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Review of Plant Essential Oils for Plant Pests Management

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Abstract This paper reviews the origins and classification of plant essential oil resources, along with prevalent extraction techniques for their active constituents. By integrating insights on the utilization of plant essential oils for plant pest management, the comprehensive analysis reveals multiple functionalities exhibited by plant essential oils, including fumigation, contact toxicity, repellent action, antifeedant activity, and growth inhibition. Furthermore, the paper highlights the challenges associated with plant essential oils in plant protection and outlines future research directions, aiming to offer valuable insights for the advancement of botanical insecticides.

Key words Plant essential oil; Insecticide; Bioactivity; Pest management; Plant protection

1 Introduction

In agricultural production, diseases and pests significantly influence plant growth, leading to decreased agricultural productivity and posing risks to food safety. Chemical pesticides have been instrumental in safeguarding plant health and advancing agricultural progress due to their cost-effectiveness and ease of application. However, in recent years, an increase in plant pest populations resistant to chemical pesticides has necessitated the excessive use of these chemicals, presenting significant challenges for agricultural ecology and food safety. During the 13^{th} Five-Year Plan, the "double reduction" initiative was implemented to curb the excessive use of agricultural fertilizers and chemicals, aiming to achieve a more regulated approach to agriculture known as One Regulatory, Two Reductions and Three Basics, with the two reductions focusing on minimizing fertilizer and pesticide usage. Consequently, in the realm of environmentally friendly agricultural practices, the conventional method of relying on chemical pesticides for pest control is no longer aligned with the principles of modern agriculture. There is an urgent need to explore and develop novel botanical agents that can serve as alternatives to traditional chemical insecticides.

Plant essential oils, as natural extracts from plants, have been recognized for their diverse physiological activities, such as antioxidant, antibacterial, insect repellent, and immune-enhancing properties[1]. These oils are extensively utilized in various fields such as medicine, food, and the chemical industry. Research indicates that the aromatic compounds present in essential oils from plant flowers and leaves can attract predators and deter pests, thereby playing a crucial role in plant protection. Due to their natural origin, complex composition, human and environmentally friendly nature, low likelihood of inducing pest resistance, plant essential oils hold significant research value in the realm of plant pest control. Consequently, the development and application of plant essential oils show great promise for the effective management of plant pests.

2 Source and classification of plant essential oils

Plant essential oils are secondary metabolic products found in aromatic plants. It is typically a liquid oil at room temperature and is volatile[2], capable of being distilled from water vapor without mixing with water. In commerce, it is called "aromatic oil", and in medicine, it is referred to as "volatile oil"[3]. Aromatic plants are a significant plant resource, and their essential oils have been identified and acknowledged since ancient times. They share common characteristics, such as containing natural chemicals that are complex and sensitive to air, sunlight, and temperature, which makes them prone to decomposition[4]. Plants containing essential oils are widely distributed in the plant kingdom. Some plant families known for their rich essential oil content include Cupressaceae, Magnoliaceae, Lauraceae, Rutaceae, Umbelliferae, Lamiaceae, Zingiberaceae, Asteraceae, Myrtaceae, Dryobalanops, Poaceae, Rosaceae, Piperaceae, Thymelaeaceae, Ericaceae, Oleaceae, and Ranunculaceae[5-6] (Table 1).

3 Active ingredients of plant essential oils and their common extraction methods

Plant essential oils are obtained by extracting aromatic plants that contain a variety of chemical compounds and demonstrate a wide range of biological properties. Typically, an essential oil consists of numerous components, comprising simple compounds with lower molecular weights that are readily absorbed by the body. The metabolic process of these oils ranges from minutes to hours, without leaving any residual or toxic effects. Consequently, they have extensive applications in pharmaceutical health care products, cosmetics, chemicals, and the food industrie, particularly in the aromatic sector[7]. Plant essential oils, known for their volatility,

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Table 1 Plant essential oil resources and their active components

