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Nematicidal Activity of Plant Essential Oils and Components from Coriander (*Coriandrum sativum*), Oriental Sweetgum (*Liquidambar orientalis*), and Valerian (*Valeriana wallichii*) Essential Oils against Pine Wood Nematode (*Bursaphelenchus xylophilus*)

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Commercial essential oils from 28 plant species were tested for their nematicidal activities against the pine wood nematode, *Bursaphelenchus xylophilus*. Good nematicidal activity against *B. xylophilus* was achieved with essential oils of coriander (*Coriandrum sativum*), Oriental sweetgum (*Liquidambar orientalis*), and valerian (*Valeriana wallichii*). Analysis by gas chromatography−mass spectrometry led to the identification of 26, 11, and 4 major compounds from coriander (*Coriandrum sativum*), Oriental sweetgum (*Liquidambar orientalis*), and valerian (*Valeriana wallichii*) oils, respectively. Compounds from each plant essential oil were tested individually for their nematicidal activities against the pine wood nematode. Among the compounds, benzaldehyde, *trans*-cinnamyl alcohol, *cis*-asarone, octanal, nonanal, decanal, *trans*-2-decenal, undecanal, dodecanal, decanol, and *trans*-2-decen-1-ol showed strong nematicidal activity. The essential oils described herein merit further study as potential nematicides against the pine wood nematode.

KEYWORDS: Coriander; Oriental sweetgum; valerian; nematicidal activity; pine wood nematode; plant essential oils

INTRODUCTION

Pine wilt disease, caused by the pine wood nematode, *Bursaphelenchus xylophilus*, has been a serious problem in southern Korea (*1*). This disease was first reported in Busan city in 1988 (*2*) and has spread to several southern and middle areas of the Korean peninsula (*3*). The damaged area was about 7871 ha in 2006 (*4*). As *Pinus densiflora* and *Pinus thunbergii* are predominant tree species in Korean forests and are very susceptible to the pine wood nematode, ecological and economic damage is substantial (*5*). Recently, infected *Pinus koreansis* has been found for the first time in Korea. Control of this disease depends primarily on fumigation of disease-infected trees, aerial application of synthetic pesticides against *Monochamus alternatus*, the insect vector of this disease, or injection of nematicides such as morantel tartrate, emamectin benzoate, and levamisole hydrochloride (*6–8*). Total budget for the control of pine wood nematode was about U.S. $61 million in 2007 (*9*). However, there are environmental and human health concerns for conventional pesticides. To avoid environmental pollution and health problems caused by the use of traditional synthetic nematicides or pesticides, there is a need to search for naturally occurring toxicants in plants. Plant essential oils may provide potential alternatives to currently used pinewood nematode control agents because they constitute a rich source of bioactive chemicals and are commonly used as fragrances and flavoring agents for foods and beverages (*10*). Furthermore, plant essential oils and their components have been reported to have nematicidal activity against pine wood nematode (*1, 11–15*).

In this study, we investigated the nematicidal activity of commercial plant essential oils and their components against pine wood nematode to find potential alternatives to currently used pine wood nematode control agents or as model compounds for the development of chemically synthesized derivatives with enhanced activity or environmental friendliness.

MATERIALS AND METHODS

Collection of Pine Wood Nematodes. *B. xylophilus* was isolated from chips of infected pine wood collected in Haman area (in March 2004), Gyoungsangnam-do province, Korea, and extracted according to the Baermann funnel method (*16*). Details of the isolation and culture of pine wood nematode are described by Park et al. (*1*).

Essential Oils and Chemicals. Plant essential oils were purchased from AYUS GmbH (Weinstrasse, Bühl/Baden, Germany) (**Table 1**). Nonane (purity = 99%), nonanol (purity = 95%), decanal (purity

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Table 1. Plant Essential Oils Tested and Their Nematicidal Activity against *B. xylophilus*

