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ORIGINAL RESEARCH ARTICLE

Insecticidal efficacy of some essential oils against adults of *Musca domestica* L. (*Diptera*: Muscidae)

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Abstract

Nowadays, the insecticidal and acaricidal properties of plant extracts and essential oils (EOs) have been evaluated as an alternative to chemical means. This study aims to assess the insecticidal efficacy of 20 commercial EOs against the adults of *Musca domestica* Linnaeus (*Diptera*: Muscidae) by the contact of insects with the residues of EOs at the bottom of glass cups. The dose effects of seven EOs (i.e. *Acorus calamus*, *Allium sativum*, *Syzygium aromaticum*, *Cymbopogon citratus*, *Juniperus communis*, *Cedrus atlantica*, and *Foeniculum vulgare*) as well as the time effects of exposure to these EOs on the mortality of flies were analyzed by probit analysis. Permethrin (technical substance) was used as a reference insecticide in the positive control and pure acetone served as the negative control. The insecticidal efficacy of the tested EOs decreased in order (based on their lethal dose $(LD)_{50}$ values): *A. calamus* > *A. sativum* > *S. aromaticum* ≥ *C. citratus* > *J. communis* > *C. atlantica* > *F. vulgare*. *A. calamus* EO was the most effective against flies and very fast acting with negligible reversibility of effect. The EOs of *A. sativum* and *S. aromaticum* had a significant time-dependent insecticidal effect. The time for 50% insecticidal effect (knockdown and mortality in total) of the *A. sativum* EO was the greatest among the seven EOs and seven times more in comparison with the positive control. Present results and literature data suggest that the aforesaid plant products could be promising as contact insecticides against adults *M. domestica*. The difference in the insecticidal properties of *A. calamus* and *A. sativum* EOs observed in the current study display the need for various approaches for their future application as insecticides.

Keywords Natural insecticides · Insecticidal properties · Contact activity · House fly

Introduction

The housefly *Musca domestica* Linnaeus is a numerous group of family Muscidae (Chavasse and Yap 1997). This species is an obligate synanthropic insect and highly deleterious owing to its ability to transmit mechanically different pathogens such as bacteria, viruses, fungi, and parasites (Khamesipour et al. 2018). Treatment with insecticides by sprays and toxic baits are still commonly used and can be effective for housefly control (Chavasse and Yap 1997; Levchenko et al. 2018; Zhu et al. 2016). Intensive use of chemical insecticides contributes to the emergence of insecticide resistance problems and has negative impacts on the environment and humans (Akiner and Cağlar 2012; Bonmatin et al. 2015; Kamdar et al. 2019). Thus, improvement of insecticides is of great importance to minimize the possible risk to the environment and humans and to expand an assortment of relatively safe means for housefly control. In the context of the development of eco-friendly products and technologies, plant extracts and their derivates as biopesticides are recognized to be a proper alternative to chemical pesticides because of their biodegradability, relatively low hazard to the environment, and attractiveness to the public (Ebadollahi 2013; Khater and Geden 2019; Singh and Singh 1991).

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As sources of a large number of biologically active compounds, plants have attracted the attention of researchers. Among various industries, medicine and agriculture are spheres for the application of products of plant origins (Ebadollahi 2013; Khater and Geden 2019). Numerous studies have attempted to evaluate insecticidal and acaricidal properties of plant extracts as an alternative to chemical means (Isman and Tak 2017; Spochacz et al. 2018; Chowański et al. 2018; Zahran et al. 2017; Cossetin et al. 2018; Chauhan et al. 2016; Klauck et al. 2018). In this regard, essential oils (EOs) have been examined as insecticidal agents (Singh and Singh 1991; Cossetin et al. 2018; Pavela 2008; Palacios et al. 2009a, b; Soonwera 2015). Pavela (2015) reviewed the available literature on EOs as potential larvicides against mosquitoes. He selected 122 plant species from 26 families and found that 68.8% of the plants were from only five families, inclusing Apiaceae, Cupressaceae, Myrtaceae, Lamiaceae, and Rutaceae. Pavela (2015) also analyzed LC_{50} values and major constituents of EOs from these plants. The insecticidal activities of 16 EOs of Egyptian plants against *Culex pipiens* L. were determined in Zahran et al. (2017) study. In another investigation the larvicidal and adulticidal efficacy of EO of *Citrus hystrix* (Rutaceae) were evaluated against three species of blowflies (*Chrysomya megacephala*, *Chrysomya rufifacies*, and *Lucilia cuprina*) and the housefly (*M. domestica*). EOs from medical plants *Artemisia campestris*, *Pulicaria arabica*, and *Saccocalyx satureioides* were tested against a mosquito (*Culex quinquefasciatus*), a fly pest (*M. domestica*), and an agricultural moth pest (*Spodoptera littoralis*), and *A. campestris* EO has been introduced as a candidate ingredient for developing botanical mosquito larvicides (Ammar et al. 2020).

