesticide. For instance, research in Immunology and Microbiology (four documents) explores cinnamon oil's potential in controlling microbial pests, which further extends its biopesticidal scope beyond just insect management. Chemistry and Medicine, each with three documents, highlight investigations into the chemical composition of cinnamon oil and its potential health implications when used in agriculture. Finally, research in Biochemistry, Genetics, and Molecular Biology, with two documents, delves

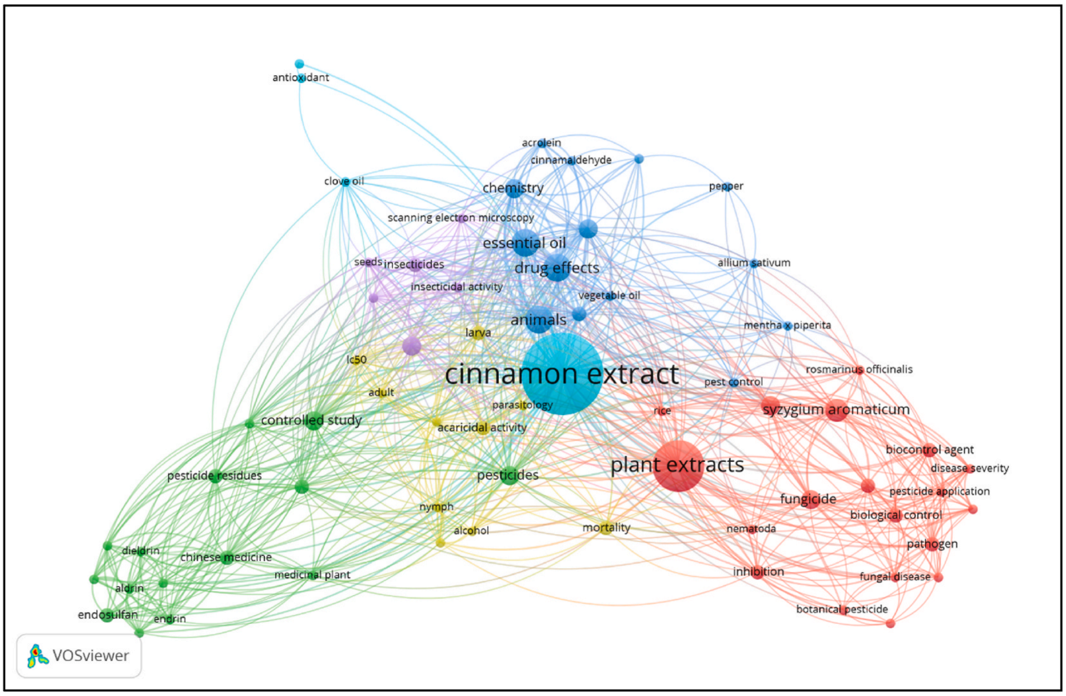

Fig. 1. Co-occurrence with minimum occurrence keyword 2 with 6 cluster.

into the molecular mechanisms behind cinnamon oil's pest control efficacy. This interdisciplinary interest underscores the wide-ranging applications of cinnamon oil, from agricultural use to its broader implications for human health and environmental safety.

The growing volume of research on cinnamon oil as a biopesticide reflects a global shift toward sustainable and natural pest control methods. Researchers from various fields are increasingly recognizing its potential, and as a result, the use of cinnamon oil in pest management strategies is expected to expand. This trend is significant not only for its agricultural benefits but also for its positive implications for environmental sustainability and public health. The current research trajectory suggests that cinnamon oil will continue to be a subject of interest as a natural biopesticide, with further studies likely to explore its application across different sectors.

8.2. Co-occurrence analysis and its thematic

Fig. 1 provides an in-depth co-occurrence network of keywords relating to cinnamon extract and its use as a biopesticide, created with a minimum keyword occurrence threshold of 2. Six thematic clusters, each represented by distinct colors, emerged from the analysis. These clusters reflect the interconnected research themes and topics in the current literature, providing a clearer picture of how cinnamon extract, alongside other plant-based biopesticides, is studied and applied.