essential oil[a]	source of plant	part	origin	mortality[b] (mean ± SE)
Ammi visnaga	*Ammi visnaga*	flowering plant	Morocco	5.7 ± 1.8ijk[2]
Artemisia arborescens	*Artemisia arborescens*	flowering plant	Morocco	13.5 ± 2.7efghijk
benzoin, abs	*Styrax benzoin*	resin	Indonesia	21.6 ± 3.3cdef
celery	*Apium graveolens*	seeds	France	49.6 ± 5.3b
chamomile, blue	*Chamomilla matricaria*	blossoms	Nepal	11.9 ± 2.7fghijkl
chamomile, Roman	*Anthemis nobilis*	blossoms	France	11.3 ± 1.9fghijkl
chamomile, wild	*Ormensis multicaulis*	blossoms	Moroco	5.5 ± 1.7ijkl
chrysantheme, abs	*Chrysanthemum morifolium*	flowering plant	China	28.2 ± 1.5 cd
coriander, herb (cilantro)	*Coriandrum sativum*	herb	Solvenia	100a
costus, root	*Saussurea lappa*	roots	India	17.5 ± 2.9defghi
cypriol (nagarmotha)	*Cyperus scariosus*	roots	India	4.6 ± 0.8jkl
elecampane roots	*Inula racemosa*	roots	India	20.0 ± 3.1cdefg
Eriocephalus punctulatus	*Eriocephalus punctulatus*	flowering plant	South Africa	7.9 ± 1.3ghijkl
Helichrysum (Immortella)	*Helichrysum angustifolium*	blossoms	Croatia	5.7 ± 1.9ijkl
kanuka	*Leptospermum ericoides*	leaves	New Zealand	1.9 ± 1.4kl
magnolia leaves	*Michelia alba*	leaves	China	24.1 ± 3.4cde
myrrh	*Commiphora myrrha*	resin	Somalia/Oman	8.3 ± 1.9ghijkl
Nigella	*Nigella sativa*	seeds	India	17.2 ± 4.1defghi
pastinak	*Pastinaca sativa*	whole plant	Croatia	30.5 ± 6.2c
patchouli	*Pogostemon patchouli*	whole plant	Indonesia	7.2 ± 1.4hijkl
Peru balm	*Miroxylon balsamum*	resin	El Salvador	31.5 ± 3.3c
Salvia stenophylla	*Salvia stenophylla*	leaves	South Africa	19.5 ± 1.4cdefgh
sandalwood	*Santalum album*	wood	India	14.9 ± 2.0efghijk
Santolina	*Santolina chamaecyparissus*	whole plant	Spain	10.7 ± 1.4fghijkl
spikenard, chin	*Nardostachys sinensis*	roots	China	6.0 ± .8ijkl
Oriental sweetgum	*Liquidambar orientalis*	resin	Turkey	100a
valerian ind. (tagar)	*Valeriana wallichii*	roots	India	100a
verbena java (zimbani)	*Lippia javanica*	flowering plant	Zimbabwe	11.3 ± 2.4fghijkl
control				0.5 ± 0.7ll

[a] 2.0 mg/mL concentration was applied. [b] Means within a column followed by the same letters are not significantly different ($P = 0.05$, Scheffe's test).

Table 2. Nematicidal Activity of Coriander, Oriental Sweetgum, and Valerian Essential Oils against *B. xylophilus*

	mortality[a] (%, mean ± SE)		
essential oils	1.0 mg/mL	0.8 mg/mL	0.6 mg/mL
coriander	100a	98.5 ± 0.6a	90.9 ± 1.7a
Oriental sweetgum	100a	98.0 ± 0.7a	86.2 ± 2.2a
valerian	48.2 ± 1.0b	27.0 ± 1.8b	2.4 ± 0.2b

[a] Means within a column followed by the same letters are not significantly different ($P = 0.001$, Scheffe's test).

= 99%), decanol (purity = 99%), *trans*-cinnamyl alcohol (purity = 98%), undecanal (purity = 97%), dodecanal (purity = 92%), *cis*-asarone (purity = 70%), *trans*-asarone (purity = 98%), *trans*-cinnamyl aldehyde (purity = 99%), benzaldehyde (purity > 99%), (+)-limonene (purity = 97%), octanal (purity = 99%), and carvone (purity = 96%) were purchased from Sigma-Aldrich (Milwaukee, WI). Terpinen-4-ol (purity = 99%), *p*-cymene (purity = 95%), γ-terpinene (purity = 97%), geraniol (purity = 96%), *cis*-ocimene (purity = 97%), linalool oxide (mixture of *cis*- and *trans*-, purity > 97%), geranyl acetate (purity = 97%), and camphor (purity = 99%) were purchased from Fluka (Buchs, Switzerland). Camphene (purity = 80%), α-pinene (purity = 95%), α-terpineol (purity = 95%), β-caryophyllene (purity = 90%), borneol (purity = 70%), acetophenone (purity = 98.5%), and β-pinene (purity = 94%) were purchased from Tokyo Kasei (Tokyo, Japan). Heptanal (purity = 95%), benzyl alcohol (purity = 99%), and linalool (purity = 98%) were purchased from Wako (Osaka, Japan). Triton X-100 was purchased from Sigma (St. Louis, MO). All other chemicals were of reagent grade.