Many plants are used by people in traditional practices for repelling housefly (Baana et al. 2018). *Cupressus sempervirens* L., *Lantana camara* L., and *Eucalyptus globulus* Labill have been noted as the main repellents against flies (Baana et al. 2018). Extracts and EOs of aromatic, medicinal, and edible plants from different families (Acoracea, Asteraceae, Myrtaceae, Lamiaceae, Pinaceae, Poaceae, Rutaceae, Verbenaceae, and other) have been examined against adult houseflies (Khater and Geden 2019; Cossetin et al. 2018; Pavela 2008; Palacios et al. 2009a, b). EOs from vetiver (*Chrysopogon zizanioides*, Family: Poaceae), cinnamon (*Cinnamomum zeylanicum*, Family: Lauraceae), lavender (*Lavandula angustifolia*, Family: Lamiaceae), and sunflower (*Helianthus annuus*, Family: Asteraceae) and their blends have been demonstrated to be toxic to houseflies through contact, fumigant, and ingestion routes (Khater and Geden, 2019). Very recently, Pavela et al. (2020) investigated the acute toxicity and sublethal effects of the root EO of *Carlina acaulis* (Compositae) on *M. domestica.* Evaluation of the insecticidal activity of the *Lavandula dentata* L. (Lamiales Lamiaceae) EO against *M. domestica* L. has shown that this compound can serve as an alternative to conventional insecticides (Cossetin et al. 2018). Chantawee and Soonwera (2018) studied the toxicity of EOs of five plants and indicated that the EOs of the *Anethum graveolens* L., *F. vulgare* Mill., and *Trachyspermum ammi* L., but not *Centratherum anthelminticum* L. and *Pimpinella anisum* L., are effective larvicidal, pupicidal and oviposition, deterrent agents. Klauck et al. (2018) deduced that the EOs of red cedar (*J. communis*), palmarosa grass (*Cymbopogon martinii*), vetiver grass (*Vetiveria zizanioides*), and bergamot (*Citrus aurantium var. bergamia*) can be applied as an alternative to traditional insecticides for the control of flies. Benelli et al. (2019) reported high acute toxicity of the jambú (*Acmella oleracea* L.) EO against the adult females of *M. domestica.*

The current study was designed to assess the contact insecticidal activities of EOs of plants, known as medicinal or culinary herbs, against the adults of *M. domestica*. The dose effects of seven EOs as well as the time effects of exposure to these compounds on the mortality of flies were analyzed.

Materials and methods

EOs samples

In this study, 20 samples of different plant extracts, which were 100% EO concentrate, were tested. The samples of plant essential oils were obtained from the Center of Aromatherapy IRIS Ltd. Company (*Abies alba* Mill, *Acorus calamus* L., *Allium sativum* L., *Cedrus atlantica* Endl., *Coriandrum sativum* L. (seeds), *Cymbopogon citratus* Stapf, *Eucalyptus globulus* L., *Foeniculum vulgare* Mill., *Juniperus communis* L. (berries), *Melaleuca alternifolia* L., *Ocimum basilicum* L., *Picea abies* L. (needles), *Pinus sylvestris* L., *Piper nigrum* L., *Syzygium aromaticum* L. (clove), *Tagetes glandulifera* Schrank), Aroma-Rus Association Ltd. Company (*Artemisia taurica* Willd), VitaInform Ltd. Company (*Juniperus communis* L. (bark), *Nicotiana tabacum* L.), and Abiceia Ltd. Company (*Citrus sinensis* L. (lemon)) (all in Russian Federation). Permethrin (technical substance) was used as a reference insecticide in the positive control.