Plant classification	Plant name	Extraction part	Extraction method	Main active substance	Literature source
Myrtaceae	*Melaleuca altemifolia*	Leaf	Steam distillation	4-Terpineol	[7]
	Eucalyptus spp.	Leaf	Steam distillation	Cineole	[8]
	Callistemon viminalis	Branch and leaf	Steam distillation	Methyleugenol	[9]
	Syzygium buxifolium	Leaf	Steam distillation	Caryophyllene	[10]
Cupressaceae	*Platycladus orientalis*	Leaf	Steam distillation	Isolimonene	[11]
	Juniperus chinensis	Needle	Solvent extraction	Caryophyllene	[11]
	Cedrus deodara	Needle	Steam distillation	Limonene	[11]
Zingiberacede	*Curcuma longa*, *Zingiber officinale*	Root tuber	Supercritical CO_2 extraction	α-Zingiberene	[12]
	Hedychium coronarium	Rhizome, leaf	Distillation extraction	1, 8-Cineole, β-pinene	[13]
Asteraceae	*Artemisia capillaris*	Flower	Steam distillation	Germacrene D	[14]
	Artemisia annua	Flower	Steam distillation	Terpinen-4-ol	[15]
	Chrysanthemum indicum	Flower	Steam distillation	Terpenes	[16]
Rosaceae	*Rosa rugosa*	Flower	Ultrasonic assisted steam distillation	Eugenol	[17 – 18]
	Cistus creticus	Flower	Ultrasonic extraction	2-Methyl-4,5-nonadiene	[19 – 20]
Piperaceae	*Piper nigrum*	Seed	Steam distillation	β-Caryophyllene	[21]
	P. nigrum fresh pepper	Fresh fruit seed	Steam distillation	β-Caryophyllene	[22]
Thymelaeaceae	*Aquilaria* spp.	Resin	Steam distillation	Sesquiterpenes	[23]
	Stellera chamaejasme	Root	Ultrasonic technology extraction	Flavone	[24]
Ericaceae	*Rhododendron anthopogonoides*	Flower	Steam distillation	Leaf alcohol	[25]
Lamiaceae	*Perilla frutescens*	Leaf	Steam distillation	Perilla ketone	[26]
	Mentha canadensis	Leaf	Ultrasonic assisted extraction	Menthone	[27 – 28]
	Agastache rugosa	Leaf	Steam distillation	Patchoulol	[29 – 30]
Umbelliferae	*Foeniculum vulgare*	Seed	Soxhlet extraction	Trans-anethole	[31]
	Cnidium monnieri	Rhizome	Supercritical CO_2 extraction	Benzofurazan	[32]
Oleaceae	*Osmanthus* sp.	Flower	Solvent extraction	Ionone	[33]
	Eugenia caryophyllata	Flower	Steam distillation	Eugenol	[34]
	Jasminum sambac	Flower	Supercritical CO_2 extraction	Linalool	[35]
Rutaceae	*Citrus reticulata* 'Dahongpao'	Pericarp	Pickling and lime method	D-Limonene	[36]
	Citrus reticulata	Pericarp	Pickling method	Limonene	[37]
	Zanthoxylum austrosinense	Fruit	Steam distillation	D-Limonene, O-Cymene	[38]
Lauraceae	*Litsea cubeba*	Fruit	Steam distillation	α-Citral	[37]
	Cinnamomum cassia	Trunk	Steam distillation	Cinnamaldehyde	[39 – 40]
	Camphora officinarum	Leaf	Steam distillation	Linalool	[41]
Magnoliaceae	*Lirianthe odoratissima*	Leaf	Petroleum ether room temperature extraction	a-Phellandrene	[42 – 43]
	Michelia figo	Flower	Supercritical CO_2 extraction	Caryophyllene oxide	[42 – 43]
	Liriodendron chinense	Leaf	Steam distillation	Nerolidol	[43]

demonstrate superior repellent or fumigation properties against pests. Additionally, certain components possess a range of properties including antifeeding, poisoning, population growth inhibition, and attraction activities. Therefore, they play a significant role in the prevention and management of plant pests as a bioactive substances.