Synthesis. 1-Phenyl-1-ethanol was obtained by reduction of acetophenone with $LiAlH_4$ (Kanto chemical, Tokyo, Japan) in the usual manner (*17*). Hydrocinnamyl alcohol (3-phenylpropan-1-ol) was prepared by hydrogenation of *trans*-cinnamyl alcohol with H_2 gas and 5% Pd on carbon (Aldrich) as described in Kim et al. (*18*). *trans*-2-Decenal was synthesized according to the procedure described in Matsuo et al. (*19*). This method gave less *cis*-2-decenal (<2%) than that using PDC or PCC. The structures of synthetic compounds were confirmed by GC-MS spectra and/or ^1H and ^{13}C NMR (500 and 125 MHz, respectively) with a Varian UI500 spectrometer using TMS in $CDCl_3$ as an internal standard at Korea Basic Science Institute (Seoul, Korea).

Hydrocinnamyl alcohol: yield, 85.6%; purity, 98.5%; GC-MS (*m*/*z*, %), 51 (8.0), 65 (22.6), 77 (25.9), 91 (99.3), 92 (44.8), 117 (100), 118 (54.9), 136 (M^+, 19.2).

1-Phenyl-1-ethanol: yield, 57.7%; purity, >99.0%; bp, 94−96 °C/22 mmHg; GC-MS (*m*/*z*, %), 51 (9.4), 77 (27.0), 91 (8.8), 107 (100), 122 (M^+, 32.9).

trans-2-Decenal: To the solution of *trans*-2-decen-1-ol 2.03 g (1.30 mmol), DBU 2.18 g (14.3 mmol, TCI), and *N*-*tert*-butylbenzenesulfenamide 236 mg (1.30 mmol, TCI) in CH_2Cl_2 (20 mL) was added *N*-chlorosuccinimide 1.91 g (14.32 mmol, TCI) in CH_2Cl_2 (50 mL) at 0 °C. After 30 min of stirring at that temperature, 2 mL of 2 N HCl was added to quench the reaction. Ether (150 mL) was added to the solution, and then the solution was washed with 5% $NaHCO_3$ and brine and dried with $MgSO_4$. After removal of the solvent, the residue was subjected to silica chromatogram. Yield, 70.4%; purity, 97.2%; GC-MS (*m*/*z*, %), 55 (100), 57(58.7), 70 (86.3), 83 (50.2), 98 (19.7), 110 (11.4), 121 (5.3), 136 (1.8), 154 (M^+, 0.04); ^1H NMR (ppm), δ 0.89 (3H, t, $J = 7.8$ Hz), 1.20 −1.38 (8H, m), 1.51 (2H, quin, $J = 7.5$ Hz), 2.34 (2H, ddt, $J_1 = 7.5$ Hz, $J_2 = 7.0$ Hz, $J_3 = 1.5$ Hz), 6.12 (1H, ddt, $J_1 = 15.5$ Hz, $J_2 = 7.0$ Hz, $J_3 = 1.5$ Hz), 6.86 (1H, dt, $J_1 = 15.5$ Hz, $J_2 = 7.0$ Hz), 9.15 (1H, d, $J = 7$ Hz); ^{13}C NMR (ppm), δ 194.1 (=CHO), 159.0 (=CH), 133.0 (=CH), 32.7 (CH_2), 31.7 (CH_2), 29.1 (CH_2), 29.0 (CH_2), 27.9 (CH_2), 22.6 (CH_2), 14.1 (CH_3).

Nematicidal Activity. Concentrations of plant essential oils and their components were prepared by serial dilution with distilled water containing Triton X-100 (5 mg/mL). Test solutions were introduced into wells of 96-well plates (Falcon). In each well, the concentration of nematodes was about 50−150 nematodes (mixture of juvenile and adult nematodes, male/female/juvenile ≈ 1:1:2) per 100 μL of water. Controls received distilled water−Triton X-100 solutions. Treated and control nematodes were held under the same conditions as used for colony maintenance. Mortality of nematodes was recorded after 24 h under a microscope. Nematodes were defined as dead if their bodies were straight and they did not move, even

Table 3. Chemical Composition of Coriander, Oriental Sweetgum, and Valerian Essential Oils