Selection and reraring of insects

Adults of the *M. domestica* laboratory strain were selected to test the insecticidal activity of EOs. They were maintained in an insectarium without contact with insecticides for more than 50 generations. Flies were then kept in metal cages (25 × 25 × 25 cm), covered with a fine mesh, in climate chambers at 26 ± 2 °C, 70 ± 5% relative humidity, and 12:12 h of light:dark photoperiod. Rearing cages were supplied with water (cotton wicks in cups with water), glucose powder, and milk powder (1:1 by weight, in Petri dishes). Three- to five-day-old adult flies (without division by sex) were included in tests.

Insecticidal activity of EO samples

To determine the contact insecticidal activity of EO samples against houseflies, a method of dosed contact for insects was applied (Pavlov and Pavlova, 2005). Briefly, a group of flies was exposed to EOs without anesthetic by forced contact with residues of EO solutions on the bottom of a glass cup for 30 min. Glass cups of 35–40 mm diameter and 40–45 mm height were used in tests. To avoid insect sticking, pieces of filter paper were placed in cups so that they fit snugly to the cup walls. Acetone solutions of each EO were prepared in two stages. At the first stage, EOs were diluted with acetone at the ratios of 1:10, 1:100, 1:500, 1:1000, and 1:10,000 and used for the selection of samples with the highest contact insecticidal activities. At the second stage, EOs prepared in five-eight different concentrations led to 0–100% mortality of flies and used to study the insecticidal characteristics of certain EO samples with the high insecticidal activity. Subsequently, 1 ml of the acetone solution of the tested sample was added to a glass cup. Six different concentrations (from 0.00039% to 0.0125%) of Permethrin® were used as the positive controls. The cups with 1 mL of pure acetone and clear cups without acetone were utilized as the negative controls. Ten flies were placed into each cup, after evaporation of acetone. Using a piston consisting of mesh cloth and a spring spacer ring, flies were moved down to the bottom and to achieve a close contact between the insects and the EO or Permethrin® residues on the bottom of the cups. After a 30-min exposure, pistons in cups were raised, and insects were given a 5% glucose solution. Flies were left in the same cups for 24 h. Immobilized or dead flies were considered as under knockdowns, and their numbers were recorded at 15 and 30 min, 1, 2, 3, 6, and 24 h after the exposure. Immobilized (or dead) flies at 24 h after the exposure were considered dead. Insecticidal efficacy of EO samples was expressed as the mortality of flies, i.e. the percentage of dead flies at 24 h relative to the total number of insects in the experiment. All experiments were performed in triplicate. Possible chemical compositions of EOs were determined based on literature data (Table 1).

Data analysis

The dose–response mortality was analyzed by probit regression analysis to calculate lethal concentrations for 50% (lethal dose$[LD]_{50}$) and 99% (LD_{99}) mortality for 95% confidence interval (CI) using the SPSS Statistics 22 software. The difference between LD_{50} values of EOs was considered as statistically significant when their 95% CIs were not overlapped. The time-dependent response mortality after exposure, due to all the tested concentrations of the certain sample, was analyzed by probit analysis to calculate the time for 50% insecticidal effect (ET_{50}) as explained before (Pavlov and Pavlova 2005). The EO samples were considered as very fast acting when ET_{50} values were < 0.3 h, fast acting when ET_{50} values were 0.3–1 h, medium acting when ET_{50} values were 1–3 h, slow acting when ET_{50} values were 3–10 h, and very slow acting when ET_{50} values were > 10 h (Pavlov and Pavlova 2005).

The reversibility of the insecticidal effect (RIE) was determined as a percentage of recovered insects at 24 h after contact with samples and calculated according to the following equation: RIE=(Mkn-Md)×100/Mkn

where M_{kn} is the maximal number of knockdown and dead flies in total, which was recorded for 24 h after the observation, and M_d is the number of dead flies at 24 h after the exposure.

The statistical significance differences between ET_{50} values and RIE values was analyzed by Kruskal–Wallis and Dunn's tests.

Results

EOs with the highest insecticidal activities

Sixteen EOs samples had 100% insecticidal effects ET_{100} on *M. domestica* adults at the dilution of 1:10, and four samples, i.e. EOs of *A. alba*, *A. taurica*, *N. tabacum*, and *P. sylvestris* showed 40%, 70%, 60%, and 60% mortality, respectively. Eight out of sixteen samples led to the mortality of flies from 0 to 30% when were tested at the 1:100 dilution and were EOs of *C. sinensis* (lemon), *C. sativum* (seeds), *E. globulus*, *J. communis* (berries), *M. alternifolia*, *O. basilicum*, *P. abies* (needles), and *P. nigrum.* At the same dilution (1:100), EOs of *C. citratus*, *C. atlantica*, *A. calamus*, *A. sativum*, *F. vulgare*, *J. communis* (bark), *S. aromaticum* (clove), and *T. glandulifera* caused 90–100% mortality of flies.