The first cluster, depicted in green, centers around *controlled study* and focuses on the evaluation of *pesticide residues* in crops and their surrounding environments. Keywords such as *dieldrin*, *aldrin*, and *endosulfan* suggest a comparative study between conventional chemical pesticides and plant-based alternatives like cinnamon extract. Research in this cluster typically assesses the extent to which natural pesticides leave fewer harmful residues compared to synthetic ones, which is critical for human health and environmental sustainability. The presence of keywords like *medicinal plant* and *Chinese medicine* indicates an interest in exploring the traditional use of plants in pest management and their integration into modern agricultural practices.

The second cluster, represented in blue, focuses primarily on *cinnamon extract* and its bioactive compounds, such as *cinnamaldehyde* and *acrolein*. This cluster explores the insecticidal properties of cinnamon extract and its essential oil, examining how these compounds affect various pest organisms. The inclusion of keywords like *animals*, *insecticidal activity*, and *drug effects* indicates that this cluster addresses both the biochemical mechanisms through which cinnamon extract exerts its effects on pests and its broader biological impact on non-target organisms, such as beneficial insects or livestock. Additionally, the study of *scanning electron microscopy* in this cluster suggests that research involves detailed investigations of structural damage inflicted by cinnamon extract on pests at the cellular or tissue level.

The third cluster, highlighted in red, revolves around *plant extracts* in general and their widespread use in pest control. Keywords such as *syzygium aromaticum* (clove), *rosmarinus officinalis* (rosemary), and *mentha piperita* (peppermint) reveal that the research extends beyond cinnamon extract to other commonly used botanical pesticides. The prominence of terms like *biological control*, *fungicide*, and *disease severity* demonstrates the focus on the application of plant extracts for controlling plant pathogens, fungi, and nematodes. This cluster indicates a broader approach to using plant-derived products in integrated pest management (IPM), which encompasses various pest species and diseases, contributing to reducing reliance on chemical pesticides.

The fourth cluster, in purple, focuses on *insecticidal activity* and examines how different plant-based insecticides affect pests, particularly in their early developmental stages. Keywords such as *seeds*, *larva*, and *insecticides* point to research assessing the effectiveness of plant extracts, including cinnamon, against insect pests at various life stages, with particular emphasis on larvae. This cluster suggests the importance of developing biopesticides that target pests early in their lifecycle, reducing the likelihood of large-scale infestations. The presence of terms like *insecticidal activity* and *LC50* (lethal concentration 50) further indicates that toxicity assessments are central to this research, ensuring that plant-based biopesticides are both effective and environmentally safe.

The fifth cluster, in yellow, centers around *acaricidal activity* and focuses on plant-based acaricides used to control mite and tick populations. Keywords such as *nymph*, *adult*, and *acaricidal activity* highlight research that assesses how these natural products affect mites and ticks at different life stages. This cluster emphasizes the need for effective alternatives to chemical acaricides, which are often used in agriculture and livestock management to combat infestations. The use of natural acaricides derived from plant extracts is particularly important for sustainable agriculture, as they can reduce the environmental and health risks associated with chemical acaricides.

The sixth cluster, shown in cyan, focuses on *antioxidant* properties and their relationship to pest control, particularly in connection with *clove oil*. This cluster highlights the multifunctional properties of plant extracts, where compounds known for their antioxidant activity, such as those found in cinnamon and clove oils, are also evaluated for their potential in pest management. The combination of antioxidant and insecticidal properties makes these extracts appealing for use in agriculture, as they may enhance plant health while simultaneously protecting against pests. The research in this cluster suggests a dual benefit of certain plant extracts in improving crop resilience and offering pest control solutions.

In summary, the co-occurrence analysis reveals the breadth of research on cinnamon extract and other plant-based biopesticides. The identified clusters provide a comprehensive view of the current trends in this field, ranging from the comparison of synthetic and natural pesticides, detailed investigations into the biological effects of plant extracts, and the broader application of these biopesticides in controlling a wide range of pests and diseases. These findings underscore the growing interest in sustainable agricultural practices and the significant role plant extracts like cinnamon play in integrated pest management.