		RI[1]		ratio (%)		
no.	compound	DB-1MS	DB-FFAP	coriander	Oriental sweetgum	valerian
1	styrene	875	1257		1.56	
2	heptanal	879	nd[b]	0.42		
3	nonane	900	900	1.24		
4	α-pinene	929	1014	3.87	1.02	
5	benzaldehyde	929	1526		0.47	
6	camphene	941	1055	0.48		
7	β-pinene	968	1100	0.37	0.15	
8	octanal	980	1286	0.82		
9	benzyl alcohol	1007	1880		1.22	
10	*p*-cymene	1011	1265	5.29		
11	limonene	1020	1192	1.16		
12	*cis*-ocimene	1027	nd			0.12
13	acetophenone	1033	1659		0.19	
14	1-phenyl-1-ethanol	1034	1815		0.17	
15	γ-terpinene	1048	1239	0.25		
16	*cis*-linalool oxide	1057	1436	1.52		
17	*trans*-linalool oxide	1071	1465	1.09		
18	nonanal	1082	1390	0.52		
19	linalool	1088	1536	49.38		0.13
20	camphor	1118	1500	2.92		
21	borneol	1148	1682	0.65		
22	terpine-4-ol	1161	nd	0.62		
23	α-terpineol	1172	nd	0.31		
24	decanal	1184	1510	3.78		
25	hydrocinnamyl alcohol	1205	2049		41.13	
26	*trans*-cinnamyl aldehyde	1230	2049		0.24	
27	geraniol	1235	1846	1.10		
28	*trans*-2-decenal	1237	1640	7.64		
29	*trans*-2-decen-1-ol	1252	1824	4.51		
30	decanol	1257	1758	2.13		
31	*trans*-cinnamyl alcohol	1279	2273		45.07	
32	undecanal	1281	nd	0.23		
33	carvone	1305	nd	0.22		
34	geranyl acetate	1356	1753	1.95		
35	dodecanal	1387	nd	1.12		
36	β-caryophyllene	1415	1587		3.60	
37	*cis*-asarone	1586	2312			88.82
38	*trans*-asarone	1639	2413			3.41
total				93.59	94.82	92.48

[1] Retention indices = van Den Dool and Kratz retention index (*21*) on DB-1MS and DB-FFAP columns, according to *n*-alkanes (C_7−C_{20}; DB-1MS, DB-FFAP). Components were identified by co-injection with authentic standard on two columns. [b] Not detected.

after transfer to clean water. Three trials on different days were used to test the nematicidal activity (four replicates in each trial), and we used the data of the trial with the lowest activity.

Gas Chromatography (GC-FID). Gas chromatography analysis was performed on the Agilent 6890N equipped with a flame ionization detector. Retention times for comparison with authentic compounds were measured with DB-1MS and DB-FFAP column (30 m × 0.25 mm i.d., 0.25 μm film thickness, J&W Scientific, Folsom, CA). The oven temperature was programmed as isothermal at 40 °C for 1 min, then raised to 250 at 6 °C/min, and held at this temperature for 4 min. Helium was used as the carrier gas at the rate of 1.5 mL/min.

Gas Chromatography−Mass Spectrometry (GC-MS). The active essential oils were analyzed on a gas chromatograph (Agilent 6890N)−mass spectrometer (Agilent 5973N MSD) equipped with a DB-5MS column (30 m × 0.25 mm i.d., 0.25 μm film thickness, J&W Scientific). The oven temperature was programmed as described in the previous paragraph. The effluent of the GC column was introduced directly into the source of the MS via a transfer line (280 °C). Ionization was obtained by electron impact (70 eV, source temperature = 230 °C). Scan range was 35−400 amu. Compounds were tentatively identified by comparison of mass spectra of each peak with those of authentic samples in the NIST MS library.

Statistical Analysis. Nematode mortality was transformed to arcsine square root values for analysis of variance (ANOVA). Treatment means were compared and separated by Scheffe's test (*20*).

RESULTS

Nematicidal Activity of Plant Essential Oils. The nematicidal activity of plant essential oils is shown in **Table 1**. Among the tested oils, coriander, Oriental sweetgum, and valerian oils showed 100% nematicidal activity at 2.0 mg/mL concentration. Celery essential oil showed moderate activity (49.6% mortality), but the other essential oils gave weak nematicidal activity against pine wood nematode. Nematicidal activities of three active oils, coriander, Oriental sweetgum, and valerian, were tested at lower concentration (**Table 2**). Coriander and Oriental sweetgum essential oils showed strong nematicidal activity at 1.0, 0.8, and 0.6 mg/mL concentrations, but the nematicidal activity of valerian was <50%.

