

REVIEW ARTICLE

Monoterpenes for Management of Field Crop Insect Pests

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ABSTRACT

The control of different agricultural insect pests still relies mainly on the use of synthetic insecticides. However, excessive use of these chemicals cause many problems, including high residue levels, harmful effects on the environment and human health, and development of insect resistance. Therefore, new strategies for the management of agricultural insects are urgently needed. Plant-based natural products are promising alternatives to be applied for pest control, with remarkable and broad-spectrum biological activities. Among the plant secondary metabolites, essential oils, and their major constituents, mainly monoterpenes, have been widely studied for their application in insect control, food additives, perfumes and cosmetics. In this review, we focus on the studies describing the toxic effects of monoterpenes, including fumigant, contact and residual toxicities against insect pests attacking economic crops in fields. Furthermore, the effects of monoterpenes on insect behaviors (antifeedant and repellent activities) and insect growth regulation are also discussed.

Keywords: Biocontrol agents, Botanical insecticides, Pest control alternatives, Synthetic insecticides.

INTRODUCTION

Currently, the management strategies of field insect pests primarily depend on the use of synthetic insecticides. However, the negative side effects on human health and environmental problems related to the repetitive application of synthetic insecticides have promoted intensive research for finding safe and effective alternatives for insect management. Many promising alternatives have been studied and used for controlling of insect pests, such as microorganisms (*Bacillus thuringiensis*, *Beauveria bassiana*, *Trichoderma viride*,

nuclear polyhedrosis viruses and granulosis viruses), microbial- derived insecticides (spinosad and abamectin), botanical insecticides (neem oil, azadirachtin, pyrethrum, vegetable oils and essential oils), natural enemies (parasitoids, predators) biochemical insecticides (antifeedants, repellents and attractants) and plant-incorporated protectants (transgenic *Bacillus thuringiensis* toxin) (Isman, 2006; Koul *et al.*, 2008; Dayan *et al.*, 2009; Seiber *et al.*, 2014; Czaja *et al.*, 2015; Atia *et al.*, 2016; El-Gaied *et al.*, 2020). However, essential oils and their main constituents (monoterpenes) are among the most effective alternatives that have been

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extensively studied by many researchers worldwide (Isman *et al.*, 2011). Essential oils and monoterpenes are relatively safe natural alternatives for the control of insect pests with high efficacy, low or no impacts on human health and environment, no residues on the treated products and high degradability. Moreover, no insect resistance has been reported for such materials until now (Isman, 2006).

Essential oils are volatile natural complex secondary metabolites characterized by a strong odor and have a generally lower density than that of water (Bruneton, 1999; Bakkali *et al.*, 2008). There are 17,500 aromatic plant species (Sharmeen *et al.*, 2021) among higher plants and approximately 3,000 essential oils are known, out of which 300 are commercially important for pharmaceuticals, cosmetics and perfume industries (Bakkali *et al.*, 2008) apart from pesticidal potential (Franzios *et al.*, 1997; Chang and Cheng, 2002). Essential oils contain a variety of volatile molecules, mainly monoterpenes, phenylpropenes and sesquiterpenes, which have both behavioral and physiological functions on living organisms, including plants and insects. Monoterpenes are the main constituents of many plant essential oils that are responsible for the odor of the plant because of their low boiling points (Seigler, 1998). In some aromatic plants, monoterpenes represent more than 90% of oil composition (De Sousa, 2011). Several hundred monoterpenes have been isolated from higher plants and their structures were identified. They are biosynthesized from geranyl pyrophosphate, the ubiquitous acyclic C₁₀ intermediate of the isoprenoid pathway (Bakkali *et al.*, 2008; Windholz *et al.*, 1983). Chemically, monoterpenes are classified into two major groups: monoterpene hydrocarbons and oxygenated monoterpenes. Both groups can be subdivided into acyclic, monocyclic, and bicyclic monoterpenes (Templeton, 1969).

Monoterpenes have a wide range of biological activities that are important in food chemistry, chemical ecology, and

pharmaceutical industry (Schewe *et al.*, 2011). They are involved in various ecological functions in plants, such as protection against herbivores and microbial diseases, attraction of pollinators, and in allelopathy (Langenheim, 1994). Monoterpenes have been shown to possess remarkable biological activities, including insecticidal (Abdelgaleil *et al.*, 2009; Kanda *et al.*, 2017), herbicidal (Duke *et al.*, 2002; Singh *et al.*, 2002; Gouda *et al.*, 2016), fungicidal (Marei *et al.*, 2012; Zhang *et al.*, 2016), and bactericidal (Cristani *et al.*, 2007; Cantore *et al.*, 2009; Silva *et al.*, 2015) properties. These activities verify that monoterpenes are potential alternative as pest control agents as well as good lead compounds for the development of safe, effective, and fully biodegradable insecticides (Isman *et al.*, 2011; Salakhutdinov *et al.*, 2017).

Due to the importance of finding safer and effective alternatives for the control of insect pests, the aim of this review was to highlight some recent studies in which monoterpenes have been proposed as safe and green insecticides in the last 20 years. This review discusses the different biological activities, such as insecticidal, repellent, antifeedant, growth regulatory effects of monoterpenes as well as the potential of monoterpenes for the control of field crop insect pests.

Contact Toxicity of Monoterpenes against Field Crop Insects

Studies on the insecticidal activities of monoterpenes by contact application against field crop insects are clarified in Table 1. Most of studies focused on lepidopteran species (55 monoterpenes), followed by Coleopterous species (20 monoterpenes), Dipterous species (12 monoterpenes) and Hemiptera species (6 monoterpenes). However, the effects of monoterpenes on mortality of insect pests of lepidopteran species are highly variable. α -Pinene had considerable effects on fall armyworm, *Spodoptera frugiperda* (LD₅₀= 0.28 μ L larva⁻¹). The high toxic effect of α -pinene on *S. frugiperda* may be due to its high

Table 1. Contact toxicity of monoterpenes against field crop insects.

