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Shared phytochemicals predict efficacy of essential oils against western flower thrips (*Frankliniella occidentalis*) in the greenhouse

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Abstract: Western flower thrips (Frankliniella occidentalis; Thysanoptera: Thripidae), or WFT, are a global pest of commercial crops, particularly those grown in greenhouses. Current management recommendations often involve judicious use of pesticides to which WFT have evolved multiple resistance phenotypes. Essential oils (EOs) have shown promise as a less toxic alternative for WFT greenhouse management. However, challenges remain in predicting which EOs are most likely to be insecticidal to WFT and ensuring that the efficacy of EOs under bioassay conditions reflect performance in whole-plant application scenarios. To address these challenges, 9 EOs were tested for contact toxicity against WFT in small container assays, then gas chromatography–mass spectroscopy (GC–MS) profiles of each EO were used to quantify concentrations of 22 chemicals shared by at least 5 or more of the plant species. Of these, 13 compounds were positively correlated with thrips mortality. Effective compounds were a mixture of sesquiterpenes, cyclic monoterpenes, and noncyclic monoterpenes. Interestingly, no bicyclic monoterpenes shared among the essential oils tested correlated with thrips mortality. Whole-plant assays of the four best EOs from the container assay showed significant reduction in the number of thrips per plant, although mortality in EO treatments in the whole plant assay was lower than in the container assay. In addition, all four EOs were as efficacious as the conventional insecticide flonicamid. Identifying other EOs with high concentrations of the efficacious compounds that were identified in this study and using container assays to screen these oils for WFT thrip mortality and phytotoxicity could help integrated pest management (IPM) practitioners and greenhouse staff to more rapidly accumulate a suite of EOs as low toxicity alternatives for management of WFT in greenhouse settings.

Keywords: Western flower thrips, Greenhouse management, Essential oils, Gas chromatography, Monoterpenes, Sesquiterpenes, Integrated pest management, Principal components analysis

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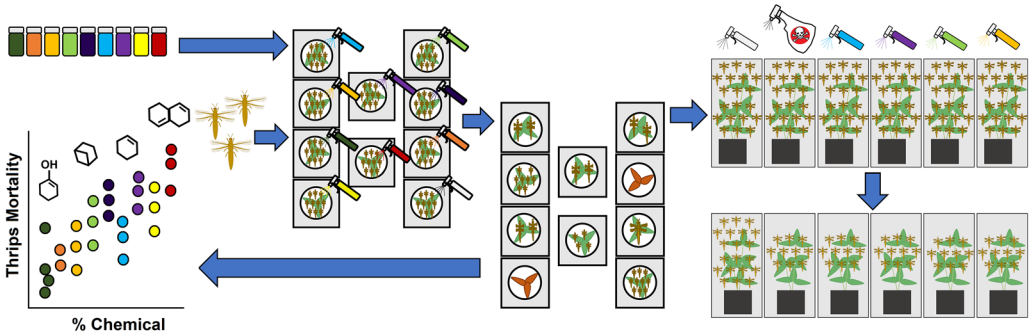
Graphical Abstract



Background

Western flower thrips (WFT; *Frankliniella occidentalis*, Thysanoptera: Thripidae) are one of the most destructive plant pests on the planet [1]. Both horticultural and food crops are susceptible to damage by WFT [2, 3]. Though feeding can be tolerated in some plants with little or no impact to yield, the discoloration and wilted appearance caused by their piercing–sucking mouthparts can quickly render produce aesthetically unmarketable. WFT can also act as a vector of major plant diseases including tomato spotted wilt virus and *Impatiens* necrotic spot virus, diseases estimated to cost billions (USD) in losses annually in the US alone [4, 5] and for which integrated disease management approaches are required.

Currently, the most successful control strategy is to target WFT with intensive pesticide applications [6]. Chemical management tactics involve targeted applications of contact pesticides including azadirachtin, insecticidal soaps, neem oil, pyrethrin, or Spinosad [6]. Systemic pesticides, most notably neonicotinoids, are also effective at managing thrips but their use is not recommended given their broader impact on beneficial species that may interact with the focal plant (e.g., pollinators and biological control agents) [1]. Furthermore, the short generation time and complex reproductive biology of WFT have facilitated their ability to evolve multiple resistance mechanisms against many active ingredients of insecticides [7]. A larger array of treatments is clearly needed for WFT, and methods for expanding the array of available treatments in the future as WFT continues to evolve.