There are four categories of essential oil ingredients: aliphatic compounds, terpenoids, aromatic compounds, and sulfur and nitrogen compounds. Among these, terpenoids are the most prevalent[34,44], exemplified by oils like peppermint, cinnamon, *Tanacetum vulgare*, and artemisia essential oils. There are various extraction techniques, comprising both conventional and innovative approaches. Conventional methods involve extrusion, steam distillation, organic solvent extraction, and adsorption. Novel methods encompass supercritical fluid extraction, solid-phase microextraction, enzyme extraction, non-solvent microwave extraction, ultrasonic-assisted extraction, molecular distillation, and simultaneous distillation headspace solid-phase microextraction[45]. With the advancement of science and technology, the extraction techniques and processes for plant essential oils are continuously evolving. This has led to the establishment of refined extraction processes tailored to different substrates, enabling the large-scale production of plant essential oils.

3.1 Terpenes Terpenes are polymers derived from isoprene and their derivatives. They can be categorized into semiterpenes (C_5H_8), monoterpenes ($C_{10}H_{16}$), sesquiterpenes ($C_{15}H_{24}$), diterpenes ($C_{20}H_{32}$), based on the quantity of isoprene units present in their structure[21]. Terpene compounds are frequently present in Rutaceae plants, such as citrus and lemons, predominantly in the roots, leaves, and stamen. Steam distillation is a commonly used method for extracting essential oils from these plants. Cai Suchuan[46] conducted steam distillation to extract red orange peel essential oil and analyzed the optimal extraction process to enhance the quality of the red orange peel essential oil. Li Kai *et al.*[36] employed pickling and lime methods to extract red orange essential oil. The study revealed that the total volatile component content of the red orange essential oil obtained through the pickling method was notably higher compared to that obtained through the lime method. Chen Yan *et al.*[47] employed the supercritical CO_2 extraction technique to isolate lemon essential oil and utilized GC-MS for the analysis of the predominant terpene compound in lemon essential oil, specifically D-limonene. Liu Yijun *et al.*[48] extracted essential oils from tender branches and leaves of *Melaleuca alternifolia* using the steam distillation method. They qualitatively analyzed the enol compounds and identified α-terpinene, γ-terpinene, and terpinen-4-ol as the main chemical components of enol compounds. Terpene compounds serve as the primary constituents responsible for the distinctive aroma of the *Rhododendron* genus. Steam distillation is commonly employed to extract the essential oil from these plants. Additionally, supercritical CO_2 extraction and headspace solid-phase microextraction are alternative techniques employed for this purpose. In their investigation of the key components contributing to the unique fragrance of the *Rhododendron* genus, Teng Xinlei *et al.*[49] identified several terpene compounds, including α-pinene, β-caryophyllene, and β-pinene, as the primary constituents of the *Rhododendron* aroma. Tan Yuqing *et al.*[50] conducted an analysis on the aroma components present in the floral organs of *Michelia platypetala* 'Hongyun' and identified them as terpene compounds.

3.2 Aromatic compounds Aromatic compounds constitute the second most significant components of plant essential oils, comprising two categories of substances: terpenoids (*e.g.*, thymol, α-curcumene) and phenylpropanoid derivatives (aldehydes, alcohols, and phenols, such as benzyl acetate, eugenol, cinnamaldehyde, elemicin, and euasarone). Commonly found in cinnamon essential oil, clove essential oil, and rose essential oil, these compounds were extracted using steam distillation by researchers such as Yao Hangcun[40], Yu Shuai[34], and An Bifang *et al.*[51].

3.3 Aliphatic compounds Additionally, the essential oil contains small molecule aliphatic compounds, such as alkanes, olefins, acids, aldehydes, ketones, alcohols, and esters. Examples include n-heptane in turpentine, isovaleraldehyde in citronella essential oil, and isovaleric acid in valerian essential oil[52]. The volatile aliphatic compounds primarily consist of ethyl butyrate, ethyl acetate, and other ester compounds.