Chemical Components of Plant Essential Oils. The chemical compositions of the three active essential oils, coriander, Oriental sweetgum, and valerian, are shown in **Table 3**. Retention indices were obtained with the equation proposed by van Den Dool and Kratz (*21*). A total of 26 compounds were identified in coriander oil. The most abundant compound was linalool, followed by *trans*-2-decenal, *p*-cymene, and *trans*-2-decen-1-ol. Hydrocinnamyl alcohol and *trans*-cinnamyl alcohol were found as the main compounds in Oriental sweetgum essential oil. Ratios of other compounds except

Table 4. Nematicidal Activity of Components from Coriander, Oriental Sweetgum, and Valerian Essential Oils at 2.0 mg/mL against *B. xylophilus*

compound	mortality[a] (%, mean ± SE)
styrene	6.7 ± 0.9ef
heptanal	40.8 ± 0.6b
nonane	1.7 ± 0.5f
benzaldehyde	100a
octanal	100a
benzyl alcohol	3.8 ± 0.7ef
ocimene	16.2 ± 1.1c
acetophenone	5.3 ± 0.8ef
1-phenyl-1-ethanol	3.0 ± 1.5ef
linalool oxide	1.8 ± 0.6f
nonanal	100a
decanal	100a
hydrocinnamyl alcohol	17.2 ± 3.6c
trans-2-decenal	100a
trans-2-decen-1-ol	100a
decanol	100a
trans-cinnamyl alcohol	100a
undecanal	100a
geranyl acetate	7.0 ± 0.9def
dodecanal	100a
cis-asarone	100a
trans-asarone	12.1 ± 2.3cde
control	1.6 ± 0.7f

[a] Means within a column followed by the same letters are not significantly different ($P = 0.05$, Scheffe's test).

β-caryophyllene were <2%. The most abundant compound in valerian oil was *cis*-asarone followed by *trans*-asarone, linalool, and *cis*-ocimene.

Nematicidal Activity of Individual Compounds. The nematicidal activity of compounds identified in coriander, Oriental sweetgum, and valerian is shown in **Table 4**. Benzaldehyde, *trans*-cinnamyl alcohol, *cis*-asarone, octanal, nonanal, decanal, *trans*-2-decenal, undecanal, dodecanal, decanol, and *trans*-2-decen-1-ol showed 100% nematicidal activity against pine wood nematode at 2.0 mg/mL concentration. Heptanal produced moderate activity (40.8% mortality). Nematicidal activities of other compounds were <20%. All of the compounds showing 100% mortality at 2.0 mg/mL were tested at lower concentrations (**Table 5**). All compounds showed >80% mortality at 1.0 mg/mL concentration, but only *trans*-2-decen-1-ol, *trans*-2-decenal, and decanol showed strong nematicidal activity at 0.2 mg/mL concentration.

DISCUSSION

Many plant essential oils and phytochemicals are known to possess nematicidal activity. Naturally occurring nematicidal phytochemicals are isothiocyanates and glucosinolates from Brassicaceae, cyanogenic glycosides, polyacetylenes from Asteraceae, alkaloids, terpenoids, and phenolics (*22*). Nematicidal activity of plant essential oils and their components against pine wood nematode has also been reported (*1, 11–15*). In our study, three plant essential oils, coriander, Oriental sweetgum, and valerian, showed good nematicidal activity among 28 plant essential oils.

Plant essential oils consist of volatile compounds such as alcohols, aldehydes, terpenoids, and phenolics. Jointly or independently, these compounds show many biological activities such as insecticidal, antifungal, and nematicidal activities. In this study, the nematicidal constituents of active oils were identified by GC-FID and GC-MS analyses. Among the identified components of the three active oils, the nematicidal activities of α-pinene, camphene, β-pinene, *p*-cymene, limonene, linalool, camphor, borneol, terpinen-4-ol, α-terpineol, cinnamyl aldehyde, geraniol, and carvone against pine wood nematode have been reported in previous studies (*1, 11–15*). Among the aromatic compounds, benzaldehyde and *trans*-cinnamyl alcohol showed good nematicidal activity, whereas styrene, acetophenone, 1-phenyl-1-ethanol, benzyl alcohol, and hydrocinnamyl alcohol produced weak activity. Among the aliphatic compounds, alcohols and aldehydes, except heptanal, generally showed good nematicidal activity. This result agreed with previous findings (*11, 15*) that aldehyde and alcohol were more effective than other hydrocarbons and ketones and that the primary alcohol was more active than secondary and tertiary alcohol. Among the tested primary alcohols of aromatic compounds, only *trans*-cinnamyl alcohol showed good nematicidal activity. This result suggests that allylic alcohol is responsible for showing nematicidal activity of primary alcohol that phenyl is substituted.