Essential oils (EOs) could provide a low-risk alternative to conventional pesticides for managing WFT [8–10]. Plants have defended against insects for millions of years, resulting in a wide range of biologically active compounds [11]. Essential oil products have many potential routes for pest management including contact toxicity, fumigant toxicity, behavioral manipulation (attraction and repellency), and gustatory effects [10]. The diversity of compounds present in EOs could allow target-specific insect control. However, given that EOs contain a wide array of phytochemicals, it can sometimes be difficult to determine which EO phytochemicals are responsible for insecticidal effects on a particular pest.

Previous work has shown that *Mentha pulegium* and *Thymus mastichina* EOs are moderately effective at reducing the population density of WFT through fumigant toxicity [12]. Other EOs have been shown to be toxic or repellent to other species of thrips, including basil (*Ocimum basilicum*), black pepper (*Piper nigrum*), true cinnamon (*Cinnamomum zeylanicum*), cassia (*Cinnamomum cassia*), myrrh (*Commiphora myrrha*), lemongrass (*Cymbopogon citratus*), marjoram (*Origanum majorana*), eucalyptus *(Eucalyptus globulus*), and citronella (*Cymbopogon nardus*) [13, 14]. However, given the diversity of EOs now commercially available, and the diversity of potentially biologically active compounds within EOs, testing every available EO for pest management of WFT would be impractical. Nevertheless, the ability of WFT to evolve resistance to insecticidal compounds [7], as well as the introduction of new EOs on the market as the EO market continues to expand globally [15], necessitates a methodology for identifying EOs that could potentially be effective and then rapidly screening them for WFT toxicity.

In this study, we tested nine essential oils in their ability to reduce active populations of WFT in container and whole plant bioassays via contact toxicity. We asked: (1) which essential oils are most effective at reducing populations of western flower thrips in a 24-h bioassay?, (2) Do results from the rapid bioassay predict performance of EOs against WFT in whole-plant

assays?, and (3) Which, if any, shared chemical constituents among the EOs' profiles correlate with WFT mortality?

Methods

Essential oils

The nine EOs we tested were arborvitae (*Thuja plicata*: Cupressaceae), cassia (*Cinnamomum cassia*: Lauraceae), eucalyptus *(Eucalyptus globulus*: Myrtaceae), ginger (*Zingiber officinale*: Zingiberaceae), oregano (*Origanum vulgare*: Lamiaceae), peppermint (*Mentha piperita*: Lamiaceae), Siberian fir (*Abies sibirica*: Pinaceae), Spearmint (*Mentha spicata*: Lamiaceae), and thyme (*Thymus vulgaris*: Lamiaceae). The EOs tested were based upon commercial availability as well as preliminary evidence from field trials (Durr, pers. comm) suggesting some insecticidal potential. Furthermore, each of these oils has been shown in previous literature to have insecticidal properties across multiple insect taxa [16–24]. All essential oils used were ordered from the supplier dōTERRA® (Pleasant Grove Utah, USA) in 2018–2019.

Essential oils used in this study were analyzed at the Aromatic Plant Research Center (Lehi, Utah, USA) by GC–MS using a Shimadzu GCMS-QP2010 Ultra operated in the electron impact (EI) mode (electron energy = 70 eV), scan range = 40–400 amu, scan rate = 3.0 scans/sec, and GC–MS solution software. The GC column was a ZB-5 fused silica capillary column with a (5% phenyl)-polymethylsiloxane stationary phase and a film thickness of 0.25 µm. The carrier gas was helium with a column head pressure of 80 psi and flow rate of 1.37 mL/min. Injector temperature was 250 °C and the ion source temperature was 200 °C. The GC oven temperature program was programmed for 50 °C initial temperature, temperature increased at a rate of 2 °C/min to 260 °C. A 5% w/v solution of the sample in CH_2Cl_2 was prepared and 0.1 µL was injected with a splitting mode (30:1). Identification of the oil components was based on their retention indices determined by reference to a homologous series of n-alkanes, and by comparison of their mass spectral fragmentation patterns with those reported in the literature [16], and stored in the research center's in-house MS library [25].

Container assays

All assays were conducted at The Land Institute in Salina, KS USA (38.767231, − 97.566029) in six blocks during 2018–2019. Blocks 1–4 were conducted June 19–20, June 21–22, June 26–27, and June 29–30 in 2018, respectively; Blocks 5–6 were conducted July 2–3 and July 6–7 in 2019, respectively. Western flower thrips were collected from 150 infested 2-month-old greenhouse alfalfa plants that had not been treated with EOs for at least 4 weeks prior to the experiment. The alfalfa plants were grown in 5.6 L tree pots (Stuewe®) in Promix BX potting mix and were watered daily. Greenhouse growing conditions were 29.4–35 °C with ambient sunlight supplemented with 400 W high intensity discharge lights. Alfalfa was selected due to its abundance in the greenhouse at the time the studies were conducted, because it has been previously used to test phytotoxicity of essential oils [26–29] and because it is a host plant for Western flower thrips [30, 31]. Due to variable availability of thrips, the assay was conducted in 6 blocks. In each block 3–6 treatments, each of a single EO, were tested plus a control treatment (water + surfactant). In total, 20 replicates were assessed for the control treatment, and 5–12 replicates for each EO. Not all EOs could be tested in every block due to limitations in the number of available containers and the availability of thrips.