EOs of *A. calamus*, *A. sativum*, *C. citratus*, *J. communis* L. (bark), *C. atlantica*, *F. vulgare*, and *S. aromaticum* (clove) had the highest insecticidal activity (≥ 60% mortality) at the dilution of 1:500, but only the first four EOs resulted in

Table 1 Chemical compositions of selected essential oils based on literature data

Plant species	Main constituents	Chemical classes of main compounds	Reference
Acorus calamus L	α-Asarone 50.09%, (E)-Methylisoeugenol 14.01%, Methyleugenol 8.59% β-Asarone 3.51%, α-Cedrene 3.09% Camphor 2.42%	Phenylpropenoid ethers	Liu et al. 2013
Allium sativum L	Diallyl disulfide 20.8–27.9%, Diallyl trisulfide 16.8–33.4%, Allyl methyl trisulfide 14.5–19.2% Allyl methyl disulfide 4.4–8.3%, Diallyl sulfide 1.9–9.5%	Alkenes	Satyal et al. 2017
Cedrus atlantica Endl	a-Pinene, up to 79.4% b-Pinene, up to 21.4% Himachalol, up to 66.2% a-Himachalene, up to 10.9% b-Himachalene, up to 19.3% g-Himachalene, up to 11.0% Himachala-2,4-diene, up to 5.7%	Terpenes (monoterpenes and sesquiterpenes)	Paoli et al. 2011
Cymbopogon citratus Stapf	alpha Citral 50.13% beta-Citral 40.31%	Terpenes (acyclic monoterpenes)	Souza et al. 2018
Foeniculum vulgare Mill	trans-Anethole 67.9% Fenchone 25.5%	Ethers	Pavela 2018
Juniperus communis L. (bark)	α–Pinene 42.9% beta-Myrcene 3.9% Limonene 17.8%	Terpenes (bicyclic monoterpenes)	Hayat and Bagci 2014
Syzygium aromaticum L. (clove)	Eugenol 63.26–89% Eugenyl acetate 5.6%	Phenols (fragrances)	Chaieb et al. 2007; Palacios et al. 2009a, b

mortality (60, 40, 10 and 10%, respectively) at the 1:1000 dilution. All seven above-mentioned EOs were chosen for the next step tests.

Dose effect of seven selected EOs

Mortality of flies (at 24 h) in the negative controls (in the pure and the acetone treatment cups) was average (1.25 ± 0.82%), while in the positive controls (in the cups with permethrin), it was dose-dependent. The seven tested EOs samples had dose-dependent insecticidal effect on the adults of *M. domestica*. Table 2 shows toxicological parameters (LD_{50} and LD_{99}) of these EOs. The LD_{50} value of the EO of *A. calamus* was less than those of *A. sativum*, *S. aromaticum*, *C. citratus*, *J. communis*, *C. atlantica*, and *F. vulgare* in 6, 9, 13, 24, 52, and 113 times, respectively. This difference was statistically significant since the 95% CI of the LD_{50} value of *A. calamus* overlapped with none of the intervals of other EOs. The

Table 2 Insecticidal characteristics of selected samples of essential oils on *M. domestica*

Treatment	n	LD_{50} (95% CI), %	LD_{99} (95% CI), %	χ^2	df	p	slope ± SE
Positive control (permethrin, technical)	180	0.00023 (0.00007–0.001)	0.001 (0.001–0.100)	0.471	3	0.925	2.969 ± 0.907
Acorus calamus L	260	0.003 (0.002–0.004)^{a}	0.033 (0.021–0.066)	2.471	5	0.781	2.315 ± 0.310
Allium sativum L	220	0.019 (0.015–0.023)^{b}	0.066 (0.051–0.105)	2.802	4	0.592	4.380 ± 0.708
Cedrus atlantica Endl	180	0.157 (0.093–0.189)^{c}	0.481 (0.332–2.313)	3.434	3	0.329	4.774 ± 1.552
Cymbopogon citratus Stapf	180	0.039 (0.025–0.050)^{d}	0.115 (0.087–0.214)	0.257	2	0.879	4.963 ± 1.145
Foeniculum vulgare Mill	180	0.338 (0.210–0.438)^{e}	1.134 (0.836–2.169)	5.474	2	0.065	4.429 ± 0.983
Juniperus communis L. (bark)	180	0.072 (0.037–0.097)^{cd}	0.227 (0.167–0.468)	3.704	1	0.054	4.692 ± 1.216
Syzygium aromaticum L. (clove)	180	0.028 (0.014–0.045)^{bd}	0.368 (0.221–0.821)	8.664	4	0.700	2.086 ± 0.324

