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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*, *Beauvera 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 C_{10} 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* (LD_{50}= 0.28 μL $larva^{-1}$). 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
Spodoptera frugiperda	Limonene	LD_{50}= 31.5 mg g^{-1}	Cruz *et al.*, 2017
	α-Pinene	LD_{50}= 0.28 µL $larva^{-1}$	Monteiro *et al.*, 2021
	Trans-anethole	LD_{50}= 0.027 mg g^{-1}	Cruz *et al.*, 2017
Spodoptera litura	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 *et al.*, 2019
Spodoptera littoralis	(−)-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 *et al.*, 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 *et al.*, 2020
	(−)-Citronellal	LD_{50}= 0.73 mg $larva^{-1}$	Al-Nagar *et al.,* 2020
	β-Citronellol	LD_{50}= 31 µg $larva^{-1}$	Pavela, 2014
	Cuminaldehyde	LD_{50}= 0.27 mg $larva^{-1}$	Al-Nagar *et al.*, 2020
	p-Cymene	LD_{50}= 0.36 mg $larva^{-1}$	Al-Nagar *et al.,* 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 *et al.*, 2020
	Piperitone	LD_{50}= 0.68 µg $larva^{-1}$	Abdelgaleil, *et al.*, 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 *et al.*, 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
Agrotis ipsilon	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} LD_{50}= Dose causing 50% mortality; LC_{50}= Concentration causing 50% mortality; M= Mortality; LT_{50}= 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
Anticarsia gemmatalis	Linalool	M= 100% (10 µL mL^{-1}	Vicenço *et al*., 2021
Chilo partellus	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
Helicoverpa armigera	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
	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
Plutella xylostella	Linalool	LC50= 3.37 ppm	Webster *et al*., 2017
	Thymol	LC50= 1.80 ppm	Webster *et al*., 2017
Agriotes obscurus	Citronellal	LD_{50}= 404.9 µg $larva^{-1}$	Waliwitiya *et al*., 2005
	Thymol	LD_{50}= 195.5 µg $larva^{-1}$	Waliwitiya *et al*., 2005
Leptinotarsa decemlineata	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
Agriotes obscurus	Citronellal	LD_{50}= 404.9 µg $larva^{-1}$	Waliwitiya *et al*., 2005
	Thymol	LD_{50}= 195.5 µg $larva^{-1}$	Waliwitiya *et al*., 2005
Leptinotarsa decemlineata	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] LD_{50}= Dose causing 50% mortality; LC_{50}= Concentration causing 50% mortality; M= Mortality; LT_{50}= Time needed to kill 50% of insect population.

Table 1 continued…

Continued of Table1. Contact toxicity of monoterpenes against field crop insects.