8.3. Future recommendation from Co-occurrence keywords

The co-occurrence analysis of keywords provides valuable insights into current research trends around cinnamon extract and plant-based biopesticides, highlighting several directions for future studies. One key recommendation is the expansion of research on plant extracts for multispecies pest control. While the analysis shows a focus on *cinnamon extract* and other *plant extracts* like *syzygium aromaticum* (clove) and *rosmarinus officinalis* (rosemary), future research should explore these extracts' effectiveness across a broader range of pest species in various environmental conditions. Additionally, the synergistic effects of combining different plant extracts to enhance biopesticidal properties should be investigated, potentially leading to more versatile and potent biopesticides for integrated pest management (IPM) systems.

Another important area for future research involves investigating the long-term environmental and health impacts of biopesticides. The keywords related to *controlled study*, *pesticide residues*, and *medicinal plant* suggest growing interest in understanding the safety and sustainability of plant-based biopesticides. Future studies should focus on the environmental impact of these biopesticides over time, particularly in terms of residue effects on soil, water, and non-target organisms. Furthermore, it is crucial to study potential health effects on humans exposed to plant extracts over extended periods, especially in agricultural settings where exposure might be frequent.

Understanding the molecular mechanisms behind biopesticide action is another area that warrants deeper investigation. Keywords such as *cinnamaldehyde*, *insecticidal activity*, and *scanning electron microscopy* indicate research exploring the biochemical processes by which cinnamon extract and other plant-based biopesticides act on pests. Future research should delve into the molecular level, utilizing advanced tools like genomics and proteomics to uncover how bioactive compounds in these biopesticides disrupt pest physiology. These insights could lead to more targeted and efficient pest management strategies.

In addition to understanding efficacy, future work should prioritize developing standardized testing protocols for biopesticides. The presence of terms like *LC50*, *insecticidal activity*, and *controlled study* underscores the importance of consistent efficacy evaluations. Standardized testing methods are needed to compare findings across different studies and to establish clear dosage guidelines for agricultural application, ensuring that biopesticides are used effectively and safely.

Finally, research should focus on the multifunctionality of plant extracts, particularly their antioxidant properties in conjunction with pest control. The cluster associated with *antioxidant* and *clove oil* suggests that plant extracts can provide dual benefits, such as enhancing crop resilience against stressors like drought and disease while simultaneously controlling pests. Future studies could explore how these multifunctional properties can be optimized in agricultural settings to improve both plant health and pest management outcomes.

In summary, future research should aim to expand and deepen our understanding of plant-based biopesticides, with a focus on multispecies efficacy, environmental and health impacts, molecular mechanisms, standardized testing protocols, and the multifunctionality of plant extracts. These directions will help optimize the use of biopesticides like cinnamon extract, making them more effective, sustainable solutions for modern agriculture.

9. Challenges and future prospects

The exploration of cinnamon oil as a biopesticide presents a promising avenue for sustainable agriculture, yet it comes with specific challenges and areas for future research that need to be addressed to fully harness its potential.

9.1. Challenges

The potential of cinnamon oil as a biopesticide faces several intricate challenges that necessitate comprehensive solutions for its broader acceptance and application.

1. **Consistency in Effectiveness:** The effectiveness of cinnamon oil as a biopesticide can vary significantly based on its concentration and the method of application. While studies such as those by Tajdar et al. [15] and Aljedani [16] indicate potent pest control capabilities at specific concentrations, achieving consistent results across various environmental conditions and pest species remains a hurdle. This inconsistency can deter its adoption by farmers who require reliable solutions. Standardizing the concentrations and formulations that work effectively across different settings is crucial for its integration into agricultural practices.
2. **Regulatory Approval:** Navigating the regulatory landscape for natural biopesticides like cinnamon oil involves extensive documentation and proof of safety and efficacy, which can be both time-consuming and costly. Research by Abdul-Karim [44] and Gomes et al. [45] shows promising pest control and antifungal benefits, yet transforming these findings into approved products demands rigorous field trials, toxicity assessments, and environmental impact studies. The complexity of regulatory pathways often acts as a barrier to the introduction of innovative natural solutions into the market.
3. **Cost-Effectiveness:** While cinnamon oil presents an eco-friendly alternative to synthetic pesticides, its economic feasibility is a significant concern. The extraction and processing required to produce cinnamon oil at a purity level effective for pest control can be expensive. Ensuring that these processes are cost-effective is vital for its widespread adoption. Farmers, particularly those in developing regions, may find the costs prohibitive compared to traditional chemical pesticides unless production and processing efficiencies can be improved.
4. **Scale of Production:** Scaling the production of cinnamon oil to meet large agricultural demands presents another challenge. The agricultural sector requires consistent and large-scale supply chains capable of delivering high volumes of biopesticides. Developing infrastructure and technologies for large-scale extraction and distribution of cinnamon oil is essential for its practical use on a global scale.

