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Screening Indoor Plants for Volatile Organic Pollutant Removal Efficiency

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Abstract. **Twenty-eight ornamental species commonly used for interior plantscapes were screened for their ability to remove five volatile indoor pollutants: aromatic hydrocarbons (benzene and toluene), aliphatic hydrocarbon (octane), halogenated hydrocarbon [trichloroethylene (TCE)], and terpene (α-pinene). Individual plants were placed in 10.5-L gas-tight glass jars and exposed to ≈10 ppm (31.9, 53.7, 37.7, 46.7, and 55.7 mg·m^{-3}) of benzene, TCE, toluene, octane, and α-pinene, respectively. Air samples (1.0 mL) within the glass containers were analyzed by gas chromatography–mass spectroscopy 3 and 6 h after exposure to the test pollutants to determine removal efficiency by monitoring the decline in concentration over 6 h within sealed glass containers. To determine removal by the plant, removal by other means (glass, plant pot, media) was subtracted. The removal efficiency, expressed on a leaf area basis for each volatile organic compound (VOC), varied with plant species. Of the 28 species tested, *Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densiflorus* had the highest removal efficiencies for all pollutants; *Tradescantia pallida* displayed superior removal efficiency for four of the five VOCs (i.e., benzene, toluene, TCE, and α-pinene). The five species ranged in their removal efficiency from 26.08 to 44.04 μg·m^{-3}·m^{-2}·h^{-1} of the total VOCs. *Fittonia argyroneura* effectively removed benzene, toluene, and TCE. *Ficus benjamina* effectively removed octane and α-pinene, whereas *Polyscias fruticosa* effectively removed octane. The variation in removal efficiency among species indicates that for maximum improvement of indoor air quality, multiple species are needed. The number and type of plants should be tailored to the type of VOCs present and their rates of emanation at each specific indoor location.**

The importance of indoor air quality to human health has become of increasing interest in developed countries where inhabitants often spend over 90% of their time indoors (Jenkins et al., 1992; Snyder, 1990). Indoor air has been reported to be as much as 12 times more polluted than that outdoors (Ingrosso, 2002; Orwell et al., 2004; Zabiegała, 2006). Indoor air pollutants primarily originate from building product emissions, human activities inside the building, and infiltration of outdoor air (Wolkoff and Nielsen, 2001; Zabiegała, 2006) and have increased as a result of the lower gas exchange rates of newer, more energy-efficient buildings (Cohen, 1996). Indoor air pollutants include volatile organic compounds (VOCs), particulate matter, ozone, radon, lead, and biological contaminants (Destaillats et al., 2008). Exposure can cause acute illnesses (e.g., asthma, nausea) and chronic diseases (e.g., cancer, immunologic, neurologic, reproductive, developmental, and respiratory disorders) (Suh et al., 2000).

VOCs emanating from paints, varnishes, adhesives, furnishings, clothing, solvents, building materials, combustion appliances, and potable water (Jones, 1999; Maroni et al., 1995; Zabiegała, 2006) have a negative effect on indoor air quality (Darlington et al., 2000). VOCs are generally classified as aromatic hydrocarbons (e.g., benzene, toluene, ethylbenzene, xylene), aliphatic hydrocarbons (e.g., hexane, heptane, octane, decane), halogenated hydrocarbons [e.g., trichloroethylene (TCE), methylene chloride], and terpenes (e.g., α-pinene, *d*-limonene) (Jones, 1999; Suh et al., 2000; Wolkoff and Nielsen, 2001; Won et al., 2005; Zabiegała, 2006). Benzene and toluene, octane, TCE, and α-pinene are representative VOCs from each class (i.e., aromatic hydrocarbons, aliphatic hydrocarbons, halogenated hydrocarbons, and terpenes, respectively) and are considered to be important indoor air pollutants as a result of their toxicity (Liu et al., 2007; Newman et al., 1997; Orwell et al., 2006).