Insect species	Monoterpene	Toxicity (LD ₅₀ , LC ₅₀ , M) ^a	Reference	
<i>Spodoptera frugiperda</i>	Limonene	LD ₅₀ = 31.5 mg g ⁻¹	Cruz <i>et al.</i> , 2017	
	α-Pinene	LD ₅₀ = 0.28 μL larva ⁻¹	Monteiro <i>et al.</i> , 2021	
	Trans-anethole	LD ₅₀ = 0.027 mg g ⁻¹	Cruz <i>et al.</i> , 2017	
<i>Spodoptera litura</i>	Carvacrol	LD ₅₀ = 42.7 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	Citronellal	LD ₅₀ = 111.2 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	d-Limonene	LD ₅₀ = 273.7 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	Pulegone	LD ₅₀ = 51.6 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	Terpinen-4-ol	LD ₅₀ = 130.4 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	α-Terpineol	LD ₅₀ = 141.3 μg larva ⁻¹	Hummelbrunner and Isman, 2001	
	Thymol	LD ₅₀ = 1.01 μg larva ⁻¹	Tharamak <i>et al.</i> , 2019	
	<i>Spodoptera littoralis</i>	(-)-Borneol	LD ₅₀ > 300 μg larva ⁻¹	Pavela, 2014
		(+)-Camphor	LD ₅₀ = 71 μg larva ⁻¹	Pavela, 2014
		Carvacrol	LD ₅₀ = 15 μg larva ⁻¹	Pavela, 2014
(-)-Carvone		LD ₅₀ = 0.15 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
l-Carvone		LD ₅₀ = 18 μg larva ⁻¹	Pavela, 2014	
Cinnamaldehyde		LD ₅₀ = 32 μg larva ⁻¹	Pavela, 2014	
1,8-Cineole		LD ₅₀ = 0.62 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
(-)-Citronellal		LD ₅₀ = 0.73 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
β-Citronellol		LD ₅₀ = 31 μg larva ⁻¹	Pavela, 2014	
Cuminaldehyde		LD ₅₀ = 0.27 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
p-Cymene		LD ₅₀ = 0.36 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
Geraniol		M= 76. 7% (1 mg larva ⁻¹)	Abdelgaleil, 2010	
(R)-(+)-Limonene		LD ₅₀ = 122 μg larva ⁻¹	Pavela, 2014	
Linalool		LD ₅₀ = 85 μg larva ⁻¹	Pavela, 2014	
Menthone		LD ₅₀ = 25 μg larva ⁻¹	Pavela, 2014	
Myrcene		LD ₅₀ = 89 μg larva ⁻¹	Pavela, 2014	
(-)-β-Pinene		LD ₅₀ = 65 μg larva ⁻¹	Pavela, 2014	
(-)-α-Pinene		LD ₅₀ = 0.63 mg larva ⁻¹	Al-Nagar <i>et al.</i> , 2020	
Piperitone		LD ₅₀ = 0.68 μg larva ⁻¹	Abdelgaleil, <i>et al.</i> , 2008	
α-Terpinene		LD ₅₀ = 34 μg larva ⁻¹	Pavela, 2014	
γ-Terpinene	LD ₅₀ = 89 μg larva ⁻¹	Pavela, 2014		
Terpinen-4-ol	LD ₅₀ = 16.20 μg larva ⁻¹	Abbassy <i>et al.</i> , 2009		
α-Terpineol	LD ₅₀ = 43 μg larva ⁻¹	Pavela, 2014		
Terpinolene	LD ₅₀ = 52 μg larva ⁻¹	Pavela, 2014		
Trans-Anethole	LD ₅₀ =18 μg larva ⁻¹	Pavela, 2014		
Thymol	LD ₅₀ = 9 μg larva ⁻¹	Pavela, 2014		
<i>Agrotis ipsilon</i>	Carvone	LC ₅₀ = 0.047%	Sharaby and El-Nujiban, 2015	
	Citronellol	LC ₅₀ = 0.034%	Sharaby and El-Nujiban, 2015	
	Linalool	LC ₅₀ = 0.199%	Sharaby and El-Nujiban, 2015	
	Nerol	LC ₅₀ = 0.025%	Sharaby and El-Nujiban, 2015	
	Phellandrene	LC ₅₀ = 0.143%	Sharaby and El-Nujiban, 2015	
	Thymol	LC ₅₀ = 0.140%	Sharaby and El-Nujiban, 2015	
α-Terpeniol	LC ₅₀ = 0.046%	Sharaby and El-Nujiban, 2015		

^a LD₅₀= Dose causing 50% mortality; LC₅₀= Concentration causing 50% mortality; M= Mortality; LT₅₀= Time needed to kill 50% of insect population. Table 1 continued...



Continue of Table 1. Contact toxicity of monoterpenes against field crop insects.

Insect species	Monoterpene	Toxicity (LD ₅₀ , LC ₅₀ , M) ^a	Reference
<i>Anticarsia gemmatalis</i>	Linalool	M= 100% (10 µL mL ⁻¹)	Vicenco et al., 2021
<i>Chilo partellus</i>	Carvacrol	LD ₅₀ = 550.3 µg larva ⁻¹	Singh et al., 2009
	1,8-Cineole	LD ₅₀ = 412.1 µg larva ⁻¹	Singh et al., 2009
	Linalool	LD ₅₀ = 462.4 µg larva ⁻¹	Singh et al., 2009
	trans-Anethole	LD ₅₀ = 409.7 µg larva ⁻¹	Singh et al., 2009
	Terpineol	LD ₅₀ = 606.0 µg larva ⁻¹	Singh et al., 2009
	Thymol	LD ₅₀ = 189.7 µg larva ⁻¹	Singh et al., 2009
<i>Helicoverpa armigera</i>	Carvacrol	LC ₅₀ = 33.5 µg mL ⁻¹ egg	Gong and Ren, 2020
		LC ₅₀ = 51.5 µg mL ⁻¹ larva	Gong and Ren, 2020
	p-Cymene	LC ₅₀ = 47.9 µg mL ⁻¹ egg	Gong and Ren, 2020
		LC ₅₀ = 121.3 µg mL ⁻¹ larva	Gong and Ren, 2020
<i>Plutella xylostella</i>	γ-Terpinene	LC ₅₀ = 56.5 µg mL ⁻¹ egg	Gong and Ren, 2020
		LC ₅₀ = 150.2 µg mL ⁻¹ larva	Gong and Ren, 2020
<i>Plutella xylostella</i>	Linalool	LC50= 3.37 ppm	Webster et al., 2017
	Thymol	LC50= 1.80 ppm	Webster et al., 2017
<i>Agriotes obscurus</i>	Citronellal	LD ₅₀ = 404.9 µg larva ⁻¹	Waliwitiya et al., 2005
	Thymol	LD ₅₀ = 195.5 µg larva ⁻¹	Waliwitiya et al., 2005
<i>Leptinotarsa decemlineata</i>	Camphene	M= 26.7% (0.30 mg cm ⁻²)	Kordali et al., 2007
	Camphor	M= 86.7% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	3-Carene	M= 100.0% (0.08 mg cm ⁻²)	Kordali et al., 2007
	Carvone	M= 90.1% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Citronella	M= 90.1% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	β-Citronellene	M= 100% (0.08 mg cm ⁻²)	Kordali, et al., 2007
	Fenchone	M= 100.0% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Fenchol	M= 6.8% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Limonene	M= 90% (0.15 mg cm ⁻²)	Kordali et al., 2007
	Linalol	M= 100.0% (0.08 mg cm ⁻²)	Mahdi et al., 2011
	Linalyl acetate	M= 90.1% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Menthol	M= 42.5% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Menthone	M= 57.8% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Myrcene	M= 100% (0.30 mg cm ⁻²)	Kordali et al., 2007
	Nerol	M= 51.0% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	α-Pinene	M= 66.7% (0.15 mg cm ⁻²)	Kordali et al., 2007
β-Pinene	M= 100% (0.15 mg cm ⁻²)	Kordali et al., 2007	
γ-Terpinene	M= 100% (0.15 mg cm ⁻²)	Kordali et al., 2007	
<i>Agriotes obscurus</i>	Citronellal	LD ₅₀ = 404.9 µg larva ⁻¹	Waliwitiya et al., 2005
	Thymol	LD ₅₀ = 195.5 µg larva ⁻¹	Waliwitiya et al., 2005
<i>Leptinotarsa decemlineata</i>	Camphene	M= 26.7% (0.30 mg cm ⁻²)	Kordali et al., 2007
	Camphor	M= 86.7% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	3-Carene	M= 100.0% (0.08 mg cm ⁻²)	Kordali et al., 2007
	Carvone	M= 90.1% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	Citronella	M= 90.1% (0.24 mg cm ⁻²)	Mahdi et al., 2011
	β-Citronellene	M= 100% (0.08 mg cm ⁻²)	Kordali, et al., 2007
	Fenchone	M= 100.0% (0.24 mg cm ⁻²)	Mahdi et al., 2011