n– the number of flies, LD_{50} and LD_{99} – the lethal dose for 50% and 99% insect mortality, respectively, CI–confidence interval, SE – standard error, the values in the same column with the different letters are considered as significantly different because of their CI are non-overlap insecticidal efficacy of the tested EOs decreased in the following order (based on their LD_{50} values): *A. calamus* > *A. sativum* > *S. aromaticum* ≥ *C. citratus* > *J. communis* > *C. atlantica* > *F. vulgare*.

Time effect of seven selected EOs

The Kruskal–Wallis analysis results showed no statistically significant time-dependent insecticidal effect in the negative and positive controls as well as in the tests with EOs, except for EOs of *A. sativum* and *S. aromaticum* (Table 3). The percentage of flies under insecticidal effects (knockdown and mortality in total) of *A. sativum*, due to all the tested concentrations, was 1.10% at 15 min after exposure, then increased gradually, from one time of observation to another, and reached its maximum value (43.89%) at 24 h after exposure. The insecticidal effect (knockdown and mortality in total) of the *S. aromaticum* EO was 36.11% at 15 min after exposure and reached its maximum value (59.44%) at 2 h and 3 h, then decreased by 52.78% at 24 h after exposure. Exposure to the *A. calamus* EO led to the highest percentage of under knockdown and/or dead flies (from 72.37% to 83.52%) throughout the observation period. The *A. sativum* EO, as represented in Table 3, displayed not any of the reversibility of insecticide effect on adult flies (0% recovered insects), while the *J. communis* EO showed the greatest reversibility (27.3% recovered insects). Minor RIE was observed when flies exposed to other EOs and they were in the positive control.

Based on Fig. 1, the time for ET_{50} (knockdown and mortality in total) indicated no significant difference between the positive control and EOs treatments, except for EOs of *A. sativum*. Dunn's test showed that the ET_{50} value of the *A. sativum* EO was seven times more than that of the positive control (Fig. 1). ET_{50} values of the *A. calamus*, *C. atlantica*, *C. citratus*, and *J. communis* EOs were similar to permethrin and were considered very fast acting because of their ET_{50} values of < 0.3 h (Fig. 1). The ET_{50} values of *S. aromaticum* (clove) and *F. vulgare* EOs were slightly more than that of permethrin and were within 0.3–1 h; thus, these samples were considered as fast acting. The *A. sativum* EO was regarded to be medium acting as its ET_{50} values were 1–3 h.

Discussion

Accumulated number of studies have revealed that EOs and derivative products from more than 30 plant species could serve as repellents or insecticides against housefly (Singh and Singh 1991; Cossetin et al. 2018; Chauhan et al. 2016; 2018; Pavela 2008; Palacios et al. 2009a; Soonwera 2015; Sinthusiri and Soonwera 2013). EOs of red cedar (*J. communis*), palmarosa grass (*Cymbopogon martinii*), vetiver

Table 3 Flies (%) under knockdowns and/or died due to all tested concentrations of certain samples at different times after exposure to selected EOs (m ± SE)