5. **Market Penetration and Farmer Adoption:** For cinnamon oil to be widely used, it must not only be effective and affordable but also accepted by farmers. This requires educational initiatives to demonstrate its benefits and efficacy compared to conventional pesticides. Building trust in natural pesticides involves transparent communication and demonstration of the product's effectiveness through pilot projects and field results.

Addressing these challenges requires a multi-faceted approach involving research and development to refine formulations, strategic partnerships to navigate regulatory frameworks, innovations to reduce production costs, and extensive outreach to educate potential users about the benefits and practical applications of cinnamon oil as a biopesticide.

9.2. Future prospects of cinnamon oil for biopesticide

The development of advanced formulations is essential for enhancing the effectiveness of cinnamon oil as a biopesticide. Research, such as that conducted by Abdul-Karim [44], has begun to explore nano formulations which could revolutionize the way cinnamon oil is delivered, increasing its stability and extending its shelf life. These innovations are crucial for ensuring that the biopesticide remains effective throughout its use in various environmental conditions. Cinnamon oil's integration into Integrated Pest Management (IPM) systems presents a sustainable approach to pest control, combining it with other biological, cultural, and chemical methods. This integration could lead to more holistic and sustainable agricultural practices. Studies, like those by Jian, Yuan et al. [41], indicate potential synergistic effects when cinnamon oil is combined with other biocontrol agents, potentially enhancing overall pest management efficacy.

Furthermore, expanding the scope of cinnamon oil applications to a broader array of pests and diseases could significantly increase its utility in agriculture. Exploring its effects on different agricultural pests and its potential benefits for plant health and yield will provide valuable insights into its broader applications in the field. Developing local production capabilities for cinnamon oil, especially in regions where cinnamon is natively grown, could also offer economic benefits and enhance sustainability. Local production would not only reduce costs associated with transportation and synthetic pesticide production but also support local economies and reduce the environmental footprint. Addressing these challenges and opportunities is crucial for translating the promising laboratory and pilot study findings of cinnamon oil into widespread real-world applications in agriculture. This transition requires a coordinated effort involving research into new formulations, integration into IPM systems, expansion of application scopes, and fostering local production capabilities.

10. Conclusion

In conclusion, cinnamon oil holds significant promise as a natural biopesticide due to its potent bioactive compounds, such as cinnamaldehyde, which exhibit strong insecticidal and fungicidal properties. Its integration into Integrated Pest Management (IPM) frameworks underscores its value in sustainable agriculture, offering a means to reduce reliance on synthetic pesticides, minimize environmental chemical loads, and promote ecosystem health. Beyond pest control, cinnamon oil has potential applications in organic farming, post-harvest treatments to reduce fungal contamination, and protecting stored grains, making it a versatile tool in chemical-free agricultural practices.

However, several challenges need to be addressed to fully realize the potential of cinnamon oil as a biopesticide. Variability in efficacy due to environmental factors, regulatory hurdles, and cost concerns remain key barriers. Advancements in formulation technologies, such as encapsulation or nanoformulation, could improve its stability, shelf life, and delivery efficiency, enhancing its practicality for widespread use. With continued research and innovation, cinnamon oil could contribute to more sustainable, locally adapted, and economically viable pest management solutions, supporting the transition toward environmentally responsible and health-conscious agricultural practices.

CRediT authorship contribution statement

Yursida Yursida: Writing – review & editing, Writing – original draft. **Frederick Andrew:** Writing – review & editing, Writing – original draft. **Karlin Agustina:** Writing – review & editing, Writing – original draft. **Evriani Mareza:** Writing – review & editing, Writing – original draft. **Ummi Kalsum:** Writing – review & editing, Writing – original draft. **Ikhwani Ikhwani:** Writing – review & editing, Writing – original draft. **Sri Rahayuningsih:** Writing – review & editing, Writing – original draft. **Erny Yuniarti:** Writing – review & editing, Writing – original draft. **Nicky Rahmana Putra:** Writing – review & editing, Writing – original draft.