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

[a] LD_{50}= Dose causing 50% mortality; LC_{50}= Concentration causing 50% mortality; M= Mortality; LT_{50}= 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* (LD_{50}= 1.01 μg larva^{-1}) (Tharamak *et al.,* 2020). Piperitone showed pronounced insecticidal activity against the third instar larvae of *S. littoralis* (LD_{50}= 0.68 μg larva^{-1}) (Abdelgaleil *et al.,* 2008). Thymol, carvacrol and *trans*-anethole were the most effective against *S. littoralis* with LD_{50} values of 9, 15 and 18 μg larva^{-1}, respectively (Pavela, 2014). (−)-Carvone displayed potent contact toxicity (LD_{50}= 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 (LC_{50}= 23.94 g L^{-1}) and terpinen-4-ol (LC_{50}= 32.94 g L^{-1} exhibited a significant insecticidal activity against *S. littoralis* (Abbassy *et al.,* 2009). Phellandrene showed remarkable effect on eggs (LC_{50}= 20 mg L^{-1}) and pupal stage (LC_{50}= 2,600 mg L^{-1}) of *Agrotis ipsilon,* while nerol (LC_{50}= 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} (Vicenço *et al.,* 2021). Carvacrol was the most effective against *Helicoverpa armigera* with LC_{50} 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* (LD_{50}= 196.0 μg larva^{-1}) (Hummelbrunner and Isman, 2001), than the citronellal (LD_{50}= 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 capitate.* 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 2^{nd} and 4^{th} 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 2^{nd} larval instar and between 14.66 and 32.02 mg L^{-1} air against 4^{th} larval instar (Al-Nagar *et al.,* 2020). Carvacrol caused 100% mortality against the adult stage of potato tuber moth *P. operculella* at 0.125 μL L^{-1} air after 6 hours, and 0.025 μL L^{-1} air after 48 hours exposure, while nerol and citronellol caused 100 and 98% mortality, respectively, at 0.025 μL 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 μL L^{-1}. Linalool was highly toxic against *D. suzukii* (EC_{50}= 1.85 μL L^{-1} air) followed by δ-carene (EC_{50}= 9.47 μL L^{-1}) and 1,8-cineole (EC_{50}= 10.71 μL L^{-1}) (Erland *et al.,* 2015). Terpinolene, 3-carene, eugenol, thymol, carvacrol, isoeugenol, citral, (±)-citronellal, cuminaldehyde, (−)-verbenone, and (+)-pulegone exhibited strong fumigant activity against *Drosophila melanogaster*, with (±)-citronellal and (+)-pulegone being the most toxic monoterpenes with LC_{50} values of 0.015 and 0.02 μL 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 μg 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 μg mL^{-1} (Abdelgaleil *et al.,* 2008). The antifeedant indices of α-terpinene, (−)-citronellal and 1,8-cineole on 2^{nd} 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
Spodoptera littoralis	Camphor	LC_{50}= 5.60 mg L^{-1}	Abdelgaleil, 2010
	(−)-Carvone	LC_{50}= 32.02 µL L^{-1}	Al-Nagar *et al.*, 2020
	1,8-Cineole	LC_{50}= 3.13 µL L^{-1}	Al-Nagar *et al.*, 2020
	(−)-Citronellal	LC_{50}> 100 µL L^{-1}	Al-Nagar *et al.*, 2020
	Cuminaldehyde	LC_{50}> 100 µL L^{-1}	Al-Nagar *et al.*, 2020
	p-Cymene	LC_{50}= 21.25 µL L^{-1}	Al-Nagar *et al.*, 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 *et al.*, 2020
	α-Terpinene	LC_{50}= 28.21 µL L^{-1}	Al-Nagar *et al.*, 2020
Phthorimaea operculella	Carvacrol	M= 100% (0.025 µL L^{-1})	Tayoub *et al.*, 2016
	Citronellol	M= 98% (0.025 µL L^{-1})	Tayoub *et al.*, 2019
	Eucalyptol	M= 17% (0.025 µL L^{-1})	Tayoub *et al.*, 2016
	Nerol	M= 1 00% (0.025 µL L^{-1})	Tayoub *et al.*, 2019
Plutella xylostella	Carvacrol	LC_{50}= 0.28 mg L^{-1} adult	Cai *et al.*, 2020
		LC_{50}= 9.40 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 2.05 mg L^{-1} egg	Cai *et al.*, 2020
	Citral	LC_{50}= 1.83 mg L^{-1} adult	Cai *et al.*, 2020
		LC_{50}= 15.24 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 4.28 mg L^{-1}egg	Cai *et al.*, 2020
	(+)-Citronellal	LC_{50}= 0.46 mg/L adult	Cai *et al.*, 2020
		LC_{50}= 7.26 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 4.50 mg L^{-1} egg	Cai *et al.*, 2020
	Cuminaldehyde	LC_{50}= 0.17 mg L^{-1} adult	Cai *et al.*, 2020
		LC_{50}= 0.55 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 1.95 mg L^{-1} egg	Cai *et al.*, 2020
	Dihydrolinalool	LC_{50}= 1.52 mg L^{-1} adult	Cai *et al.*, 2020
		LC_{50}> 100 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 2.46 mg L^{-1} egg	Cai *et al.*, 2020
	Thymol	LC_{50}= 1.56 mg L^{-1} adult	Cai *et al.*, 2020
		LC_{50}= 1.99 mg L^{-1} larvae	Cai *et al.*, 2020
		LC_{50}= 3.67 mg L^{-1} egg	Cai *et al.*, 2020
Bemisia tabaci	Citronellol	M=100 % at 0.5 µL L^{-1}	Baldin *et al.*, 2015
	Geraniol	M=100 % at 0.5 µL L^{-1}	Baldin *et al.*, 2015
	Linalool	M=100 % at 0.5 µL L^{-1}	Baldin *et al.*, 2015
Aphis gossypii	Anethole	LT_{50}= 12.6 h (1.7 mg L^{-1})	Erler and Tunc, 2005
	Carvacrol	LT_{50}= 25.1 h (1.7 mg L^{-1})	Erler and Tunc, 2005
	1,8-Cineole	LT_{50}= 100.0 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	ρ-Cymene	LT_{50}= 12.6 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Menthol	LT_{50} = 158.5 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	γ -Terpinene	LT_{50}= 25.1 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Terpinen-4-ol	LT_{50}= 50.1 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Thymol	LT_{50}= 25.1 h (1.7 mg L^{-1})	Erler and Tunc, 2005
Frankliniella occidentalis	Anethole	LT_{50}= 125.9 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Carvacrol	LT_{50}= 251.2 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	ρ-Cymene	LT_{50}= 199.5 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	γ -Terpinene	LT_{50}= 125.9 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Terpinen-4-ol	LT_{50}= 251.2 h (13.6 mg L^{-1})	Erler and Tunc, 2005
	Thymol	LT_{50}= 100.0 h (13.6 mg L^{-1})	Erler and Tunc, 2005