For each study replicate, 10 WFT were placed in a $11.43 \times 11.43 \times 3.81$ cm clear plastic seed germination boxes with tight closing lids. One alfalfa leaf, approximately 2 cm^2 in size, was also placed in each container as a temporary food source for thrips and as an indicator for phytotoxicity of the EOs tested. Essential oil treatments consisted of a 0.08% dilution with 60 mL RO water, plus 0.05 mL of soap (Dr. Bronner Unscented Castile Soap) as a surfactant, and 0.05 mL of the EO. These solutions were made in Boston Round spray bottles with a separate, designated bottle used for each treatment. The control treatment consisted of 60 mL RO water with 0.05 mL of soap. Each treatment was applied to the container via a small pump sprayer with two sprays per container, for a total volume of 0.33 mL solution per container (0.00027 mL EO per container, or $5.58 * 10^{-7}$ mL EO per cm^3). After treatment, thrips were allowed to feed on the alfalfa tissue for 24 h in a climate-controlled insect rearing chamber (25 ℃, 40% RH, 16:8 L:D) and number of surviving thrips was recorded. From these data the proportion thrips mortality (surviving WFT/total WFT per container) was calculated.

Whole plant assay

To test how EOs would perform in a more realistic greenhouse pest management scenario, whole-plant assays were performed on four of the most successful EOs from the container assays (peppermint, Siberian fir, arborvitae, and thyme). Though oregano and cassia were highly successful at reducing survival of WFT in the container assays, they were also highly phytotoxic to the red clover, and hence, excluded from the whole-plant assays. These four EOs were also compared to the conventional insecticide flonicamid (Aria; manufacturer specifics), which is

commonly used for WFT management in greenhouses, and a water-only control treatment.

The whole plant assays were conducted in 17 cm × 8 cm × 28 cm, 3.8 L capacity clear plastic cereal containers (Buddeez®) that were modified to grow plants inside, in a completely pest- and insecticide-free environment, before WFT applications occurred. Container lids were cut out leaving only the outermost portion that closed around the container, and the holes were covered with LS Econet 1515 Insect Screen (Ludvig Svensson Inc., Charlotte, NC USA) to allow for air and humidity exchange, but prevent WFT from entering or exiting the containers. Two 1.5 cm diameter holes were also drilled into the bottom of each container and covered with the same mesh netting to allow for drainage when watering. Containers were filled with 2 L of Promix BX, and twenty organic red clover (*Trifolium pratense*) seeds were shallowly seeded into each container. Containers were held in climate-controlled growth chambers (32 °C; 40% RH; 16:8 L:D) until at least two true leaves had formed on at least 50% of the seedlings.

Once the seedlings had established, WFT adults were taken from infested greenhouse plants using the same protocol as the container assays. Twenty WFT were added to each container and allowed to feed on the red clover for 24 h before one of the six treatments were applied. Essential oil solutions consisted of the same 0.08% dilutions and controls again consisted of 60 mL DI water with 0.05 mL of soap. Flonicamid was mixed at 0.008 g active ingredient in 60 mL water as per the manufacturer specifications, plus 0.05 mL of soap. Treatments were applied directly to the seedlings with a small pump sprayer until all leaf tissue was damp but not dripping. This was a total of 6 mL solution per container (0.005 EO mL per container, or $2.63 * 10^{-6}$ mL EO per cm^3; 0.0008 g flonicamid per container, or $4.20 * 10^{-7}$ g flonicamid per cm^3) with 20 replicates used for each treatment and the control.

Treatments were applied once and after 24 h a 7.6 × 12.7 cm yellow sticky card (Pestrap®) was adhered to the inside of each container. Containers were left for another 24 h to allow capture of surviving WFT. Cards were then removed and the number of WFT per card was recorded. Proportion mortality was calculated by dividing the number of WFT per card by the total number of WFT added to each container. The assay was conducted in 4 blocks with 3 replicates of control and each EO treatment per block ($n = 12$ per treatment), and 3 replicates of flonicamid treatment in 3 of the 4 blocks ($n = 9$).