3.4 Sulfur and nitrogen compounds These compounds constitute a small proportion with low concentrations in plant essential oils; however, they exert a significant influence on the aroma of plant essential oils, and some can dictate the characteristic scent of plants or spices[52-53]. For instance, nitrogen sulfur compounds are frequently identified in garlic essential oil and pepper essential oil.

4 Mechanism of plant essential oils for plant pest control

Plant essential oils contain various ingredients with insecticidal properties, often comprising a range of analogues and isomers that collectively exhibit insecticidal activity. These components primarily consist of terpenes, flavonoids, alkaloids, and other compounds. Plant essential oils exhibit a range of effects on pest management, including stomach action, fumigation, contact toxicity, antifeeding properties, and repellent action. These impacts influence the neural, digestive, respiratory systems, and hormonal metabolism of insects[54]. The combination of various functions and mechanisms in plant essential oils reflects their unique advantages in the prevention and control of pests. The diversity of pest control is influenced by the variety of active substances available, the range of pests in nature, and their behavioral patterns. This diversity offers significant potential for utilizing plant essential oils in the development of botanical insecticides, thereby establishing a highly efficient green biological control approach[55].

4.1 Stomach action, fumigation and contact toxicity Toxicity encompasses stomach action, fumigation, and contact toxicity, with numerous plant essential oils exhibiting toxic effects. Plant essential oils are frequently utilized to modulate the neural system of pests by disrupting nerve signaling, affecting nerve transmitter release, and inhibiting nerve receptor binding. Additionally, some essential oils can disrupt or impede the digestive and respiratory systems of pests, ultimately resulting in paralysis, coma, or fatality. Wang Rong *et al.*[56] proposed that the active component extracts of essential oils from *Syringa oblata*, *Glycyrrhiza uralensis*, *Heracleum hemsleyanum*, *Paeonia lactiflora*, and *Illicium verum* demonstrated significant contact toxicity and stomach action on *Plutella xylostella*. Among these extracts, *S. oblata* extract showed the highest toxicity towards both the eggs and larvae of *P. xylostella*. Additionally, the essential oil extracts from these five plants affected the egg development of *P. xylostella*, impeding tissue organ development and resulting in malformed larvae. Sun Yuting *et al.*[57] discovered that the essential oil derived from *Asarum heterotropoides* demonstrated inhibitory effects on the activities of acetylcholinesterase (AchE) and carboxylesterase (CarE) in *Bactrocera dorsalis*. This led to the disruption of the nervous, digestive, and respiratory systems, ultimately exerting an insecticidal effect. Moreover, the essential oil of *A. heterotropoides* exhibited significant contact toxicity and fumigation activity against *B. dorsalis*, showing particularly potent contact toxicity. Wang Yingying *et al.*[1] demonstrated that cinnamaldehyde, the primary component of cinnamon essential oil, has a significant impact on the activity of three protective enzymes in the body of *Tribolium castaneum*. This compound also exerts a toxic effect, with the most effective fumigation observed in adults exposed to 2.5 μL/L of cinnamaldehyde for 72 h. Zhang Jiafeng[4] demonstrated that the oil extracted from *Chenopodium ambrosiodes* exhibited a notable fumigation effect on *Plodia interpunctella* larvae. The mortality rate of the larvae reached 100% after fumigation with 20 μL per dish for 48 h. Wagner *et al.*[58] discovered that the essential oils derived from *Mentha spicata* and *Rosmarinus officinalis* exhibited potent fumigation activity against *Epicauta atomaria*, with LC_{50} values of 21.7 and 23.3 μL/L, respectively. Liu Chenyu[59] discovered that a mixed solution of L-carvone and cuminalcohol exhibited contact toxicity towards *Arma chinensis* and *Myzus persicae*. Additionally, it was observed to influence the predatory behavior of *A. chinensis* towards *M. persicae*, displaying a certain level of repellent and non-selective antifeeding effects on *A. chinensis*. The contact toxicity was found to increase gradually with longer processing times and higher concentrations.