Treatment	n	Time after exposure to selected samples essential oils							p	RIE, %
		0.25 h	0.5 h	1 h	2 h	3 h	6 h	24 h		
Negative control	180	0.94 ± 0.66	1.79 ± 0.84	1.56 ± 0.81	1.07 ± 0.70	1.50 ± 0.79	2.24 ± 0.79	1.25 ± 0.82	0.980	33.33 ± 33.33
Positive control (permethrin, technical)	180	43.33 ± 3.47	48.89 ± 2.42	48.89 ± 2.42	nd	48.33 ± 1.92	nd	47.78 ± 1.11	0.732	3.22 ± 1.81
Acorus calamus L	260	72.37 ± 2.93	80.56 ± 0.30	82.85 ± 0.91	nd	nd	82.34 ± 1.77	83.52 ± 1.91	0.059	0.63 ± 0.63
Allium sativum L	220	1.10 ± 0.56	5.99 ± 1.48	15.20 ± 3.35	27.19 ± 5.09	34.18 ± 4.94*	nd	43.89 ± 5.44*	0.008	0 ± 0
Cedrus atlantica Endl	180	31.67 ± 2.89	34.44 ± 0.56	37.22 ± 2.22	38.33 ± 3.33	33.89 ± 2.42	nd	35.56 ± 1.11	0.580	7.77 ± 5.54
Cymbopogon citratus Stapf	180	31.11 ± 1.47	nd	31.67 ± 1.67	30.00 ± 1.67	30.56 ± 2.00	30.56 ± 2.00	28.33 ± 3.33	0.929	12.60 ± 6.43
Foeniculum vulgare Mill	180	28.51 ± 1.34	30.37 ± 0.42	34.11 ± 1.65	35.04 ± 1.33	nd	nd	33.64 ± 1.33	0.050	3.97 ± 0.17
Juniperus communis L. (bark)	180	35.56 ± 2.94	37.78 ± 2.00	38.89 ± 3.38	41.11 ± 3.09	nd	34.44 ± 3.89	30.00 ± 4.19	0.406	27.30 ± 6.87
Syzygium aromaticum L. (clove)	180	36.11 ± 4.94	47.22 ± 2.94	50.56 ± 3.09	59.44 ± 1.11*	59.44 ± 1.11*	57.22 ± 4.34	52.78 ± 2.42	0.016	12.63 ± 4.87

Flies were considered as under knockdowns when they were immobilized or dead, n– the number of flies, nd — not determined, m – means, SE – standard error of the mean, p – p value according to Kruskal–Wallis test, * –the significant difference ($p \leq 0.05$) compared to the value at 0.25 h according to Dunn's test. RIE – the reversibility of the insecticidal effect was determined as a percentage of recovered insects at 24 h after exposure to EOs

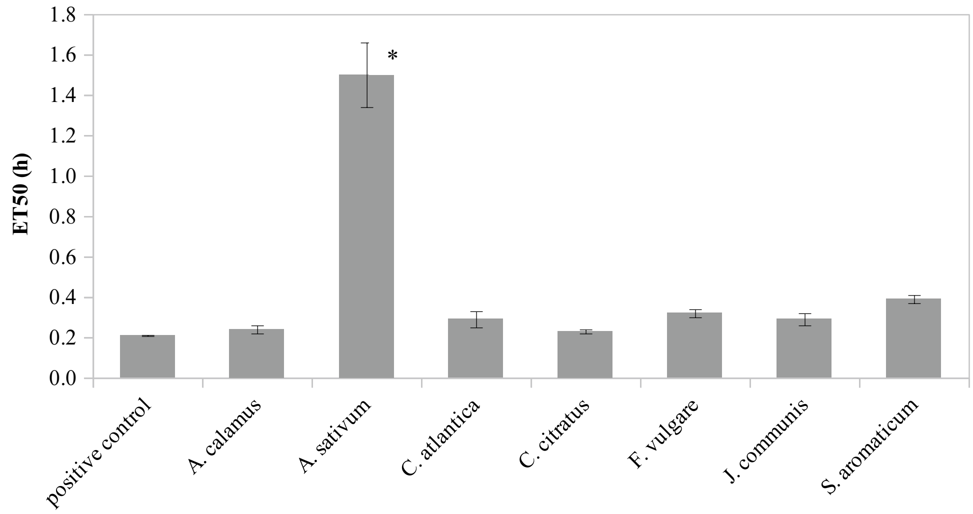

Fig. 1 The time for 50% (ET50) insecticidal effect (knockdown and mortality in total) due to all tested concentrations of the certain EOs (m ± SE): m – means, SE – standard error of the mean, * – the significant difference ($p \leq 0.05$) compared to the value of the positive control according to Dunn's test

grass (*Vetiveria zizanioides*), and bergamot (*Citrus aurantium var. bergamia*) have been introduced as natural alternatives to chemical insecticides for the control of flies (Klauck et al. 2018). We screened contact insecticidal activities of 20 plant EOs to select samples with the highest efficacy against *M. domestica* and to characterize their dose and time effects. The first stage of this study showed that among EOs tested, only EOs of *A. calamus*, *A. sativum*, *C. atlantica*, *C. citratus, F. vulgare, J. communis* L. (bark), and *S. aromaticum* (clove) had the highest insecticidal activity (≥ 60% mortality) at the 1:500 dilution. According to literature data provided in Table 1, the main chemical constituents of the above-mentioned EOs belonged to the terpenes (acyclic or bicyclic monoterpene), alkenes, phenylpropanoid ethers, and phenols (fragrances) chemical classes.