Statistics

To test the relative success of the treatments in reducing WFT populations for both the container and whole plant assays, mixed ANOVAs (PROC GLM, SAS 9.4) were performed on proportion WFT mortality. Data for the container assay were arcsine-square root transformed, and data for the whole plant assay were square root transformed, to meet the test assumptions of normality and homoscedasticity of residuals. Treatment was coded as the independent fixed factor with proportion WFT mortality as the response variable; block was coded as a random effect. For tests with a significant treatment effect, pairwise comparisons were performed using the Tukey–Kramer adjustment for multiple comparisons.

For the chemical analyses, we used the GC–MS data for all EOs to determine which compounds were shared among at least 5 of the nine EOs tested. We then conducted a simple regression of % mortality from each replicate of the container assay and the concentration of each chemical compound (PROC REG, SAS 9.4). Control treatment replicates were excluded from the regression analyses.

We also conducted a principal components analysis, or PCA (PROC CALIS, SAS 9.4) on the shared 22 compounds of the 9 EOs. This qualitative analysis was used to determine whether shared compounds with similar toxicity to thrips were "bundled" in orthogonal trait-space and allowed us to visualize the distributions of the essential oils within this phytochemical trait-space.

For the shared 22 EO chemical compounds, a literature search was conducted to determine if: (1) Each compound had been previously measured in EOs, (2) Each compound had been previously shown to be insecticidal,

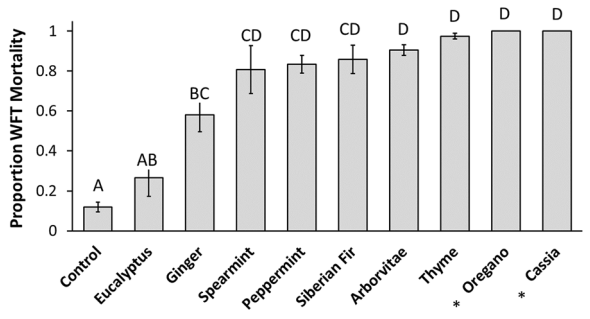


Fig. 1 Proportion mortality of thrips in the container assay 24 h post-application of control (no essential oil) versus nine essential oil treatments. Error bars denote standard error, while bars with shared letters indicate treatments that do not significantly differ. Treatments with an asterisk exhibited phytotoxicity when applied to the alfalfa leaves in the containers

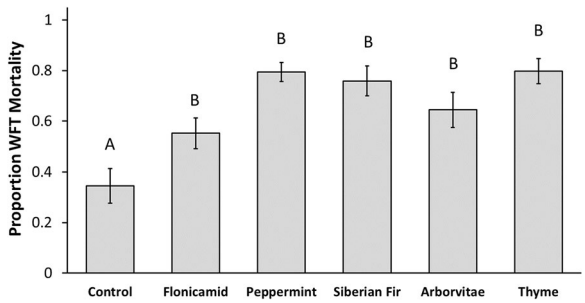


Fig. 2 Proportion morality of thrips in the whole plant assay 48 h post-application of control (no essential oil or insecticide) versus the conventional thrips insecticide flonicamid and four essential oil treatments. Error bars denote standard error, while bars with shared letters indicate treatments that do not significantly differ

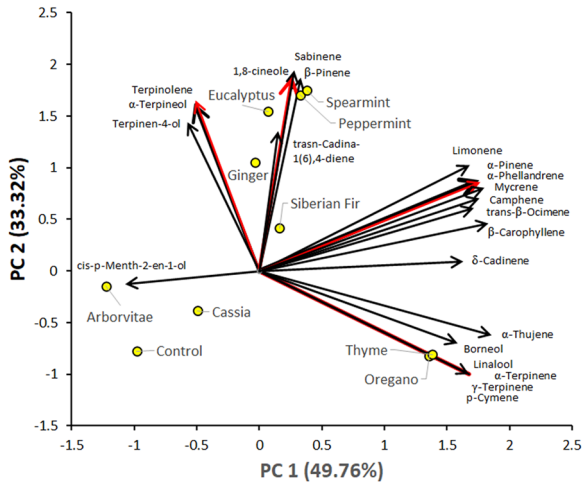


Fig. 3 Principal component analysis (PCA) of the 22 chemical compounds shared among 5 or more of the 9 essential oils tested in the container assay. Black arrows indicate a single chemical compound, while red arrows indicate 2 or more chemical compounds. Yellow data points indicate the location of the nine essential oils within the phytochemical PCA trait-space

and (3) Each compound had been previously shown to be insecticidal to thrips of any species.