Plants remove VOCs from indoor air through stomatal uptake, absorption, and adsorption to plant surfaces (Beattie and Seibel, 2007; Korte et al., 2000; Sandhu et al., 2007). Several indoor species have been screened for their ability to remove benzene (Liu et al., 2007), some of which could remove 40 to 88 mg·m^{-3}·d^{-1} (Orwell et al., 2004), in addition to other VOCs (e.g., toluene, TCE, *m*-xylene, hexane) (Cornejo et al., 1999; Orwell et al., 2006; Wood et al., 2002; Yoo et al., 2006). The efficiency of VOC removal varies substantially among species (Yoo et al., 2006) and with the molecular characteristics of each compound. To date, only a limited number of indoor species have been tested for their phytoremediation potential and the range of pollutants assessed is even more limited (Cornejo et al., 1999; Ugrekhelidze et al., 1997; Wolverton et al., 1989; Wood et al., 2002). It is evident that a better understanding of the phytoremediation potential of a diverse range of indoor plants is needed. In this study, a cross-section of indoor plants (28 species) was screened for their ability to remove five important VOCs with differing chemistries (benzene, toluene, octane, TCE, and α-pinene).

Materials and Methods

Plant material. Twenty-eight species of popular indoor ornamental plants available in the southeastern United States, which represented 26 genera and 15 botanical families (Table 1), were obtained from commercial sources. After the media was washed from the roots, the plants were repotted in 10-cm (500-cc) pots using a growing media comprised of peatmoss, pine bark, and perlite/vermiculite (2:1:1, v/v) (Fafard 3B; Fafard, Anderson, SC) and grown in a shade house for 8 weeks before acclimatization for 12 weeks under indoor conditions, 22 ± 1 °C, 50% relative humidity, and 5.45 μmol·m^{-2}·s^{-1} photosynthetically active radiation (*PAR*) (LI-COR LI-189 light meter with a line quantum sensor; LI-COR, Lincoln, NE). The plants were watered as needed during growth and acclimatization periods. At the end of the experiment, the leaf areas were determined using a LI-3100c leaf area meter (LI-COR) to allow expressing the removal efficiency on a leaf area basis.

Introduction of volatile organic compounds. Plants were placed in 10.5-L gas-tight glass jars (one plant/jar) with the lid fitted with welded stainless steel tubing inlet and outlet ports. To facilitate a uniform distribution of the gases in the jar, the inlet tubing extended downward within the jar following the contour of the side of the jar, three-fourths of the distance to the base. The lids were sealed using specially constructed 11.8 cm o.d. × 9.8 cm i.d.

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Table 1. Family, Latin binomial, common name, and leaf area of test plants exposed to five representative volatile organic compounds (benzene, toluene, octane, trichloroethylene, and α-pinene) over 6 h during the day.

No.	Family	Latin binomial	Common name	Leaf area (cm^2/plant)
1	Acanthaceae	*Fittonia argyroneura* Coem.	Silver-net leaf	660 ± 45
2	Acanthaceae	*Hemigraphis alternata* (Burm.f.) T. Anders 'Exotica'	Purple waffle	352 ± 37
3	Agavaceae	*Dracaena fragrans* (L.) Ker-Gawl.	Corn plant	712 ± 39
4	Agavaceae	*Sansevieria trifasciata* Prain	Snake plant	346 ± 51
5	Anthericaceae	*Chlorophytum comosum* (Thunb.) Jacq. 'Fire Flash'	Spider plant	574 ± 76
6	Araceae	*Anthurium andreanum* Linden	Flamingo flower	616 ± 76
7	Araceae	*Dieffenbachia seguine* (Jacq.) Schott[z]	Dumb cane	670 ± 52
8	Araceae	*Philodendron scandens* ssp. *oxycardium*	Heart leaf philodendron	1085 ± 28
9	Araceae	*Epipremnum aureum*[y]	Pothos	1201 ± 136
10	Araceae	*Spathiphyllum wallisii* Regal	Peace lily	598 ± 58
11	Araceae	*Syngonium podophyllum* Schott	Arrowhead vine	718 ± 54
12	Araliaceae	*Schefflera arboricola* (Hayata) Merr. 'Variegata'	Variegated schefflera	587 ± 56
13	Araliaceae	*Schefflera elegantissima* (Hort. Veitch ex Mast.) Lowry & Frodin[x]	False aralia	372 ± 68
14	Araliaceae	*Hedera helix* L.	English ivy	319 ± 20
15	Araliaceae	*Polyscias fruticosa* (L.) Harms	Ming aralia	477 ± 26
16	Asclepiadaceae	*Hoya carnosa* (L.f.) 'Variegata'	Variegated wax plant	452 ± 51
17	Bromeliaceae	*Guzmania* sp.	Guzmani bormeliad	535 ± 78
18	Commelinaceae	*Tradescantia pallida* (Rose) D.R. Hunt 'Purpurea'	Purple heart plant	253 ± 33
19	Euphorbiaceae	*Codiaeum variegatum* (L.) Blume	Croton	926 ± 48
20	Geraniaceae	*Pelargonium graveolens* L'Her. ex Ait.	Rose geranium	501 ± 79
21	Liliaceae	*Asparagus densiflorus* (Kunth) Jessop 'Sprengeri'	Asparagus fern	337 ± 9
22	Liliaceae	*Aspidistra elatior* Blume 'Milky Way'	Cast iron plant	1079 ± 192
23	Marantaceae	*Calathea roseopicta* (Linden) Regal	Peacock plant	650 ± 78
24	Marantaceae	*Maranta leuconeura* E. Morren	Prayer plant	574 ± 13
25	Moraceae	*Ficus benjamina* L.	Weeping fig	482 ± 36
26	Moraceae	*Ficus elastica* Roxb. Rubra	Red rubber tree	562 ± 34
27	Palmae	*Howea belmoreana* (C. Moore & F. Muell.) Becc.	Sentry palm	769 ± 108
28	Piperaceae	*Peperomia clusiifolia* (Jacq.) Hook. 'Variegata'	Variegated red-edged peperomia	935 ± 22