^a LD₅₀= Dose causing 50% mortality; LC₅₀= Concentration causing 50% mortality; M= Mortality; LT₅₀= Time needed to kill 50% of insect population.

Table 1 continued...

Continued of Table 1. Contact toxicity of monoterpenes against field crop insects.

Insect species	Monoterpene	Toxicity (LD ₅₀ , LC ₅₀ , M) ^a	Reference
<i>Drosophila suzukii</i>	δ-Carene	LC ₅₀ = 2.38%	Erland <i>et al.</i> , 2015
	Carvacrol	LD ₅₀ = 1.30 µg male ⁻¹ fly	Park <i>et al.</i> , 2016
		LD ₅₀ = 2.60 µg female ⁻¹ fly	Park <i>et al.</i> , 2016
	1,8-Cineole	LC ₅₀ = 0.67%	Erland <i>et al.</i> , 2015
	Limonene	LT ₅₀ = 11.78h (80 mg L ⁻¹)	De Souza <i>et al.</i> , 2021
	Linalool	LC ₅₀ = 9.85%	Erland <i>et al.</i> , 2015
	Thymol	LD ₅₀ = 1.63 µg male fly ⁻¹	Park <i>et al.</i> , 2016
		LD ₅₀ = 2.68 µg female fly ⁻¹	Park <i>et al.</i> , 2016
<i>Ceratitis capitata</i>	Limonene	LD ₅₀ = 8.34 nL male fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
		LD ₅₀ = 31.72 nL female fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
	Linalool	LD ₅₀ = 10.37 nL male fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
		LD ₅₀ = 49.39 nL female fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
	α-Pinene	LD ₅₀ = 7.71 nL male fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
		LD ₅₀ = 17.20 nL female fly ⁻¹	Papanastasiou <i>et al.</i> , 2017
<i>Bactrocera zonata</i>	(R)-Camphor	LC ₅₀ = 23.68 mg kg ⁻¹	El-Minshawy <i>et al.</i> , 2018
	(R)-Carvone	LC ₅₀ < 20 mg kg ⁻¹	El-Minshawy <i>et al.</i> , 2018
	Menthol	LC ₅₀ < 20 mg kg ⁻¹	El-Minshawy <i>et al.</i> , 2018
<i>Aphis fabae</i>	γ-Terpinene	LC ₅₀ = 12.24 g L ⁻¹	Abdelgaleil <i>et al.</i> , 2010
	Terpinen-4-ol	LC ₅₀ = 14.86 g L ⁻¹	Abdelgaleil <i>et al.</i> , 2010
<i>Bemisia tabaci</i>	1,8-Cineole	M= 91.2% (1000 mg/L)	Araújo <i>et al.</i> , 2003
	Citronellol	M= 100% (0.5 µL L ⁻¹)	Baldin <i>et al.</i> , 2015
	Geraniol	M= 100% (0.5 µL L ⁻¹)	Baldin <i>et al.</i> , 2015
	Linalool	M= 100% (0.5 µL L ⁻¹)	Baldin <i>et al.</i> , 2015

^a LD₅₀= Dose causing 50% mortality; LC₅₀= Concentration causing 50% mortality; M= Mortality; LT₅₀= Time needed to kill 50% of insect population.

penetration rate inside insect body and reaching to target sites, such as adenosine triphosphates and acetyl cholinesterase (Monteiro *et al.*, 2021). While thymol induced strong mortality against tobacco cutworms, *S. litura* (LD₅₀= 1.01 µg larva⁻¹) (Tharamak *et al.*, 2020). Piperitone showed pronounced insecticidal activity against the third instar larvae of *S. littoralis* (LD₅₀= 0.68 µg larva⁻¹) (Abdelgaleil *et al.*, 2008). Thymol, carvacrol and *trans*-anethole were the most effective against *S. littoralis* with LD₅₀ values of 9, 15 and 18 µg larva⁻¹, respectively (Pavela, 2014). (-)-Carvone displayed potent contact toxicity (LD₅₀= 0.15 mg larva⁻¹) against the 4th larval instars of *S. littoralis* (Al-Nagar *et al.*, 2020). Furthermore, 1,8-cineole and (-)-carvone showed moderate toxicity against 2nd larval instar of *S. littoralis* with 97.0% and 100.0% mortality, respectively, at 2,000 mg kg⁻¹ after 9 days of exposure (Abdelgaleil *et al.*, 2020). γ-Terpinene (LC₅₀= 23.94 g L⁻¹) and terpinen-4-ol (LC₅₀= 32.94 g L⁻¹) exhibited a significant insecticidal activity against *S.*