4.2 Repellent, antifeeding and attractive effect Many insects exhibit sensitivity to the distinct aroma of plant essential oils, leading them to avoid areas treated with such oils. Consequently, essential oils possess a repellent effect on insects. Kang Peng[60] discovered that the primary insecticidal compounds in *Stellera chamaejasme* and *Thymus mongolicus*, such as daphneantoxin, thymol, and azadirachtin, demonstrated a notable inhibitory impact on the *in vivo* ATPase, AChE, and total esterase activities of *Oedaleus decorus asiaticus*. These compounds exhibited certain insecticidal properties along with evident repellent effects. The toxicity performance was ranked as non-selective antifeeding effect > selective antifeeding effect > stomach action > contact toxicity, with a repellent rate exceeding 80%. Azadirachtin exhibited the most potent antifeeding effect.

The process of insect feeding typically comprises four sequential stages: host recognition and location, initiation of feeding, sustained feeding, and cessation of feeding. Certain plant essential oils have the ability to activate the nervous systems of insects, thereby deterring them from feeding. This action can disrupt the insects' taste receptors, leading to reduced appetite and impacting subsequent stages of their feeding process. Consequently, this can result in starvation, dehydration, progressive mortality, or developmental abnormalities because of adequate nutritional intake. According to the study of Santos *et al.* [61], the utilization of *Pogostemon cablin* essential oil has been shown to diminish the reproductive capability of *Hypothenemus hampei*, elevate their locomotor activity, and induce alterations in the histopathology of the midgut tissue, leading to a pronounced antifeeding response. Yu Minghui *et al.* [62] disclosed that *Mythimna separate* and *Athetis lepigone* exhibited a significant antifeeding response to piperine found in *Piper nigrum* and *Zanthoxylum bungeanum*. In contrast, sanshool demonstrated antifeeding properties exclusively against *Spodoptera exigua* larvae. Song Chengfei *et al.* [63] found that the essential oil of *Ruta graveolens* demonstrated a notable selective and non-selective antifeeding effect on the 3^{rd} instar larvae of *P. xylostella*. Particularly, at a concentration of 15 μg/μL for 24 and 48 h, the selective antifeeding rates reached 100.00% and 92.84%, respectively.

Attraction frequently leverages the distinctive scent or other chemical characteristics of plant essential oils to attract pests and facilitate their targeted eradication. Xu Tong *et al.* [64] discovered that certain volatiles, including (±)-limonene, γ-terpinene, nonanal, β-caryophyllene, and α-farnesene, derived from four host plants (*Citrus reticulata*, *Melia azedarach*, *Koelreuteria bipinnata*, and *Casuarina equisetifolia*), played a crucial role in the attraction of *Anoplophora chinensis*. These compounds were found to elicit a potential response in the antennae of the insect. Particularly, β-caryophyllene and γ-terpinene exhibited a significant attracting effect on *A. chinensis*. Yuan Shengyong *et al.* [65] proposed that four plant volatiles, namely 3-nonen-1-ol, n-hexadecane, octadecene, and cis-3-hexen-1-ol, demonstrated a trapping effect on *Bactrocera tau* adults, with cis-3-hexen-1-ol showing the most effective trapping capability.