Results

There was a significant effect of treatment ($F_{9,92}=53.03$, $p<0.0001$) but no significant block effect ($F_{5,92}=1.69$, $p=0.1439$) in the container assay (Fig. 1). Arborvitae, thyme, oregano, and cassia applications had the highest mortality, while eucalyptus was the least successful (NS). Though cassia and oregano had a high rate of mortality, they were noticeably phytotoxic to the red clover leaves and were excluded from the whole plant assays.

Whole plant assays had a significant effect of treatment ($F_{5,60}=16.05$, $p<0.0001$) as well as a significant block effect ($F_{3,60}=27.59$, $p<0.0001$). Every EO treatment tested—peppermint, Siberian fir, arborvitae, and thyme—significantly reduced the population of WFT relative to the control (Fig. 2). Flonicamid also significantly reduced WFT relative to control, but it did not differ in efficacy compared to any of the EO treatments.

The principal component analysis (Fig. 3) showed some evidence of grouping of EO species according to taxonomic similarity, such as the closely related thyme and oregano [32] and peppermint and spearmint, both in the *Mentha* genus [32], respectively, being located similarly in phytochemistry trait-space. However, similarity of these EOs in their shared compounds was not consistently closely correlated with phylogeny. For example, cassia (order Laurales) and arborvitae (order Pinales) were more phytochemically similar than Siberian fir (order Pinales) was to arborvitae. Similarly, spearmint and peppermint (order Lamiales) were more similar in shared phytochemical compounds to eucalyptus (order Myrtales) and ginger (order Zingiberales) than to thyme or oregano (also order Lamiales) [33].

Using the GC–MS data available for these EOs (Additional file 1: Table S1), we were able to find significant positive correlations between 13 shared phytochemicals and EO efficacy against WFT (Fig. 4, Table 1). An additional compound, 1,8-cineole, was negatively correlated with thrips mortality (Fig. 4, Table 1). Previous studies have demonstrated that all 14 compounds have at least some documented insecticidal effects (Table 2), though not always on thrips. Eight compounds that were correlated with WFT mortality in this study have not previously been documented correlating with thrips mortality or thrips feeding: α-Thujene, γ-terpinene, Terpinolene, cis-p-Menth-2-en-1-ol, Terpinen-4-ol, β-caryophyllene, δ-cardinene, and trans-Cadina-1(6),4-diene. However, six compounds that have shown to correlate with thrips mortality or feeding in previous studies—α-phellandrene, limonene, α-terpineol, α-pinene, β-pinene, and camphene—were not found to correlate with WFT in our analyses.

Discussion

Essential oils could provide a low-risk alternative to pesticides for managing greenhouse pests [10, 34]. Our results show the possibility of essential oils in managing western flower thrips. Every EO, except for eucalyptus, had a pronounced impact on mortality in the container assays. We also found that four of most effective EOs from the container assay—peppermint, Siberian fir, arborvitae, and thyme—reduced WFT survival with comparable success to flonicamid when applied to infested whole plants,