littoralis (Abbassy *et al.*, 2009). Phellandrene showed remarkable effect on eggs (LC₅₀= 20 mg L⁻¹) and pupal stage (LC₅₀= 2,600 mg L⁻¹) of *Agrotis ipsilon*, while nerol (LC₅₀= 250 mg L⁻¹) was very effective on the larval stage (Sharaby and El-Nujiban, 2015). Linalool induced full mortality to third instar larvae of *Anticarsia gemmatalis* at a concentration of 10 µL mL⁻¹ (Vicenco *et al.*, 2021). Carvacrol was the most effective against *Helicoverpa armigera* with LC₅₀ value of 51.5 µg mL⁻¹, and it was little toxic against *Chilo partellus* (Gong and Ren, 2020; Singh *et al.*, 2009). On the other hand, thymol was more effective on the late instars of *Agriotes obscurus* (LD₅₀= 196.0 µg larva⁻¹) (Hummelbrunner and Isman, 2001), than the citronellal (LD₅₀= 404.9 µg larva⁻¹) (Waliwitiya *et al.*, 2005). Fenchone, linalool, citronellal and menthone showed a strong toxicity against Colorado potato beetle, *Leptinotarsa decemlineata* Say, while camphor, carvone and linalyl acetate showed moderate toxicity (Mahdi *et al.*, 2011). Similarly, β-pinene, γ-terpinene, 3-



carene, myrcene, 1,8-cineole, fenchone, linalool and terpinen-4-ol showed potent toxicity against *L. decemlineata* (Kordali *et al.*, 2007). Araújo *et al.* (2003) found that 1,8-cineole had a pronounced insecticidal effect against *Bemisia tabaci*. 1,8-Cineole exhibited strong insecticidal activity against *Drosophila suzukii* (EC_{50} = 0.67%) followed by δ -carene (EC_{50} = 2.38%) and linalool (EC_{50} = 9.85%) (Erland *et al.*, 2015). Limonene, linalool and α -pinene revealed high toxicity to adult of medflies of Mediterranean fruit flies *Ceratitis capitata*. Males were more sensitive than females to all the three compounds. These different responses to monoterpenes in the toxicity between male and female are attributed to variability in adult size. Hence, female medflies are larger than males. Other factors that may account for this difference in mortality between the two sexes are metabolism and behavior (Papanastasiou *et al.*, 2017). (R)-Camphor, (R)-carvone and (1R,2S,5R)-menthol revealed high efficiency against the second-instar larvae of *Bactrocera zonata* (El-Minshawy *et al.*, 2018) and the adults (Abdelgaleil *et al.*, 2019).

Fumigant Toxicity of Monoterpenes against Field Crop Insects

The fumigant toxicity of many monoterpenes has been evaluated and they showed pronounced activity against wide ranges of insects (Table 2). 1,8-Cineole revealed high fumigant toxicity against the 2nd and 4th larval instars of *S. littoralis* with LC_{50} values of 2.32 and 3.13 mg L⁻¹ air, respectively. Moreover, the LC_{50} of *p*-cymene, α -terpinene, (-) α -pinene and (-)-carvone ranged between 7.35 and 13.79 mg L⁻¹ air against 2nd larval instar and between 14.66 and 32.02 mg L⁻¹ air against 4th larval instar (Al-Nagar *et al.*, 2020). Carvacrol caused 100% mortality against the adult stage of potato tuber moth *P. operculella* at 0.125 μ L L⁻¹ air after 6 hours, and 0.025 μ L L⁻¹ air after 48 hours exposure, while nerol

and citronellol caused 100 and 98% mortality, respectively, at 0.025 μ L L⁻¹ air after 6 hours (Tayoub *et al.*, 2019). Baldin *et al.* (2015) reported that geraniol, linalool, and citronellol killed 100% of *B. tabaci* at 0.5 μ L L⁻¹. Linalool was highly toxic against *D. suzukii* (EC_{50} = 1.85 μ L L⁻¹ air) followed by δ -carene (EC_{50} = 9.47 μ L L⁻¹) and 1,8-cineole (EC_{50} = 10.71 μ L L⁻¹) (Erland *et al.*, 2015). Terpinolene, 3-carene, eugenol, thymol, carvacrol, isoeugenol, citral, (\pm)-citronellal, cuminaldehyde, (-)-verbenone, and (+)-pulegone exhibited strong fumigant activity against *Drosophila melanogaster*, with (\pm)-citronellal and (+)-pulegone being the most toxic monoterpenes with LC_{50} values of 0.015 and 0.02 μ L L⁻¹, respectively (Zhang *et al.*, 2016).

Deterrent and Antifeedant Effects of Monoterpenes against Field Crop Insects

Several studies reported the deterrent and antifeedant activities of monoterpenes against the field crop insects (Table 3). Hummelbrunner and Isman (2001) reported that thymol had a deterrent effect on tobacco cutworms, *S. litura* (DC_{50} = 85.6 μ g cm⁻²). α -Phellandrene and β -ionone completely inhibited the feeding of *Pieris brassicae* caterpillars with feeding Deterrence Index (DI) values of 59.0 and 52.0, respectively. Moreover, α -terpinene, α -ionone, citronellol, (-)-linalool and *p*-cymene were strong deterrents with DI values of 36.0, 34.0, 27.0, 24.0 and 21.0, respectively, while, γ -terpinene, and (S)-(+)-carvone were moderate deterrents (DI= 17) (Kordan and Gabryś, 2013). Piperitone completely inhibited the feeding of the third instar larvae of *S. littoralis* at a concentration of 1,000 μ g mL⁻¹ (Abdelgaleil *et al.*, 2008). The antifeedant indices of α -terpinene, (-)-citronellal and 1,8-cineole on 2nd larval instar of *S. littoralis* ranged between 51.3 and 77.6% (Abdelgaleil *et al.*, 2020). Baldin *et al.* (2015) reported that citronellol and geraniol were effective as repellents against *B. tabaci* and they significantly affected the

Table 2. Fumigant toxicity of monoterpenes against field crop insects.