4.3 Growth inhibition The diverse bioactive constituents found in plant essential oils, including phenols, esters, ketones, and terpenoids, exhibit a range of effects on pests. These components have the potential to influence the synthesis and release of specific insect hormones, and disrupt the normal physiological metabolism of insects, ultimately impeding their growth and development or inducing growth abnormalities. Certain essential oils have the capability to disrupt the incubation process of eggs, leading to a decrease in the incubation rate. This disruption can have implications on the reproductive capacity of adult insects, resulting in a reduction in the quantity of eggs laid and a decrease in the incubation rate of those eggs. Song Chengfei *et al.* [63] demonstrated that essential oils extracted from *Polygonum hydropiper*, *Rosmarinus officinalis*, *Ruta graveolens*, and *Perilla frutescens* exhibited a notable inhibitory effect on the growth of the 3^{rd} instar larvae of *P. xylostella*. Chen Junhua *et al.* [66] discovered that the essential oil extracted from *Chenopodium ambrosioides* exhibited various biological effects on *Ectropis grisescens*, including inhibiting larval growth, decreasing pupation rates, reducing the fecundity of offspring, and so forth. Wang Rong *et al.* [56] demonstrated that the growth of *P. xylostella* eggs was influenced by essential oils extracted from *S. oblata*, *G. uralensis*, *H. hemsleyanum*, *P. lactiflora*, and *I. verum*, resulting in impaired development of the tissue organs within the eggs or causing deformities in the larvae.

5 Research and application of plant essential oil in plant pest control

Plant essential oils encompass a varied array of insecticidal active compounds that collaboratively enhance insecticidal efficacy. The synergistic interactions and mechanisms of these compounds underscore the unique benefits of plant essential oils in pest management and control. The diversity of pest control is influenced by the variety of active substances and the range of pests in nature, along with their living habits[67]. This diversity offers significant potential for the advancement of plant essential oils as botanical insecticides, establishing them as a highly efficient green environmental biological control method (Table 2).

In recent years, an increasing number of researchers have been conducting studies on the utilization of plant essential oils for the prevention and management of plant pests. Zhang Xuying[68] investigated the repellent properties of volatile oils derived from 23 non-host plants and their primary chemical compositions on male and female *Diaphorina citri*. The study revealed that citronella oil, coriander oil, and ginger oil exhibited notable repellent effects on *D. citri* at a concentration of 100 μL/mL, with repellent rates of 68.45%, 66.37%, and 61.9%, respectively. These oils can serve as efficient repellents against *D. citri*. Guo Feng[69] investigated

Table 2 Plant resources with insecticidal properties and their insecticidal active ingredients at home and abroad

Insecticidal mechanism	Plant	Insecticidal active ingredient	Literature source
Stomach action	*Stellera chamaejasme*	Coumarin active compounds	[60]
	Artemisia annua	4-Quinolinecarboxaldehyde	[72]
	Pongamia pinnata pod	Hydroxanthin	[73]
	Lavandula angustifolia	1,8-Cineole	[74]
Fumigation	*Asarum heterotropoldes*	Methyleugenol	[57]
	Illicium verum	Trans-anethole	[56]
	Nepeta cataria	Menthone	[75]
	Elsholtzia ciliata	Carvone	[76]
	Cinnamomum cassia	Cinnamaldehyde	[1, 77]
	Anethum graveolens	D-Carvone	[78]
	Isodon excisus	O-Cymene	[78]
	Dysphania ambrosioides	α-Terpinene	[5]
	Mentha spicata	I-Pulegone, isopulegone	[58]
	Rosmarinus officinalis	Camphor, 1,8 -cineole, α-pinene	[58]
Contact toxicity	*Artemisia annua*	4-Quinolinecarboxaldehyde	[72]
	A. heterotropoldes	Methyleugenol	[78]
	E. ciliata	Carvone	[76]
	Syringa oblata	Eugenol	[56]
	Mirabilis jalapa	4-Quinolinecarboxaldehyde	[79]
	Corydalis edulis	Isoquinoline alkaloids	[80]
	Taxodium 'Zhongshanshan' leaf	n-Butanol	[81]
Repellent action	*Thymus mongolicus*	Thymol	[60]
	Stellera chamaejasme	5-Diphenyl-2-penten-1-one	[60]
	E. ciliata	Carvone	[76]
	Cymbopogon citratus	Linalool, α- Terpineol, Decanal, geraniol	[68]
	Coriandrum sativum		[68]
	Zingiber officinale		[68]
	Salvia japonica	Eucalyptol	[71]
Antifeeding effect	*Artemisia annua*	4-Quinolinecarboxaldehyde	[72]
	Azadirachta indica	Azadirachtin	[60]
	L. angustifolia	1, 8-Cineole	[74]
	Piper nigrum	Sanshool, piperine	[62]
	Zanthoxylum bungeanum	Piperine	[62]
	Ruta graveolens	β-Caryophyllene	[63]
	Pogostemon cablin	Patchouli alcohol, a-Guaiene	[61]
Growth inhibition	*P. pinnata* pod	Hydroxanthin	[56]
	E. ciliata	Carvone	[73]
	S. oblata	Eugenol	[76]
	D. ambrosioides	α-Terpinene	[66]
	S. oblata	Eugenol	[56]
	I. verum	Trans-anethole	[56]
	Heracleum hemsleyanum	Acetone extract	[56]
Attraction	*Citrus reticulata*	(±)- Limonene	[64]
	Melia azedarach	α-Farnesene	[64]
	Casuarina equisetifolia	Nonanal	[64]
	Koelreuteria bipinnata	Nonanal, α-farnesene, γ-terpinene	[64]
	Cucurbita moschata, *Cucumis sativus*	cis-3-Hexen-1-ol	[65]
		n-Hexadecane	
		Octadecene	
		(E)-3-Nonen-1-ol	