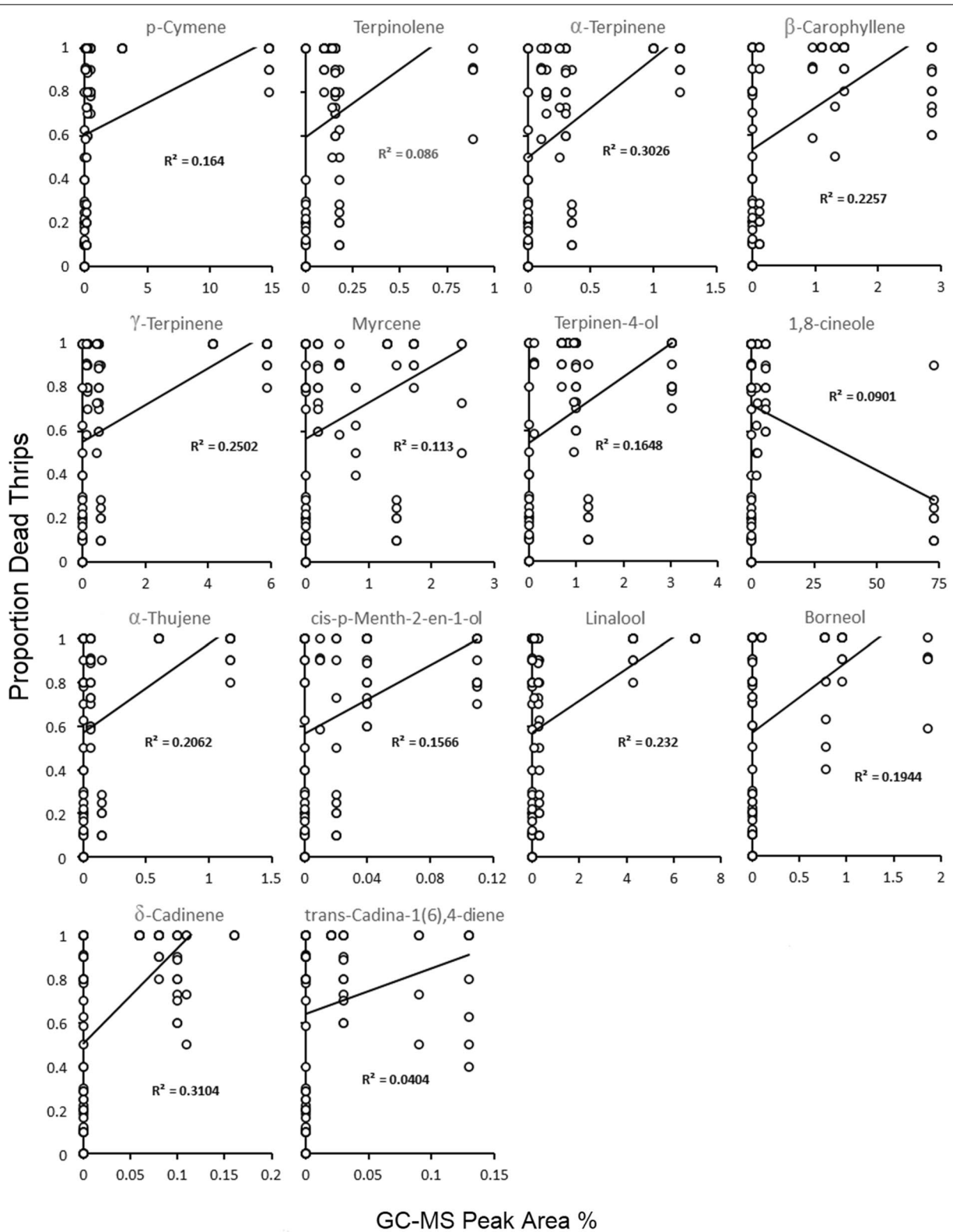


Fig. 4 Significant correlations between 14 common chemicals, those present in at least 5 of the 9 essential oils tested, and proportion thrips mortality in replicates of the container assays

Table 1 Regression results for the 22 chemical compounds that contributed to each of the principal component axes in the PCA analysis, with WFT proportion mortality as the dependent variable

Variable	df	Intercept	Slope	P
1,8-Cineole	1, 105	0.71797	− 0.00594	0.0017**
α-Phellandrene	1, 105	0.657	0.24033	0.4376
α-Pinene	1, 105	0.66399	0.01484	0.3152
α-Terpinene	1, 105	0.49807	0.45603	< 0.0001***
α-Terpineol	1, 105	0.70117	− 0.01815	0.3449
α-Thujene	1, 105	0.57096	0.40532	< 0.0001***
β-Caryophyllene	1, 105	0.53305	0.19010	< 0.0001***
β-Pinene	1, 105	0.64921	0.09011	0.186
Borneol	1, 105	0.56638	0.32176	< 0.0001***
Camphene	1, 105	0.6697	0.00840	0.2841
cis-p-Menth-2-en-1-ol	1, 105	0.56625	3.87660	< 0.0001***
δ-Cadinene	1, 105	0.50281	4.38670	< 0.0001***
γ-Terpinene	1, 105	0.55162	0.08426	< 0.0001***
Limonene	1, 105	0.68095	− 0.00012	0.9897
Linalool	1, 105	0.56847	0.07272	< 0.0001***
Myrcene	1, 105	0.56738	0.16378	0.0004***
p-Cymene	1, 105	0.6011	0.02961	< 0.0001***
Sabinene	1, 105	0.7086	− 0.19549	0.1479
Terpinen-4-ol	1, 105	0.53989	0.15193	< 0.0001***
Terpinolene	1, 105	0.59369	0.61683	0.0022**
trans-β-Ocimene	1, 105	0.71073	− 0.66029	0.1510
trans-Cadina-1(6),4-diene	1, 105	0.64205	2.04926	0.0379*

without causing visual phytotoxicity. Given that WFT has evolved resistance to many active ingredients of pesticide formulations [6], our data show great promise for the use of at least some EOs for management of WTFs in greenhouses.