Insect species	Monoterpene	Toxicity (LC ₅₀) ^a	Reference
<i>Spodoptera littoralis</i>	Camphor	LC ₅₀ = 5.60 mg L ⁻¹	Abdelgaleil, 2010
	(-)-Carvone	LC ₅₀ = 32.02 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	1,8-Cineole	LC ₅₀ = 3.13 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	(-)-Citronellal	LC ₅₀ > 100 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	Cuminaldehyde	LC ₅₀ > 100 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	p-Cymene	LC ₅₀ = 21.25 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	(L)-Fenchone	LC ₅₀ = 2.27 mg L ⁻¹	Abdelgaleil, 2010
	Limonene	LC ₅₀ = 11.36 mg L ⁻¹	Abdelgaleil, 2010
	Menthol	LC ₅₀ = 9.36 mg L ⁻¹	Abdelgaleil, 2010
	(-)-α-Pinene	LC ₅₀ = 14.66 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
	α-Terpinene	LC ₅₀ = 28.21 µL L ⁻¹	Al-Nagar <i>et al.</i> , 2020
<i>Phthorimaea operculella</i>	Carvacrol	M= 100% (0.025 µL L ⁻¹)	Tayoub <i>et al.</i> , 2016
	Citronellol	M= 98% (0.025 µL L ⁻¹)	Tayoub <i>et al.</i> , 2019
	Eucalyptol	M= 17% (0.025 µL L ⁻¹)	Tayoub <i>et al.</i> , 2016
	Nerol	M= 100% (0.025 µL L ⁻¹)	Tayoub <i>et al.</i> , 2019
<i>Plutella xylostella</i>	Carvacrol	LC ₅₀ = 0.28 mg L ⁻¹ adult	Cai <i>et al.</i> , 2020
		LC ₅₀ = 9.40 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020
		LC ₅₀ = 2.05 mg L ⁻¹ egg	Cai <i>et al.</i> , 2020
	Citral	LC ₅₀ = 1.83 mg L ⁻¹ adult	Cai <i>et al.</i> , 2020
		LC ₅₀ = 15.24 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020
		LC ₅₀ = 4.28 mg L ⁻¹ egg	Cai <i>et al.</i> , 2020
	(+) -Citronellal	LC ₅₀ = 0.46 mg/L adult	Cai <i>et al.</i> , 2020
		LC ₅₀ = 7.26 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020
		LC ₅₀ = 4.50 mg L ⁻¹ egg	Cai <i>et al.</i> , 2020
	Cuminaldehyde	LC ₅₀ = 0.17 mg L ⁻¹ adult	Cai <i>et al.</i> , 2020
		LC ₅₀ = 0.55 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020
		LC ₅₀ = 1.95 mg L ⁻¹ egg	Cai <i>et al.</i> , 2020
	Dihydrolinalool	LC ₅₀ = 1.52 mg L ⁻¹ adult	Cai <i>et al.</i> , 2020
		LC ₅₀ > 100 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020
LC ₅₀ = 2.46 mg L ⁻¹ egg		Cai <i>et al.</i> , 2020	
Thymol	LC ₅₀ = 1.56 mg L ⁻¹ adult	Cai <i>et al.</i> , 2020	
	LC ₅₀ = 1.99 mg L ⁻¹ larvae	Cai <i>et al.</i> , 2020	
	LC ₅₀ = 3.67 mg L ⁻¹ egg	Cai <i>et al.</i> , 2020	
<i>Bemisia tabaci</i>	Citronellol	M=100 % at 0.5 µL L ⁻¹	Baldin <i>et al.</i> , 2015
	Geraniol	M=100 % at 0.5 µL L ⁻¹	Baldin <i>et al.</i> , 2015
	Linalool	M=100 % at 0.5 µL L ⁻¹	Baldin <i>et al.</i> , 2015
<i>Aphis gossypii</i>	Anethole	LT ₅₀ = 12.6 h (1.7 mg L ⁻¹)	Erlar and Tunc, 2005
	Carvacrol	LT ₅₀ = 25.1 h (1.7 mg L ⁻¹)	Erlar and Tunc, 2005
	1,8-Cineole	LT ₅₀ = 100.0 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	p-Cymene	LT ₅₀ = 12.6 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Menthol	LT ₅₀ = 158.5 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	γ -Terpinene	LT ₅₀ = 25.1 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Terpinen-4-ol	LT ₅₀ = 50.1 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Thymol	LT ₅₀ = 25.1 h (1.7 mg L ⁻¹)	Erlar and Tunc, 2005
<i>Frankliniella occidentalis</i>	Anethole	LT ₅₀ = 125.9 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Carvacrol	LT ₅₀ = 251.2 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	p-Cymene	LT ₅₀ = 199.5 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	γ -Terpinene	LT ₅₀ = 125.9 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Terpinen-4-ol	LT ₅₀ = 251.2 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005
	Thymol	LT ₅₀ = 100.0 h (13.6 mg L ⁻¹)	Erlar and Tunc, 2005

^a LC₅₀= Concentration causing 50% mortality; M= Mortality; LT₅₀= Time needed to kill 50% of insect population.

Continued...



Continued of Table 2. Fumigant toxicity of monoterpenes against field crop insects.