Data availability statement

Data available on request from the authors.

Declaration of generative ai and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Quilbott and ChatGPT in order to paraphrase the language and check the language grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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References

[1] M.S. Ayilara, B.S. Adeleke, S.A. Akinola, C.A. Fayose, U.T. Adeyemi, L.A. Gbadegesin, O.O. Babalola, Biopesticides as a promising alternative to synthetic pesticides: a case for microbial pesticides, phytopesticides, and nanobiopesticides, Front. Microbiol. 14 (2023) 1040901.
[2] S. Chaudhary, R.K. Kanwar, A. Sehgal, D.M. Cahill, C.J. Barrow, R. Sehgal, J.R. Kanwar, Progress on Azadirachta indica based biopesticides in replacing synthetic toxic pesticides, Front. Plant Sci. 8 (2017) 610.
[3] E.O. Fenibo, G.N. Ijoma, T. Matambo, Biopesticides in sustainable agriculture: current status and future prospects, New and Future Development in Biopesticide Research: Biotechnological Exploration (2022) 1–53.
[4] I. Ikhwani, S. Rahayuningsih, E. Yuniarti, H.S. Kusuma, H. Darmokoesomo, N.R. Putra, Mapping the trend of evolution: a bibliometric analysis of biopesticides in fruit crop protection, J. Plant Dis. Prot. (2024) 1–20.
[5] H. Archana, K. Darshan, M.A. Lakshmi, T. Ghoshal, B.M. Bashayal, R. Aggarwal, Biopesticides: a key player in agro-environmental sustainability, in: Trends of Applied Microbiology for Sustainable Economy, Elsevier, 2022, pp. 613–653.
[6] A. Ali, E.N. Ponnampalam, G. Pushpakumara, J.J. Cottrell, H.A. Suleria, F.R. Dunshea, Cinnamon: a natural feed additive for poultry health and production—a review, Animals 11 (7) (2021) 2026.
[7] Z. Dianbo, M. Yanqing, W. Shaodan, W. Wenwen, Antibacterial mechanism of cinnamon essential oil nanoemulsion against Pseudomonas deceptionensis CM2 based on non-targeted metabolomics, Science and Technology of Food Industry 44 (17) (2023) 168–175, https://doi.org/10.13386/j.issn1002-0306.2023030151.
[8] B. Li, K. Zheng, Y. Ma, Q. Xiang, Antibacterial mechanism of cinnamon essential oil against Pseudomonas deceptionensis CM2 isolated from chicken meat, Food Ferment. Ind. 49 (6) (2023) 156–161and169, https://doi.org/10.13995/j.cnki.11-1802/ts.031587.
[9] L.T.K. Phan, A.T.H. Le, N.T.N. Hoang, E. Debonne, S. De Saeger, M. Eeckhout, L. Jacxsens, Evaluation of the efficacy of cinnamon oil on Aspergillus flavus and Fusarium proliferatum growth and mycotoxin production on paddy and polished rice: towards a mitigation strategy, Int. J. Food Microbiol. 415 (2024), https://doi.org/10.1016/j.ijfoodmicro.2024.110636.
[10] O.A. Berktas, E.G.G. Peker, The investigation of the protective effect of cinnamon water extract and vitamin e on malathion-induced oxidative damage in rats, Toxicology Research 10 (3) (2021) 627–630, https://doi.org/10.1093/toxres/tfab021.
[11] P. Gupta, M. Shahnawaz, V. Zambare, N. Kumar, A. Thakur, Natural compounds as pesticides, emerging trends, prospects, and challenges, New Horizons in Natural Compound Research (2023) 391–414.
[12] A. Khursheed, M.A. Rather, V. Jain, S. Rasool, R. Nazir, N.A. Malik, S.A. Majid, Plant based natural products as potential ecofriendly and safer biopesticides: a comprehensive overview of their advantages over conventional pesticides, limitations and regulatory aspects, Microb. Pathog. (2022) 105854.
[13] N.R. Putra, A. Ismail, D.P. Sari, N. Nurcholis, T.T. Murwatono, R. Rina, P. Virliani, A bibliometric analysis of cellulose anti-fouling in marine environments, Heliyon (2024) e28513.