[a] LC_{50}= Concentration causing 50% mortality; M= Mortality; LT_{50}= 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
Myzus persicae	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
	Geramyl 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
Drosophila melanogaster	(−)-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
	ρ-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
	a-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
Drosophila suzukii	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
	a-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] LC_{50}= Concentration causing 50% mortality; M= Mortality; LT_{50}= Time needed to kill 50% of insect population.

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

Insect species	Monoterpene	Effect (AF, DC_{50}, DI)[a]	Reference
Spodoptera littoralis	(−)-Carvone	AF= 0.0% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
	1,8-Cineole	AF= 51.3% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
	(−)-Citronellal	AF= 77.6% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
	P-Cymene	AF= 46.5% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
	(−)α-Pinene	AF= 56.0% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
	Piperitone	AF= 100% (1000 µg mL^{-1})	Abdelgaleil *et al.*, 2008
	α-Terpinene	AF= 62.8% (2000 mg kg^{-1})	Abdelgaleil *et al.*, 2020
Spodoptera litura	Carvacrol	DC_{50}= 115.1 µg cm^{-2}	Hummelbrunner and Isman, 2001
	α-Terpineol	DC_{50}= 130.2 µg cm^{-2}	Hummelbrunner and Isman, 2001
	Thymol	DC_{50}= 85.6 µg cm^{-2}	Hummelbrunner and Isman, 2001
Pieris brassicae	(S)-(+)-Carvone	DI= 17	Kordan and Gabryś, 2013
	Citronellol	DI= 27	Kordan and Gabryś, 2013
	p-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
Agrotis ipsilon	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
Plutella xylostella	Carvacrol	DC_{50}= 0.075 µL mL^{-1}	Araújo *et al.*, 2020
	Caryophyllene oxide	DC_{50}= 23.69 µL mL^{-1}	Araújo *et al.*, 2020
	β-Caryophyllene	DC_{50}= 35.85 µL mL^{-1}	Araújo *et al.*, 2020
	Limonene	DC_{50}= 73.11 µL mL^{-1}	Araújo *et al.*, 2020
	β-Pinene	DC_{50}= 52.19 µL mL^{-1}	Araújo *et al.*, 2020
	α-Pinene	DC_{50}= 37.43 µL mL^{-1}	Araújo *et al.*, 2020
	Terpinolene	DC_{50}= 35.18 µL mL^{-1}	Araújo *et al.*, 2020
	Thymol	DC_{50}= 5.38 µL mL^{-1}	Araújo *et al.*, 2020
Chilo partellus	Carvacrol	FI_{50}= 230.1 (mg cm^{-2})	Singh *et al.*, 2009
	1,8-Cineole	FI_{50}= 158.2 (mg cm^{-2})	Singh *et al.*, 2009
	Linalool	FI_{50}= 162.5 (mg cm^{-2})	Singh *et al.*, 2009
	trans-Anethole	FI_{50}= 207.6 (mg cm^{-2})	Singh *et al.*, 2009
	Terpineol	FI_{50}= 165.2 (mg cm^{-2})	Singh *et al.*, 2009
	Thymol	FI_{50}= 151.8 (mg cm^{-2})	Singh *et al.*, 2009
Helicoverpa armigera	Limonene	DC_{50} = 182.3 µg sq^{-1} cm^{-1}	Kiran *et al.*, 2007