The results disclosed that the *A. calamus* EO was the most effective insecticide against flies and very fast acting with negligible RIE. In Singh and Singh's (1991) investigation, among the 31 EOs studied, *A. calamus* EO at 2% concentration showed more insecticidal activities to the adults of *M. domestica* and gave 60.46% and 38.09% knockdown/mortality effects after 2 h and 24 h, respectively. In this study, the *A. calamus* EO toxicity to flies (based on $LD_{99} = 0.033\%$, i.e. 99% mortality at 0.033% of concentration) was more than that reported in the Singh and Singh's (1991) research. A possible explanation for this difference is that in our study, flies contacted with residues of EOs, but in Singh and Singh's (1991) research work, EOs were tested by topical application method. In the current study, another EO sample with high insecticidal efficacy ($LD_{99} = 0.066\%$, which means 99% mortality at 0.066% concentration) was *A. sativum* EO. The insecticidal effect (knockdown and mortality in total) of *A. sativum*, due to all tested concentrations, depended on time, which increased gradually and reached its maximum value (43.89%) at 24 h after exposure. Despite a medium speed of acting, the *A. sativum* sample had an irreversible insecticidal effect. Literature data confirmed the insecticidal properties of *A. sativum* extracts. Meriga et al. (2012) showed the effectiveness of *A. sativum* against *Spodoptera litura* larvae when water and methanol extracts of *A. sativum* were applied at the concentration of 1000 ppm (or 0.1%) and reaching 81% and 64% mortality of larvae, respectively. Prowse et al. (2006) tested *A. sativum* juice against *M. domestica* and achieved high mortality of flies (about 90%) by using juice at 5% concentration. Our results demonstrated that the EO of *A. sativum* gave high mortality (99%) at 0.066% concentration (Table 3). Discrepancies in the insecticidal activity of the juice and the EO of *A. sativum* are probably associated with differences in their preparation methods and quantity of active components in juices and extracts.

The results from the present study indicated that EOs of *S. aromaticum* and *C. citratus* had no significant difference in toxicity to the adults of *M. domestica* as well as in RIE, while the time effect of these two EOs differed. According to Sinthusiri and Soonwera (2013), the exposure of *M. domestica* to the ethanol solution of *C. citratus* EO at 5% concentration caused 100% mortality of flies after 24 h, and LC_{50} of this EO was 2.22%. In our study, the LD_{50} value of the *C. citratus* EO against *M. domestica* was 100 times less than that obtained by Sinthusiri and Soonwera (2013). Repellent and larvicidal properties of the *C. citratus* EO have been reported against *M. domestica*, as well (Kumar et al. 2011).

Notwithstanding reports on the insecticidal properties of plant extracts, insecticidal effects against house flies of certain EOs tested in the current study have not been described in published researches. For *F. vulgare, J. communis* L. (bark), and *S. aromaticum* (clove) EOs tested, insecticidal effects on other insect species are known. For instance, Tian et al. (2015) demonstrated the high contact insecticidal effectiveness of the EO of clove buds against *Cacopsylla chinensis* (Hemiptera: Psyllidae). Ethanol solutions of the juniper EO at 2.5%, 5%, and 10% concentrations were tested as repellents against *Paederus* beetles (Gaffari et al. 2016). Pavela (2015) reviewed insecticidal activities of EOs against mosquito larvae and described larvicidal properties of the *F. vulgare* EO against *Aedes aegypti.*