[14] N.R. Putra, D.N. Rizkiyah, M.A. Che Yunus, H.S. Kusuma, H. Darmokoesoemo, Mapping the landscape of clove oil as essential oil for health and wellness: a bibliometric review of advances, challenges, and future directions, Journal of Essential Oil Bearing Plants (2024) 1–27.
[15] A. Tajdar, A. Ishfaq, M. Sarmad, S.M. Zaka, Repellent and oviposition deterrent effect of bio-rational green extracts against Peach fruit fly Bactrocera zonata (Saunders), J. Kans. Entomol. Soc. 92 (4) (2019) 617–626, https://doi.org/10.2317/0022-8567-92.4.617.
[16] D.M. Aljedani, Evaluation of some plant extracts effectiveness on the termites Reticulitermes spp. (Isoptera: Rhinotermitidae), Pol. J. Environ. Stud. 32 (4) (2023) 3015–3024, https://doi.org/10.15244/pjoes/162305.
[17] A.K. Tiwari, IPM Essentials: combining biology, ecology, and agriculture for sustainable pest control, Journal of Advances in Biology & Biotechnology 27 (2) (2024) 39–47.
[18] Y. Jian, S. Li, D. Li, C. Ning, S. Zhang, F. Jian, H. Si, Evaluation of the in vitro acaricidal activity of ethanol extracts of seven Chinese medicinal herbs on Ornithonyssus sylviarum (Acari: Macronyssidae), Exp. Appl. Acarol. 87 (1) (2022) 67–79, https://doi.org/10.1007/s10493-022-00716-9.
[19] M. Pušić, M. Ljubojević, D. Prvulović, R. Kolarov, M. Tomić, M. Simikić, T. Narandžić, Bioenergy and biopesticides production in Serbia—could invasive alien species contribute to sustainability? Processes 12 (2) (2024) 407.
[20] I. Gupta, R. Singh, S. Muthusamy, M. Sharma, K. Grewal, H.P. Singh, D.R. Batish, Plant essential oils as biopesticides: applications, mechanisms, innovations, and constraints, Plants 12 (16) (2023) 2916.
[21] P. Rana, S.-C. Sheu, Discrimination of four Cinnamomum species by proximate, antioxidant, and chemical profiling: towards quality assessment and authenticity, J. Food Sci. Technol. 60 (10) (2023) 2639–2648, https://doi.org/10.1007/s13197-023-05788-y.
[22] D.K. Pandey, R. Chaudhary, A. Dey, S. Nandy, R.M. Banik, T. Malik, P. Dwivedi, Current knowledge of Cinnamomum species: a review on the bioactive components, pharmacological properties, analytical and biotechnological studies, in: J. Singh, V. Meshram, M. Gupta (Eds.), Bioactive Natural Products in Drug Discovery, Springer Singapore, Singapore, 2020, pp. 127–164.
[23] R. Romano, L. De Luca, A. Aiello, D. Rossi, F. Pizzolongo, P. Masi, Bioactive compounds extracted by liquid and supercritical carbon dioxide from citrus peels, Int. J. Food Sci. Technol. 57 (6) (2022) 3826–3837, https://doi.org/10.1111/ijfs.15712.
[24] H. Baseri, M.N. Lotfollahi, A.H. Asl, Effects of some experimental parameters on yield and composition of supercritical carbon dioxide extracts of cinnamon bark, J. Food Process. Eng. 34 (2) (2011) 293–303.
[25] S. Zhao, H. Liang, Study of extraction of cinnamon oils from the bark of Cinnamomum cassia Presl by supercritical carbon dioxide, Pol. J. Chem. 80 (1) (2006) 99–105.
[26] S. Masghati, S.M. Ghoreishi, Supercritical CO2 extraction of cinnamaldehyde and eugenol from cinnamon bark: optimization of operating conditions via response surface methodology, J. Supercrit. Fluids 140 (2018) 62–71, https://doi.org/10.1016/j.supflu.2018.06.002.
[27] P.I. Modi, J.K. Parikh, M.A. Desai, Intensified approach towards isolation of cinnamon oil using microwave radiation: parametric, optimization and comparative studies, Ind. Crop. Prod. 173 (2021) 114088, https://doi.org/10.1016/j.indcrop.2021.114088.
[28] L. Kurniasari, P. Kusumo, Kinetics of cinnamon oleoresin extraction using Microwave-Assisted Extractor, in: Paper Presented at the Journal of Physics: Conference Series, 2019.