[a] AF= Antifeedant; DC_{50}= 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
Leptinotarsa decemlineata	(-)-Borneol	AF = 21.15% (50 µg cm^{-2})	Elguea-Culebras, *et al.*, 2017
	(-)-Bornyl acetate	AF = 29.00% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(+) -Camphene	AF = 37.28% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(+/-)-Camphor	AF = 63.36% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Carvacrol	AF = 90.92% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	β-caryophyllene	AF = 34.70% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	p-Cymene	AF = 44.6% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Eucalyptol	AF = 46.98% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(S)-(-)-Limonene	AF = 50.87% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(R)-(+) -Limonene	AF = 38.45% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Linalool	AF = 41.70% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Linalyl acetate	AF = 60.65% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Myrcene	AF = 35.57% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(+/-)-α-Pinene	AF = 51.66% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(-) -β-Pinene	AF = 33.70% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	γ- Terpinene	AF = 18.62% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(+)-Terpinen-4-ol	AF = 87.08% (50 µg cm^{-2})	
Leptinotarsa decemlineata	α- Terpineol	AF= 39.97% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	Thymol	AF= 81.54% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017
	(1S)-(-)-Verbenone	AF= 72.90% (50 µg cm^{-2})	Elguea-Culebras *et al.*, 2017

[a] AF= Antifeedant; DC_{50}= 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 2^{nd} 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 (1*S*)-(-)-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 LC_{50} 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
Spodoptera littoralis	(−)-Carvone	M= 90.0% (1000 mg L^{-1})	Al-Nagar, *et al.*, 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 *et al.*, 2009
	Terpinen-4-ol	LD50= 32.94 g L^{-1}	〃
Plutella xylostella	Carvacrol	LC_{50}= 6.03 µL mL^{-1} larvae	Araújo *et al.*, 2020
	Caryophyllene oxide	LC_{50}= 60.99 µL mL^{-1} larvae	〃
	β-Caryophyllene	LC_{50}= 40.46 µL mL^{-1} larvae	〃
	Terpinolene	LC_{50}= 9.03 µL mL^{-1} larvae	〃
	Thymol	LC_{50}= 13.60 µL mL^{-1} larvae	〃
Aphis fabae	γ –Terpinene	LD50= 18.03 g L^{-1} adult	Abbassy *et al.*, 2009
	Terpinen-4-ol	LD50= 20.77 g L^{-1} adult	〃

[a] M= Mortialty; LD_{50}= Dose causing 50% mortality; LC_{50}= Concentration causing 50% mortality.

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

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

[a] GI= Growth Index; EC_{50}= Effective Concentrations of essential oil compounds that inhibited growth (% of controls).

of *Aphis fabae* with LD_{50} 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 2^{nd} and 4^{th} larval instars of *S. littoralis*, and found that cuminaldehyde and 1,8-cineole induced strong inhibition of growth of 2^{nd} 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 4^{th} 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 EC_{50} 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, filed application, and registration of monoterpenes.

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مونوترپن ها برای مدیریت آفات حشره‌ای محصولات زراعی

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چکیده

امروزه مهار آفات حشره‌ای مختلف در کشاورزی غالبا متکی بر استفاده از حشره‌کش‌های 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 جایگزین‌های امیدوارکننده‌ای برای مهار آفات است که دارای فعالیت‌های بیولوژیک قابل توجه و وسیع هستند. در میان متابولیت‌های ثانویه گیاهی، اسانس‌ها و ترکیبات اصلی آن‌ها، یعنی مونوترپن‌ها، برای کاربرد در کنترل حشرات، افزودنی‌های غذایی، عطر و لوازم آرایشی مورد مطالعه قرار گرفته‌اند. در این پژوهش، تاکید ما روی مطالعاتی است مربوط به اثرات سمی مونوترپن‌ها، از جمله سمیت‌های بخور (fumigant) و سمیت‌های تماسی مواد باقیمانده که علیه آفات حشره‌ای گیاهان ومحصولات 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.