Plants have evolved a vast arsenal of chemically distinct defensive compounds [35], so determining which EO compounds are correlated with toxicity to a specific pest is key to determining which EOs may be effective against a given pest species. For example, eucalyptus, a plant with a wide spectrum of biologically active compounds [36, 37], did not have a statistically meaningful impact on mortality in WFT. However, screening all possible EOs for insecticidal properties against every target pest would be expensive and logistically challenging. Our data-driven approach, combining GC–MS obtained chemical quantities with toxicity results from a set of EO container assays, allows us to determine the suite of chemicals that are correlated with the specific pest mortality. Scientists and greenhouse managers could subsequently use this information to seek out other EOs with similar chemical properties for management of that pest.

One limitation to our approach is that principal component analysis groups the compounds by their quantities rather than chemical structure/property, so its utility for identifying effective classes of chemicals is limited. For example, the thirteen chemicals statistically associated with thrips mortality were terpenoids with similar, cyclical structures (Table 1), but they did not cluster in the PCA (Fig. 3). Incorporating a structural comparison of the compounds that assigns a similarity value could allow compounds to be clustered based on their physical attributes, which directly relates to function. Furthermore, incorporating detailed structural comparisons within our framework could allow synergistic chemicals, i.e., compounds that strengthen the effect of the other, or the most likely modes of action, to be identified more efficiently. Given that chemical reactions only occur when specific conformations of specific molecules are present under specific conditions, it is safe to assume that structural comparisons would inform these relationships.

While it is unclear why bicyclic monoterpenes were effective but sesquiterpenes were not, the importance of structure in chemical effect cannot be overstated. The key structural variation between bicyclic monoterpenes and sesquiterpenes is in the placement of the rings. Sesquiterpenes have planar, adjacent rings, while bicyclic monoterpenes have two cyclical portions that overlap. Though the physiological route of these EO constituents in thrips is, to our knowledge, unknown, this structural variation could be the defining feature of their effectiveness.

Thrips have evolved resistance to at least 9 chemical classes with varying modes of action due to their fast generation time and diverse detoxification enzymes including cytochrome P-450 monooxygenases, esterases, and glutathione S-transferases [7]. Depending on the mode of action, essential oils could allow novel management tactics for pests that continue to escape conventional products. In addition, work in other systems has shown that essential oils can not only have synergistic effects with other essential oils, but also pesticides. For example, cytochrome P-450 activity of bed bugs (*Cimex lectularius* L.) that had developed resistance to deltamethrin was inhibited when essential oil constituents were included in the pesticide treatment, greatly increasing the toxicity [38].

Another limitation to our approach is that it cannot identify unique compounds within EOs that may prove effective against specific pests. For example, peppermint EO has high concentrations of isomethone, which may have insecticidal properties [39, 40], but this compound was scarce in spearmint and absent in the other EOs tested in this study. Similarly, Siberian Fir contains a high percentage of bornyl acetate, which is insecticidal

Table 2 The 22 most shared chemical compounds by compound class, and their insecticidal properties in previous literature

Compound	Compound class	Effect in this study?	Found in insecticidal essential oils?	Specific chemical insecticidal?	Against thrips?	References
Linalool	Noncyclic monoterpene	Y	Y	Sometimes	Y	[13, 43–46]
Myrcene	Noncyclic monoterpene	Y	Y	Sometimes	Boosted when thrips feed	[41, 44, 47, 48]
trans-β-Ocimene	Noncyclic monoterpene	N	Y	Is nematicidal	Could not find	[49, 50]
1,8-Cineole	Cyclic monoterpene	Y, neg	Y	Sometimes	Y	[13, 43, 44, 51]
α-Phellandrene	Cyclic monoterpene	N	Y	Y	Boosted when thrips feed	[41, 48]
α-Terpinene	Cyclic monoterpene	Y	Y	Sometimes	Y	[13, 43, 48, 52]
α-Thujene	Cyclic monoterpene	Y	Y	N	Could not find	[46, 47, 52]
Borneol	Cyclic monoterpene	Y	Y	Sometimes	Y	[13, 43–45, 53]
p-Cymene	Cyclic monoterpene	Y	Y	Y	N	[13, 52–54]
γ-Terpinene	Cyclic monoterpene	Y	Y	Sometimes	Could not find	[43, 52]
Limonene	Cyclic monoterpene	N	Y	Y	Boosted when thrips feed	[41, 43, 44, 48]
Terpinolene	Cyclic monoterpene	Y	Y	Y	Could not find	[41]
cis-p-Menth-2-en-1-ol	Terpene alcohol, cyclic monoterpene	Y	Y	Could not find	Could not find	[55]
Terpinen-4-ol	Terpene alcohol, cyclic monoterpene	Y	Y	Y	Could not find	[43, 44, 46, 52]
α-terpineol	Terpene alcohol, cyclic monoterpene	N	Y	Sometimes	Y	[13, 43–45, 56]
α-Pinene	Bicyclic monoterpene	N	Y	Sometimes	Y	[13, 41, 43, 44, 46–48]
β-Pinene	Bicyclic monoterpene	N	Y	Sometimes	Y	[13, 46, 47, 57]
Camphene	Bicyclic monoterpene	N	Y	Y	Y	[13, 44]
Sabinene	Bicyclic monoterpene	N	Y	Sometimes	Could not find	[41, 51, 58]
β-caryophyllene	Bicyclic sesquiterpene	Y	Y	Y	Could not find	[47, 52, 57, 59]
δ-Cadinene	Bicyclic sesquiterpene	Y	Y	Could not find	Could not find	[57]
trans-Cadina-1(6),4-diene	Cadinene sesquiterpene	Y	Y	Could not find	Could not find	[14, 54]