[29] A.-H.A.S. Al-Ajalein, M.H. Shafie, P.-G. Yap, M.A. Kassim, I. Naharudin, T.-W. Wong, C.-Y. Gan, Microwave-assisted extraction of polysaccharide from Cinnamomum cassia with anti-hyperpigmentation properties: optimization and characterization studies, Int. J. Biol. Macromol. 226 (2023) 321–335.

[30] N. Jeyaratnam, A.H. Nour, J.O. Akindoyo, The potential of microwave assisted hydrodistillation in extraction of essential oil from Cinnamomum Cassia (cinnamon), ARPN J. Eng. Appl. Sci. 11 (4) (2016) 2179–2183.

[31] G. Chen, F. Sun, S. Wang, W. Wang, J. Dong, F. Gao, Enhanced extraction of essential oil from Cinnamomum cassia bark by ultrasound assisted hydrodistillation, Chin. J. Chem. Eng. 36 (2021) 38–46.

[32] P. Li, L. Tian, T. Li, Study on ultrasonic-assisted extraction of essential oil from cinnamon bark and preliminary investigation of its antibacterial activity, in: Paper Presented at the Advances in Applied Biotechnology: Proceedings of the 2nd International Conference on Applied Biotechnology (ICAB 2014), 2015 vol. I.

[33] K.A. Qureshi, S.A. Mohammed, O. Khan, H.M. Ali, M.Z. El-Readi, H.A. Mohammed, Cinnamaldehyde-Based Self-Nanoemulsion (CA-SNEDDS) accelerates wound healing and exerts antimicrobial, antioxidant, and anti-inflammatory effects in rats' skin burn model, Molecules 27 (16) (2022) 5225.

[34] R. Persaud, A. Khan, W.A. Isaac, W. Ganpat, D. Saravanakumar, Plant extracts, bioagents and new generation fungicides in the control of rice sheath blight in Guyana, Crop Protect. 119 (2019) 30–37, https://doi.org/10.1016/j.cropro.2019.01.008.

[35] L. Dėnė, A. Valiuškaitė, Sensitivity of botrytis cinerea isolates complex to plant extracts, Molecules 26 (15) (2021), https://doi.org/10.3390/molecules26154595.

[36] A. Asadi, M. Ghadamyari, S. Ramzi, Effect of some botanical insecticides and formulated extract of Sophora pachycarpa on Pseudococcus viburni under laboratory conditions, Plant Pest Research 14 (1) (2024) 1–17, https://doi.org/10.22124/iprj.2024.26642.1560.

[37] C. Gaidau, M. Niculescu, E. Stepan, D.G. Epure, M. Gidea, New mixes based on collagen extracts with bioactive properties, for treatment of seeds in sustainable agriculture, Curr. Pharmaceut. Biotechnol. 14 (9) (2013) 792–801, https://doi.org/10.2174/1389201014666131227112020.

[38] H. Huang, Y. Li, A. Huang, X. Wang, X. Zheng, W. Lu, Oviposition preference of Bactrocera dorsalis (Hendel) to five varieties of pitaya, J. Fruit Sci. 38 (3) (2021) 394–402, https://doi.org/10.13925/j.cnki.gsxb.20200258.

[39] S.O.W.M. Reuben, S.N. Yahya, R.N. Misangu, L.S. Mulungu, Field evaluation on effects of common spices in the control of diamondback moth (Plutella xylostella L.) pest of Chinese cabbage (Brassica campestris L.) commercial cultivar, Asian J. Plant Sci. 5 (1) (2006) 85–90, https://doi.org/10.3923/ajps.2006.85.90.

[40] R.A. Cloyd, C.L. Galle, S.R. Keith, N.A. Kalscheur, K.E. Kemp, Effect of commercially available plant-derived essential oil products on arthropod pests, J. Econ. Entomol. 102 (4) (2009) 1567–1579.