the toxic and oviposition-repellent effects of 10 plant essential oils on *Bactrocera dorsalis*. The study revealed that *Cymbopogon citratus* essential oil, *Cymbopogon citratus* essential oil, *Thymus mongolicus* essential oil, and *Litsea cubeba* essential oil exhibited significant toxicity towards *B. dorsalis*. Among these, *C. citratus* essential oil demonstrated the most effective repellent properties, achieving an oviposition repellent rate of 80.77% at a concentration of 7 mg/mL. Song Chengfei *et al.* [63] investigated the biological activity of essential oils extracted from non-host plants, including *P. hydropiper*, *R. officinalis*, *R. graveolens*, and *P. frutescens*, on *P. xylostella*. The study revealed that both female and male adults of *P. xylostella* exhibited certain antennal responses and repellent activities towards the essential oils of these plants. Specifically, the essential oil from *P. hydropiper* demonstrated the highest toxicity against the 2nd instar larvae of *P. xylostella*, while the essential oil from *R. graveolens* exhibited growth inhibition and selective and non-selective antifeeding effects on the 3rd instar larvae. Moreover, at a concentration of 15 μg/μL for 24 and 48 h, the selective antifeeding rates of the 3rd instar larvae of *P. xylostella* were 100.00% and 92.84%, respectively, indicating the significant biological activity of the essential oil from *R. graveolens* against *P. xylostella*. These findings suggest the potential of developing targeted insecticides against *P. xylostella* using the essential oil from *R. graveolens*. Tu Juan *et al.* [70] investigated the impact of *Allium sativum* essential oil on *Ectropis grisescens*, focusing on stomach action, contact toxicity, antifeeding, repellent, and egg-killing effects. The study revealed a positive correlation between stomach action, contact toxicity, and non-selective antifeeding effect with treatment concentration. Additionally, *A. sativum* essential oil exhibited selective antifeeding and repellent effects on *E. grisescens* across all concentrations, resulting in a hatching rate of 0 for *E. grisescens* eggs. Yuan Shengyong *et al.* [65] examined the olfactory behavioral responses of *B. tau* adults to (E)-3-nonen-1-ol, n-hexadecane, octadecene, and cis-3-hexen-1-ol. The study revealed that these four plant volatiles exhibited a trapping effect on *B. tau* adults, suggesting their potential use as ingredients in botanical attractants. Among these compounds, cis-3-hexen-1-ol demonstrated the highest trapping capability. Yu Minghui *et al.* [62] conducted a study on the antifeeding properties of piperine and sanshool, compounds found in *P. nigrum* and *Z. bungeanum*, on four species of Lepidoptera larvae. The study revealed that *M. separate* and *A. lepigone* showed a notable antifeeding reaction to piperine. Consequently, piperine demonstrated the potential to serve as the fundamental structural basis for broad-spectrum antifeedants against Lepidoptera larvae in summer maize fields. Wang Rong *et al.* [56] investigated the bioactivity of essential oil extracts from *S. oblata*, *G. uralensis*, *H. hemsleyanum*, *P. lactiflora*, and *I. verum* on the various life stages of *P. xylostella*. Their study revealed that these plant extracts exhibited significant insecticidal effects on the eggs and larvae of *P. xylostella*. Moreover, the extracts influenced the egg development of *P. xylostella*, hindering the development of tissue organs and leading to the formation of malformed larvae. Consequently, these extracts could serve as valuable resources for the development of environmentally friendly agents for the prevention and control of *P. xylostella*.