Insect species	Monoterpene	Toxicity (LC ₅₀) ^a	Reference	
<i>Myzus persicae</i>	Bornyl Acetate	LC ₅₀ = 2.64 mg L ⁻¹	Zhou et al., 2021	
	Carvacrol	LC ₅₀ = 1.56 mg L ⁻¹	Zhou et al., 2021	
	Citronellyl Acetate	LC ₅₀ = 4.03 mg L ⁻¹	Zhou et al., 2021	
	Geranyl Acetate	LC ₅₀ = 9.64 mg L ⁻¹	Zhou et al., 2021	
	Linalyl Acetate	LC ₅₀ = 9.28 mg L ⁻¹	Zhou et al., 2021	
	Neryl Acetate	LC ₅₀ = 13.17 mg L ⁻¹	Zhou et al., 2021	
	Terpinolene	LC ₅₀ = 2.75 mg L ⁻¹	Zhou et al., 2021	
	Terpinyl Acetate	LC ₅₀ = 2.83 mg L ⁻¹	Zhou et al., 2021	
<i>Drosophila melanogaster</i>	(-)-Borneol	LC ₅₀ = 0.22 μL L ⁻¹	Zhang et al., 2016	
	Bornyl acetate	LC ₅₀ = 0.27 μL L ⁻¹	Zhang et al., 2016	
	3-Carene	LC ₅₀ = 0.28 μL L ⁻¹	Zhang et al., 2016	
	Carvacrol	LC ₅₀ = 0.04 μL L ⁻¹	Zhang et al., 2016	
	(-)-Carvone	LC ₅₀ = 0.54 μL L ⁻¹	Zhang et al., 2016	
	1,8-Cineole	LC ₅₀ = 0.45 μL L ⁻¹	Zhang et al., 2016	
	Citral	LC ₅₀ = 0.06 μL L ⁻¹	Zhang et al., 2016	
	(±)-Citronellal	LC ₅₀ = 0.015 μL L ⁻¹	Zhang et al., 2016	
	β-Citronellene	LC ₅₀ = 1.96 μL L ⁻¹	Zhang et al., 2016	
	R-Citronellol	LC ₅₀ = 0.82 μL L ⁻¹	Zhang et al., 2016	
	Citronellyl acetate	LC ₅₀ = 0.16 μL L ⁻¹	Zhang et al., 2016	
	Cuminaldehyde	LC ₅₀ = 0.07 μL L ⁻¹	Zhang et al., 2016	
	p-Cymene	LC ₅₀ = 1.39 μL L ⁻¹	Zhang et al., 2016	
	Dihydrolinalool	LC ₅₀ = 0.15 μL L ⁻¹	Zhang et al., 2016	
	(-)-Fenchone	LC ₅₀ = 0.35 μL L ⁻¹	Zhang et al., 2016	
	Geraniol	LC ₅₀ = 0.31 μL L ⁻¹	Zhang et al., 2016	
	Geranyl acetate	LC ₅₀ = 0.24 μL L ⁻¹	Zhang et al., 2016	
	(±)-Limonene	LC ₅₀ = 2.18 μL L ⁻¹	Zhang et al., 2016	
	Linalool	LC ₅₀ = 0.35 μL L ⁻¹	Zhang et al., 2016	
	Linalyl acetate	LC ₅₀ = 1.09 μL L ⁻¹	Zhang et al., 2016	
	(±)-Menthol	LC ₅₀ = 0.14 μL L ⁻¹	Zhang et al., 2016	
	(-)-Menthone	LC ₅₀ = 0.19 μL L ⁻¹	Zhang et al., 2016	
	Myrcene	LC ₅₀ = 4.44 μL L ⁻¹	Zhang et al., 2016	
	Nerol	LC ₅₀ = 0.11 μL L ⁻¹	Zhang et al., 2016	
	Neryl acetate	LC ₅₀ = 0.11 μL L ⁻¹	Zhang et al., 2016	
	(-)-α-Pinene	LC ₅₀ = 4.12 μL L ⁻¹	Zhang et al., 2016	
	(-)-β-Pinene	LC ₅₀ = 1.44 μL L ⁻¹	Zhang et al., 2016	
	(+)-Pulegone	LC ₅₀ = 0.02 μL L ⁻¹	Zhang et al., 2016	
	α-Terpinene	LC ₅₀ = 1.96 μL L ⁻¹	Zhang et al., 2016	
	γ-Terpinene	LC ₅₀ = 1.68 μL L ⁻¹	Zhang et al., 2016	
	Terpinolene	LC ₅₀ = 0.09 μL L ⁻¹	Zhang et al., 2016	
α-Terpineol	LC ₅₀ = 0.31 μL L ⁻¹	Zhang et al., 2016		
(±)-Terpinen-4-ol	LC ₅₀ = 0.12 μL L ⁻¹	Zhang et al., 2016		
Terpinyl acetate	LC ₅₀ = 0.29 μL L ⁻¹	Zhang et al., 2016		
Thymol	LC ₅₀ = 0.07 μL L ⁻¹	Zhang et al., 2016		
(-)-Verbenone	LC ₅₀ = 0.03 μL L ⁻¹	Zhang et al., 2016		
<i>Drosophila suzukii</i>	Carvacrol	LC ₅₀ = 0.84 μL L ⁻¹	Finetti et al., 2021	
	δ-Carene	LC ₅₀ = 9.47 μL L ⁻¹	Erland et al., 2015	
	1,8-Cineole	LC ₅₀ = 10.71 μL L ⁻¹	Erland et al., 2015	
	Linalool	LC ₅₀ = 1.85 μL/L	Erland et al., 2015	
	Menthol	LC ₅₀ = 1.88 mg L ⁻¹	male fly	Park et al., 2016
		LC ₅₀ = 1.94 mg L ⁻¹	female fly	Park et al., 2016
	Menthone	LC ₅₀ = 5.76 mg L ⁻¹	male fly	Park et al., 2016
		LC ₅₀ = 5.13 mg L ⁻¹	female fly	Park et al., 2016
	α-Terpineol	LC ₅₀ = 0.98 μL L ⁻¹	Finetti et al., 2021	
	Thymol	LC ₅₀ = 0.60 μL L ⁻¹	Finetti et al., 2021	

^a LC₅₀= Concentration causing 50% mortality; M= Mortality; LT₅₀= Time needed to kill 50% of insect population. Continued...

Table 3. Deterrent and antifeedant activities of monoterpenes against field crop insects.

Insect species	Monoterpene	Effect (AF, DC ₅₀ , DI) ^a	Reference
<i>Spodoptera littoralis</i>	(-)-Carvone	AF= 0.0% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
	1,8-Cineole	AF= 51.3% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
	(-)-Citronellal	AF= 77.6% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
	P-Cymene	AF= 46.5% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
	(-)- α -Pinene	AF= 56.0% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
	Piperitone	AF= 100% (1000 μ g mL ⁻¹)	Abdelgaleil <i>et al.</i> , 2008
	α -Terpinene	AF= 62.8% (2000 mg kg ⁻¹)	Abdelgaleil <i>et al.</i> , 2020
<i>Spodoptera litura</i>	Carvacrol	DC ₅₀ = 115.1 μ g cm ⁻²	Hummelbrunner and Isman, 2001
	α -Terpineol	DC ₅₀ = 130.2 μ g cm ⁻²	Hummelbrunner and Isman, 2001
	Thymol	DC ₅₀ = 85.6 μ g cm ⁻²	Hummelbrunner and Isman, 2001
<i>Pieris brassicae</i>	(S)-(+)-Carvone	DI= 17	Kordan and Gabryś, 2013
	Citronellol	DI= 27	Kordan and Gabryś, 2013
	<i>p</i> -Cymene	DI= 21	Kordan and Gabryś, 2013
	β -Ionone	DI= 52	Kordan and Gabryś, 2013
	α -Ionone	DI= 34	Kordan and Gabryś, 2013
	(-)-Linalool	DI= 24	Kordan and Gabryś, 2013
	α -Phellandrene	DI= 59	Kordan and Gabryś, 2013
	α -Terpinene	DI= 36	Kordan and Gabryś, 2013
	γ -Terpinene	DI= 17	Kordan and Gabryś, 2013
<i>Agrotis ipsilon</i>	Carvone	AF= 90.67%	Sharaby and El-Nujiban, 2015
	Citronellol	AF= 14.66%	Sharaby and El-Nujiban, 2015
	Linalool	AF= 68.66%	Sharaby and El-Nujiban, 2015
	Nerol	AF= 60.00%	Sharaby and El-Nujiban, 2015
	Phellandrene	AF= 94.62%	Sharaby and El-Nujiban, 2015
	α -Terpineol	AF= 76.57%	Sharaby and El-Nujiban, 2015
	Thymol	AF= 82.67%	Sharaby and El-Nujiban, 2015
<i>Plutella xylostella</i>	Carvacrol	DC ₅₀ = 0.075 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	Caryophyllene oxide	DC ₅₀ = 23.69 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	β -Caryophyllene	DC ₅₀ = 35.85 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	Limonene	DC ₅₀ = 73.11 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	β -Pinene	DC ₅₀ = 52.19 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	α -Pinene	DC ₅₀ = 37.43 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	Terpinolene	DC ₅₀ = 35.18 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
	Thymol	DC ₅₀ = 5.38 μ L mL ⁻¹	Araújo <i>et al.</i> , 2020
<i>Chilo partellus</i>	Carvacrol	FI ₅₀ = 230.1 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
	1,8-Cineole	FI ₅₀ = 158.2 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
	Linalool	FI ₅₀ = 162.5 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
	trans-Anethole	FI ₅₀ = 207.6 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
	Terpineol	FI ₅₀ = 165.2 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
	Thymol	FI ₅₀ = 151.8 (mg cm ⁻²)	Singh <i>et al.</i> , 2009
<i>Helicoverpa armigera</i>	Limonene	DC ₅₀ = 182.3 μ g sq ⁻¹ cm ⁻¹	Kiran <i>et al.</i> , 2007