In the literature, there are descriptions of modes of action of plant pesticides used for a long time, while modes of action of most novel plant extracts with insecticidal properties have poorly been understood (George et al. 2014). Plant extracts and EOs are a complex mixture of chemicals, some of which are able to penetrate insect organisms and to affect their physiological functions, others may act as neurotoxins (George et al. 2014). Based on literature data, properties of plant extracts are determined by their chemical compositions that may vary with geographical distribution, harvesting time, growing conditions, and method of extraction (Ebadollahi 2013; Paoli et al. 2011; Huzar et al. 2018). Chen et al. (2015) described the variation of chemical constituents and the proportion of each chemical constituent of the EO of *A. calamus* in different plant populations. Moreover, repellent and insecticidal activities have been shown for predominant components of the *A. calamus* EO such as shyobunone and isoshyobunone (Chen et al. 2015), α-asarone (Hematpoor et al. 2017), and β-asarone (Yooboon et al. 2019). The mode of action of α-asarone from *A. calamus* EO has similarity with organophosphates due to the ability to inhibit acetylcholinesterase (Hematpoor et al. 2017). The Yooboon et al. (2019) findings have suggested that β-asarone inhibits the proliferation of insect cells through the apoptosis induction and thus exerts insecticidal effects.

Among the EOs tested in this study, only three (i.e. *C. atlantica*, *C. citratus*, and *J. communis*) contained terpenes. Terpenes and their derivates terpenoids are the largest groups of a wide variety of volatile substances released by plants and serve to protect them from herbivorous insects (Sharma et al. 2017). Several reviews have recognized terpenes from EOs as neurotoxins acting on multiple targets in insects such as GABA, tyramine and octopamine receptors/synapses, or acetylcholinesterase (Regnault-Roger et al. 2012; George et al. 2014). Yeom et al. (2012) had shown that the nervous system in insects might be disturbed by terpenoids such as α-pinene and β-pinene (components of *C. atlantica* and *J. communis* EOs), which inhibit acetylcholinesterase.

Acetylcholinesterase is an enzyme affected by the main components of the *A. sativum* EO, diallyl disulfide, and diallyl trisulfide (Plata-Rueda et al. 2017). The toxic effects of trans-anethole (*F. vulgare* EO) and limonene are also associated with the inhibition of acetylcholinesterase (Cruz et al. 2017). Monoterpenoid linalool was considered as an inhibitor of this enzyme from some insects (Lopez and Pascual-Villalobos 2014). Based on evidence, eugenol from *S. aromaticum* has acaricidal (Pasay et al. 2010) and insecticidal effects (Lee et al. 2016) that may be due to the inhibition of neuronal activity by acting on acetylcholinesterase (Regnault-Roger et al. 2012).

Since EOs are usually a multicomponent mixture, there is the possibility of a synergy effect. This effect has already been shown, for example, for terpenes (Scalerandi et al 2018), which may be a part of EOs such as *C. atlantica* (Paoli et al. 2011), *C. citratus* (Souza et al. 2018), *J. communis* (Hayta and Bagci 2014) tested in the current study. According to Scalerandi et al. (2018), the synergy mechanism of terpene mixtures explains that one component (in a higher dose) is under detoxification, and another component (in a smaller amount) acts as an insecticide.

There are limitations in the current study that could be addressed in future research. First, the study focused on the dose and time effects of EOs and described their chemical compositions based on literature data only. Next, the assessment of EO insecticidal activity by contacting flies with residues of EO solutions on the bottom of a glass cup makes demarcating difficult to the contact and fumigant activities. A similar approach has been used by Khater and Geden (2019) to estimate contact/fumigant toxicity of EOs for adult flies. The last one is that the time effect of EOs was assessed for 24 h only and the insecticidal effect of some EOs probably may lasting for a longer period of time. Recording of the insecticidal effect of EOs at seven-time points for the first 24 h after the exposure helped us to observe the difference in the insecticidal properties of *A. calamus* and *A. sativum* EOs. Research is needed to determine how long insecticidal effect of each EOs can last. Thus the design of the current study let us choose the several EOs that possessed high insecticidal activities against adults of *M. domestica* and showed that at least seven of EOs need to be more analyzed by chemical and entomological studies.

Conclusion

In conclusion, obtained results and literature data suggest that EOs of plants such as *A. calamus*, *A. sativum*, *C. atlantica*, *C. citratus*, *F. vulgare*, *J. communis* (bark), and *S. aromaticum* (clove) are promising and might be applied as contact insecticides against adult *M. domestica.* The difference in the insecticidal properties of *A. calamus* and *A. sativum* EOs observed in this study signifies the need for various approaches for their future application as insecticides. Insecticides of natural origin have an advantage over chemical insecticides in terms of safety for the environment, low toxic and hygienic requirements for their use, and availability of raw materials. Therefore, further entomological, chemical and toxicological studies of plant extracts would be rational.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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