There was a significant difference in nematicidal activity between *cis*- and *trans*-asarone. Nematicidal activity was much more pronounced in *cis*-asarone than in *trans*-asarone. Park et al. (*23*) reported that the insecticidal activity of *cis*-asarone was more pronounced against adults of *Sitophilus oryzae*, *Callosobruchus chinensis*, and *Lasioderma serricorene* than that of *trans*-asarone. Lee et al. (*24*) also reported that there was a difference in insecticidal activity between *cis*- and *trans*-asarone. Comparison of the results of previous studies and our results suggests that the geometrical structure of asarone is critical in the nematicidal activity against pine wood nematode. The tested aliphatic aldehydes with C_8-C_{12} chain length showed very strong nematicidal activity against pine wood nematode at 2.0 mg/mL concentration, whereas

Table 5. Nematicidal Activity of Active Compounds from Coriander, Oriental Sweetgum, and Valerian Essential Oils against *B. xylophilus*

	mortality[a] (%, mean ± SE)				
compound	1.0 mg/mL	0.8 mg/mL	0.6 mg/mL	0.4 mg/mL	0.2 mg/mL
benzaldehyde	94.1 ± 1.6abc	77.5 ± 3.9c	45.6 ± 3.4c	7.4 ± 1.0ef	1.9 ± 0.7d
octanal	89.0 ± 3.5bc	79.3 ± 6.8bc	55.2 ± 11.3c	31.2 ± 4.5cde	3.5 ± 0.9 cd
nonanal	95.8 ± 1.1abc	83.4 ± 1.2abc	59.5 ± 9.4c	3.6 ± 0.7f	1.1 ± 0.2d
decanal	100a	97.3 ± 1.0ab	34.2 ± 7.1c	25.1 ± 4.0cdef	3.0 ± 0.7 cd
trans-2-decenal	100a	100a	100a	100a	100a
trans-2-decen-1-ol	100a	100a	100a	100a	98.0 ± 0.9a
decanol	100a	100a	100a	100a	100a
trans-cinnamyl alcohol	100a	100a	99.5 ± 0.4a	57.6 ± 5.2b	11.3 ± 2.7bcd
undecanal	98.7 ± 1.0ab	90.5 ± 5.0abc	64.1 ± 3.0bc	34.1 ± 7.9bcd	17.8 ± 5.1b
dodecanal	86.3 ± 2.6c	77.8 ± 0.7c	37.6 ± 4.9c	20.8 ± 5.6ef	11.5 ± 2.8bcd
cis-asarone	100a	100a	96.2 ± 0.5ab	47.9 ± 0.7bc	15.8 ± 0.4bc

[a] Means within a column followed by the same letters are not significantly different ($P = 0.001$, Scheffe's test).

heptanal revealed moderate activity. In the nematicidal activity test of active compounds, 2-decenal, an α,β-unsaturated aldehyde, showed highest nematicidal activity through all ranges of concentration. Choi et al. (*11*) reported that citral was a more effective compound than citronellol. This and an earlier study (*11*) suggest that the enhancement of nematicidal activity of aldehyde is attributed to the existence of a double bond at the α,β-position of the carbonyl group.

The mode of action of oils and their constituents is of practical importance for nematode control because it gives useful information to develop the most appropriate formulation and delivery means. In this study, the dead body of *B. xylophilus* treated with essential oils usually showed straight bodies without movement. Kong et al. (*25*) reported that pine wood nematode bodies treated with the muscle activity blockers levamisole hydrochloride and morantal tatrate usually exhibited semicircular and coiling shapes, respectively. These results suggest that the nematicide mode of action between the essential oils and commercial nematicides might be different. Some essential oils have been reported to interfere with the neuromodulator octopamine (*26*) or GABA-gated chloride channels of insect pests (*27*). However, the exact mode of action of essential oils and their components against pine wood nematode is unclear.

In conclusion, coriander (*C. sativum*), Oriental sweetgum (*L. orientalis*), and valerian (*V. wallichi*) essential oils and their components appear to be useful as natural nematicides for *B. xylophilus*. For the practical use of the three essential oils and their components as novel nematicides to proceed, further study is necessary on systemic action, phytotoxicity, and formulation for improving nematicidal potency and stability and reducing cost.

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