^a AF= Antifeedant; DC₅₀= Concentration causing 50% deterrent effect; DI= Deterrence Index; FI= Feeding Index.

Continued...

**Continued of Table 3.** Deterrent and antifeedant activities of monoterpenes against field crop insects.

Insect species	Monoterpene	Effect (AF, DC ₅₀ , DI) ^a	Reference
<i>Leptinotarsa decemlineata</i>	(-)-Borneol	AF = 21.15% (50 µg cm ⁻²)	Elguea-Culebras, <i>et al.</i> , 2017
	(-)-Bornyl acetate	AF = 29.00% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(+) -Camphene	AF = 37.28% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(+/-)-Camphor	AF = 63.36% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Carvacrol	AF = 90.92% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	β-caryophyllene	AF = 34.70% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	<i>p</i> -Cymene	AF = 44.6% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Eucalyptol	AF = 46.98% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(S)-(-)-Limonene	AF = 50.87% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(R)-(+)-Limonene	AF = 38.45% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Linalool	AF = 41.70% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Linalyl acetate	AF = 60.65% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Myrcene	AF = 35.57% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(+/-)-α-Pinene	AF = 51.66% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(-) -β-Pinene	AF = 33.70% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	γ- Terpinene	AF = 18.62% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(+)-Terpinen-4-ol	AF = 87.08% (50 µg cm ⁻²)	
<i>Leptinotarsa decemlineata</i>	α- Terpineol	AF= 39.97% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	Thymol	AF= 81.54% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017
	(1S)-(-)-Verbenone	AF= 72.90% (50 µg cm ⁻²)	Elguea-Culebras <i>et al.</i> , 2017

^a AF= Antifeedant; DC₅₀= Concentration causing 50% deterrent effect; DI= Deterrence Index; FI= Feeding Index.

mean number of eggs deposited on tomato leaflets. Phellandrene, carvone, thymole, α-terpeneol, linalool and nerol had variable antifeedant effects against 2nd larval instar of *A. ipsilon* with antifeedant values of 94.62, 90.67, 82.67, 76.57, 68.66, and 60%, respectively, while citronellol showed the lowest value of antifeedant (14.66%) (Sharaby and El-Nujiban, 2015). Carvacrol recorded a feeding inhibition activity of 90.9% on *L. decemlineata*, followed by (+)-terpinen-4-ol (87.1%) and thymol (81.5%), while (1S)-(-)-verbenone (72.9%), (+/-)-camphor (63.4%) and linalyl acetate (60.7%) showed moderate activity (Elguea-Culebras *et al.*, 2017). Citronellol, limonene, camphor and thymol showed repellent action against insect pests (Pavoni *et al.*, 2019). Citral, linalool, camphene, S-limonene, α-ionone, β-ionone, R-pulegone, *p*-cymene, β-pinene, R-limonene, S-pulegone and α-terpineol were found to possess repellent and feeding deterrent effects on the peach potato aphid *Myzus persicae* (Gabryś *et al.*, 2005). The monoterpenoids (thymol and carvacrol) exhibited antifeeding

and antioviposition deterrent effect to Western flower thrips, *Frankliniella occidentalis* (Peneder and Koschier, 2011; Allsopp *et al.*, 2014).

Residual Toxicity of Monoterpenes against Field Crop Insects

Few studies reported the residual toxicity of monoterpenes against field crop insects (Table 4). Only 16 monoterpenes have been tested for their residual effect against three insect species. Carvone was highly effective against *S. littoralis* larvae with mortality of 90% at 1,000 mg L⁻¹ when compared with other monoterpenes, such as 1,8-cineole, (-)-citronellal, cuminaldehyde, *P*-cymene, (-)α-pinene, α-terpinene and terpinen-4-ol (Al-Nagar *et al.*, 2020). Carvacrol and terpinolene showed higher insecticidal activity against larvae of *Plutella xylostella* than caryophyllene oxide, β-caryophyllene and thymol with LC₅₀ values of 6.03 and 9.03 µL mL⁻¹, respectively (Araújo *et al.*, 2020). Also, γ-terpinene was more effective than terpinen-4-ol against adult

Table 4. Residual activity of monoterpenes against field crop insects.