Sayed *et al.*[71] investigated the toxicity, deterrent, and repellent properties of essential oils from *Mentha piperita*, *Mentha longifolia*, *Salvia officinalis*, and *Salvia rosmarinus* against *Aphis punicae*. The study revealed that the essential oils from *S. officinalis* exhibited significant deterrent and repellent effects on *A. punicae*, indicating their potential as effective natural aphicides.

6 Conclusions and prospects

There are approximately 500 000 plant species worldwide. Incomplete statistics suggest that there are over 1 000 plant species containing insecticidal active ingredients[55], providing a basis for advancing the use of essential oils from plants to combat plant pests. Among them, there are nearly 700 species of plants that exhibit repellent, antifeeding, and attracting effects on plant pests, while 35 species induce insect infertility or inhibit growth[82]. Photoactive toxins are present in various plants, and α-terthienyl, the primary insecticidal component in *Tagetes erecta* essential oil, is a common photoactive toxin. This compound exhibits significant toxicity to *Tylenchulus semipenetrans*[83].

As an agrarian nation, China is currently grappling with a significant environmental challenge stemming from the excessive use of chemical insecticides in agricultural practices. Consequently, there has been a rapid advancement in the research and development of plant essential oil insecticides, which offer environmental benefits in pest prevention and control within the pesticide sector. However, plant essential oils encounter challenges in agricultural production and product development. Firstly, essential oils are characterized by high volatility and sensitivity to environmental factors such as air, sunlight, and temperature, which leads to rapid degradation following oxidation. Secondly, the production process of plant essential oils is intricate, and the field efficacy is suboptimal. Thirdly, the performance of plant essential oil pesticides is relatively unstable, hindering their industrial application. Lastly, there is a greater focus on research related to the production of essential oils in China, while there is comparatively less emphasis on studies regarding the properties, development, and utilization of essential oils.

Future studies should broaden the scope of screening plant resources with insecticidal properties. It is advisable to choose plants abundant in natural resources that are easily accessible for research and development purposes. Furthermore, researchers should investigate the insecticidal properties of various families, genera, and species of well-known plant resources to maximize their utilization[84]. In the process of extracting and developing effective components for plant essential oil insecticides, it is crucial to select active ingredients that are environmentally friendly and have stable efficacy. Additionally, there is a need to target the screening of active metabolites from plant essential oils that exhibit synergistic effects with chemical pesticides. This approach can offer a wider range of products to reduce the application of chemical pesticides while enhancing efficiency. Ultimately, this strategy aims to replace or partially substitute for chemical pesticides for controlling plant pests. Including compound tests of plant essential oil insecticides in field trials can address the issue of botanical insecticides having minimal or no impact on non-target pests. The research, development, and utilization of plant essential oil insecticides align with the principles of "green agriculture" and cater to the demand for pollution-free agricultural products. China possesses abundant plant resources and offers distinctive conditions conducive to research in this field. This paper provides a summary of the insecticidal active ingredients and functions found in plant essential oil resources. It also discusses the insecticidal mechanism of these active ingredients and the current status of plant pest control. The aim is to offer theoretical guidance for research on plant essential oil insecticides and to serve as a reference for the development of botanical insecticides utilizing plant essential oils.

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