[41] Y. Jian, H. Yuan, D. Li, Q. Guo, X. Li, S. Zhang, F. Jian, Evaluation of the in vitro acaricidal activity of Chinese herbal compounds on the poultry red mite (Dermanyssus gallinae), Front. Vet. Sci. 9 (2022), https://doi.org/10.3389/fvets.2022.996422.

[42] J. Zorzetti, P.M.O.J. Neves, K.C. Constanski, P.H. Santoro, I.C.B. Fonseca, Plant extracts on Hypothenemus hampei (Coleoptera: Curculionidae) and Beauveria bassiana, Semina Ciências Agrárias 33 (SUPPL.1) (2012) 2849–2862, https://doi.org/10.5433/1679-0359.2012v33Supl1p2849.

[43] R.A. Cloyd, C.L. Galle, S.R. Keith, N.A. Kalscheur And, K.E. Kemp, Effect of commercially available plant-derived essential oil products on arthropod pests, J. Econ. Entomol. 102 (4) (2009) 1567–1579, https://doi.org/10.1603/029.102.0422.

[44] E.K. Abdul-Karim, The efficiency of magnesium oxide, nano magnesium oxide and cinnamon alcoholic extract in controlling FUSARIUM oxySPorum F.SP. Lycopersici WHICH causes FUSARIUM wilt on tomato, International Journal of Agricultural and Statistical Sciences 17 (2021) 1611–1618. Retrieved from, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85124492501&partnerID=40&md5=f84b2661414240ef50902e563d40dbca.

[45] E.M.C. Gomes, A.V. Firmino, R.D.C.M. Pena, S.S.M.D.S. de Almeida, Inhibitory effect in vitro of extracts Cinnamomum zeylanicum blume in control of Cylindrocladium candelabrum, Ciência Florest. 28 (4) (2018) 1559–1567, https://doi.org/10.5902/1980509835103.

[46] C.F. Nwanade, M. Wang, T. Wang, X. Zhang, C. Wang, Z. Yu, J. Liu, Acaricidal activity of Cinnamomum cassia (Chinese cinnamon) against the tick Haemaphysalis longicornis is linked to its content of (E)-cinnamaldehyde, Parasites Vectors 14 (1) (2021), https://doi.org/10.1186/s13071-021-04830-2.

[47] F. Ling, C. Jiang, G. Liu, M. Li, G. Wang, Anthelmintic efficacy of cinnamaldehyde and cinnamic acid from cortex cinnamon essential oil against Dactylogyrus intermedius, Parasitology 142 (14) (2015) 1744–1750, https://doi.org/10.1017/S0031182015001031.

[48] T. Cakmak, E. Hernández-Suárez, M.B. Kaydan, D.A. Tange, S. Perera, A. Piedra-Buena Díaz, Laboratory and field trials to identify reduced-risk insecticides for the control of the golden twin-spot moth chrysodeixis chalcites (esper) (Lepidoptera: noctuidae) in banana plantations, Agronomy 12 (12) (2022), https://doi.org/10.3390/agronomy12123141.

[49] N. Najdabbasi, S.M. Mirmajlessi, K. Dewitte, S. Landschoot, M. Mänd, K. Audenaert, G. Haesaert, Biocidal activity of plant-derived compounds against Phytophthora infestans: an alternative approach to late blight management, Crop Protect. 138 (2020), https://doi.org/10.1016/j.cropro.2020.105315.

[50] S. Ayvar-Serna, J.F. Díaz-Nájera, M. Vargas-Hernández, G.A. Enciso-Maldonado, O.G. Alvarado-Gómez, A.I. Ortíz-Martínez, Antifungal activity of biological, botanical and chemical pesticides on the causal agent of wild diseases of tomato, Rev. Fitotec. Mex. 44 (4) (2021) 617–624. Retrieved from, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85123896637&partnerID=40&md5=4513dc0855e6745e02b7f8bbb335888d.

[51] G.M.W. Lengai, E.R. Mbega, J.W. Muthomi, Activity of ethanolic extracts of spices grown in Tanzania against important fungal pathogens and early blight of tomato, Bulgarian Journal of Agricultural Science 27 (6) (2021) 1108–1117. Retrieved from, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85123527413&partnerID=40&md5=6a7fbf2889e8e186ad8ef4fe50e5901d.