Insect species	Monoterpene	Effect (LD, LC ₅₀ , M) ^a	Reference
<i>Spodoptera littoralis</i>	(-)-Carvone	M= 90.0% (1000 mg L ⁻¹)	Al-Nagar, <i>et al.</i> , 2020
	1,8-Cineole	M= 76.7% (4000 mg L ⁻¹)	"
	(-)-Citronellal	M= 83.3% (2000 mg L ⁻¹)	"
	Cuminaldehyde	M= 86.7% (4000 mg L ⁻¹)	"
	P-Cymene	M= 50.0% (2000 mg L ⁻¹)	"
	(-) α -Pinene	M= 70.0% (4000 mg L ⁻¹)	"
	α -Terpinene	M= 93.3% (4000 mg L ⁻¹)	"
	γ -Terpinene	LD50= 23.94 g L ⁻¹	Abbassy <i>et al.</i> , 2009
	Terpinen-4-ol	LD50= 32.94 g L ⁻¹	"
<i>Plutella xylostella</i>	Carvacrol	LC ₅₀ = 6.03 μ L mL ⁻¹ larvae	Araújo <i>et al.</i> , 2020
	Caryophyllene oxide	LC ₅₀ = 60.99 μ L mL ⁻¹ larvae	"
	β -Caryophyllene	LC ₅₀ = 40.46 μ L mL ⁻¹ larvae	"
	Terpinolene	LC ₅₀ = 9.03 μ L mL ⁻¹ larvae	"
	Thymol	LC ₅₀ = 13.60 μ L mL ⁻¹ larvae	"
<i>Aphis fabae</i>	γ -Terpinene	LD50= 18.03 g L ⁻¹ adult	Abbassy <i>et al.</i> , 2009
	Terpinen-4-ol	LD50= 20.77 g L ⁻¹ adult	"

^a M= Mortality; LD₅₀= Dose causing 50% mortality; LC₅₀= Concentration causing 50% mortality.

Table 5. Growth inhibitory effects of monoterpenes against field crop insects.

Insect species	Monoterpene	Effect (GI%, EC ₅₀) ^a	Reference
<i>Spodoptera littoralis</i>	(-)-Carvone	GI= 83.3% (1000 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 87.6 % (1000 mg kg ⁻¹) 4st larva	Al-Nagar <i>et al.</i> , 2020
	1,8-Cineole	GI= 100.0% (1000 mg/kg) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 91.3 % (1000 mg kg ⁻¹) 4st larva	Al-Nagar <i>et al.</i> , 2020
	(-)-Citronellal	GI= 80.3% (1000 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 92.5 % (1000 mg kg ⁻¹) 4st larva	Al-Nagar <i>et al.</i> , 2020
	Cuminaldehyde	GI= 96.2% (500 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 86.6% (4000 mg kg ⁻¹) 4st larva	Al-Nagar <i>et al.</i> , 2020
	P-Cymene	GI= 78.8% (500 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 86.4% (1000 mg kg ⁻¹) 4st larva	Al-Nagar <i>et al.</i> , 2020
	Farnesol	GI= 58.9% (500 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
	(Z,E)-Nerolidol	GI= 71.0% (1000 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
	(-) α -Pinene	GI= 70.5% (1000 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
		GI= 93.2% (1000 mg kg ⁻¹) 4st larva	Al-Nagar, <i>et al.</i> , 2020
	α -Terpinene	GI= 79.5% (1000 mg kg ⁻¹) 2st larva	Abdelgaleil <i>et al.</i> , 2020
GI= 89.5% (1000 mg kg ⁻¹) 4st larva		Al-Nagar, <i>et al.</i> , 2020	
<i>Chilo partellus</i>	Carvacrol	EC50= 2.55 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010
	1,8-Cineole	EC50= 1.70 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010
	Linalool	EC50= 1.95 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010
	Trans-anethole	EC50= 2.38 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010
	Terpineol	EC50= 2.23 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010
	Thymol	EC50= 1.41 mg mL ⁻¹ larva	Singh <i>et al.</i> , 2010

^a GI= Growth Index; EC₅₀= Effective Concentrations of essential oil compounds that inhibited growth (% of controls).

of *Aphis fabae* with LD₅₀ value of 18030 mg L⁻¹ (Abbassy *et al.*, 2009).

Growth Inhibitory Effects of Monoterpenes against Field Crop Insects

The effect of monoterpenes on the growth inhibition of field crop insects was poorly

studied. Table 5 shows the summary of some studies on the potential effects of monoterpenes on growth inhibition of lepidopteran larvae. Abdelgaleil *et al.* (2020) and Al-Nagar *et al.* (2020) evaluated 9 monoterpenes on 2nd and 4th larval instars of *S. littoralis*, and found that cuminaldehyde and 1,8-cineole induced strong inhibition of growth of 2nd larval instar with 96.2 and



100% at 500 and 1,000 mg kg⁻¹), respectively. Furthermore, α -pinene, citronellal, 1,8-cineole and α -terpinene inhibited the growth of the 4th larval instar with inhibition of 93.2, 92.5, 91.3, and 89.5% at 1000 mg/kg, respectively. Thymol, 1,8-cineole and linalool caused remarkable growth inhibition to *Chilo partellus* larvae with EC₅₀ values of 1.41, 1.70 and 1.95 mg mL⁻¹, respectively (Singh et al., 2010).

CONCLUSIONS

Health and environmental concerns due to the adverse effects of synthetic insecticides have prompted the development of safe pest control agents. Essential oils and their major constituents, monoterpenes, could be used as one of the most promising tools in IPM. They are environmentally friendly products with remarkable insecticidal activity. Meanwhile, they have diverse targets within insects and modes of action that may delay the development of insect resistance. Therefore, this review highlights the importance of monoterpenes as biocontrol agents for field crops insects. However, further efforts must be made on environmental fate, field application, and registration of monoterpenes.

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مونوترپن ها برای مدیریت آفات حشره ای محصولات زراعی

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چکیده

امروزه مهار آفات حشره ای مختلف در کشاورزی غالباً متکی بر استفاده از حشره کش های مصنوعی است. با اینهمه ، استفاده بیش از حد از این مواد شیمیایی باعث مشکلات بسیاری از جمله مقادیر بالای مواد باقی مانده، اثرات زیانبار بر محیط زیست و سلامت انسان و ایجاد مقاومت در حشرات می شود. بنابراین، راهبرد های نوین برای مدیریت حشرات کشاورزی به فوریت مورد نیاز است. محصولات طبیعی مبتنی بر گیاه جایگزین های امیدوارکننده ای برای مهار آفات است که دارای فعالیت های بیولوژیک قابل توجه و وسیع هستند. در میان متابولیت های ثانویه گیاهی، اسانس ها و ترکیبات اصلی آنها، یعنی مونوترپن ها، برای کاربرد در کنترل حشرات، افزودنی های غذایی، عطر و لوازم آرایشی مورد مطالعه قرار گرفته اند. در این پژوهش، تاکید ما روی مطالعاتی است مربوط به اثرات سمی مونوترپن ها، از جمله سمیت های بخور (fumigant) و سمیت های تماسی مواد باقیمانده که علیه آفات حشره ای گیاهان و محصولات اقتصادی در مزارع به کار میروند. افزون بر این، اثرات مونوترپن ها بر رفتار حشرات (فعالیت های ضد تغذیه (antifeedant) و دفع کننده (repellent) و تنظیم رشد حشرات نیز مورد بحث قرار می گیرد.