[41], but this compound was scarce or absent in all other EOs tested. Research on novel phytochemicals will continue to be necessary to expand the repertoire of insecticides needed to manage pests that can rapidly evolve insecticide resistance. However, rigorous tests of novel compounds are impractical to implement in a working greenhouse facility. Greenhouse managers must be able to select and implement new treatments rapidly. The advantage of the shared compound approach is that it allows managers to quickly search for and select new EOs that are likely to be effective.

Even if a novel EO has shared chemical properties that predict it to be a good candidate for pest management, it is still important to test the EO prior to widespread implementation. The container assay that we employed is a simple methodology that could be used to rapidly screen multiple types of EOs for both insecticidal efficacy and phytotoxicity. The toxicity of the EOs to thrips, as indicated by percent mortality, were higher in the container assays than the whole plant assays. This could be either due to an increase in the amount of EO applied per area in the container assays, more limited food availability (i.e., plant clippings instead of whole plants), or higher exposure to the spray than in a whole-plant scenario, which has much greater habitat complexity that could reduce contact exposure of WFT to the EO spray However, in both assays the four EOs tested significantly increased WFT mortality, and showed a lack of phytotoxicity when tested in both conditions. Significant mortality could also be assessed in the most effective EOs with as few as 5 replicates of the container assay. These results suggest that a container assay approach may be sufficient to rapidly test candidate EOs for phytotoxicity and pest management efficacy, before implementing at a larger scale.

We tested the efficacy of a single bottle of each EO, sourced from a single batch extraction of that EO. One point of concern in the use of EOs in greenhouse management is that EOs can vary in quality and consistency among commercial blends, as: (1) The type or percentage of proprietary ingredients of EOs are often not included on the product label, and (2) The quantity of insecticidal phytochemicals can vary from one batch to another within a single product, due to the inherent differences in chemical concentration of the plants from which the EOs are distilled [42]. Fortunately, consumer demand for high quality EOs for therapeutic purposes has resulted in multiple EO manufacturers that test the chemical composition of their products on a regular basis. Sourcing EOs from companies that provide GC–MS data on their EOs, especially on individual batches, and using those data if necessary to tailor the concentrations of EOs when applying them as insecticides, could help to increase the efficacy and reliability of EOs in greenhouse pest management.

Conclusions

Western flower thrips are a global pest requiring continuous research attention and frequent updates in management protocols. As a vector of tomato spotted wilt virus and *Impatiens* necrotic spot virus, their potential to cause damage is often more severe than immediately apparent. The short generation time and complex reproductive biology of WFT have facilitated their resistance to pesticides applied as a management strategy against disease transmission. Our work provides an affordable, rapid screening approach for selecting and testing essential oils, a low-risk alternative to pesticides, against WFT populations. Out of 9 essential oils tested, 4 were viable treatments for managing WFT on Red clover. Additional trials could be performed to test a broader range of essential oils with comparable phytochemistries.

Abbreviations

WFT: Western flower thrips; EO: Essential oil; PCA: Principal components analysis; IPM: Integrated pest management; GC–MS: Gas chromatography–mass spectroscopy.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40538-022-00328-w.

Additional file 1: Table S1. The complete list of chemicals, by % total composition and Retention index (RI) values (indicated with italics), identified in each essential oil tested via GC–MS.

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Author contributions

TD conceived of the bioassay experiments, conducted the experiments, and assisted with manuscript writing. CS assisted with manuscript writing and interpretation of chemistry results. ND and PS conducted the GC–MS analyses on the essential oils and assisted with manuscript writing. EM assisted with experimental design and manuscript writing, conducted the statistical analyses, and performed the literature review of phytochemical effects on thrips and other insects.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

TD is a member of the DoTerra® Wellness Advocate program. No other authors declare competing interests.

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