Data are means ± SEM (n = 3).
[z]Syn. *Diffenbachia amoena* Hort. and Bull.
[y]Syn. *Scindapsus aureus* Engl.
[x]Syn. *Dizygotheca elegantissima* (Veitch) R.Vig. and Guillaumin.

gaskets in which a 4.2-mm-thick EPDM rubber gasket was sealed within a Teflon envelope (Phelps Industrial Products, Elkridge, MD). The inlet port was connected to a charcoal filter [Pyrex glass tube (10 cm × 1 cm i.d.) with 2.5 g of charcoal (Alltech Assoc. Inc., Deerfield, IL)] such that purified air was introduced into the jar at 150 $ml \cdot min^{-1}$. The plants were placed in the jars 24 h before treatment and were maintained at ≈5.45 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PAR* during a light period (12 h). Just before the introduction of the VOCs, the inlet and outlet ports were closed using gas-tight Swagelok fittings (Georgia Valve & Fitting, Co., Alpharetta, GA). The exit port was configured with Swagelok fittings holding a gas-tight gas chromatography septum that was capped to prevent leakage. The cap was briefly removed when a gas sample was drawn for analysis. The individual plants were exposed to ≈10 ppm (31.9, 53.7, 37.7, 46.7, and 55.7 $mg \cdot m^{-3}$) of high-purity analytical-grade benzene, TCE, toluene, octane, and α-pinene (Table 2), respectively, in the gas-tight glass jars. Through preliminary tests, concentrations of 9.66 (30.9), 11.00 (59.1), 9.66 (36.4), 9.49 (44.3), and 9.82 (54.7) ppm ($mg \cdot m^{-3}$) of each compound were created by introducing 2.0, 2.7, 2.4, 4.0, and 4.0 μL of benzene, TCE, toluene, octane, and α-pinene, respectively, into the jar using a microsyringe (Agilent Technologies, Wilmington, DE) and calibrating the amount of each compound adsorbed onto the inner surface of the jar. A small 4 cm diameter 6-V DC brushless fan (RadioShack, Fort Worth, TX) was placed near the top of each jar to ensure adequate mixing of the volatiles. The gas concentration within the jar was determined after 3 and 6 h during the day. Three replications of each species were tested at a setting with a fourth jar used as a control without the potted plant to measure the concentration of airborne VOCs within the empty jar. Leak tests were carried out on the empty jar before every fourth experiment; no leakage was found during the 6-h test period.

Analysis of volatile organic compounds. Air samples (1.0 mL) within the glass containers were removed during the light period from the outlet port using a gas-tight syringe (Agilent Technologies) 3 and 6 h after exposure to the test VOCs and analyzed by capillary gas chromatography–mass spectroscopy (GC-MS) (6890N/5973; Agilent, Palo Alto, CA) equipped with a 30 m length (0.25 mm i.d., 0.25 μm film thickness of 5% phenyl methyl siloxane) capillary column (HP-5MS; Agilent). The injection port temperature was 225 °C and was operated in the splitless mode. Helium was used as the carrier gas at a flow rate of 1.8 $mL \cdot min^{-1}$. The column temperature was held at 36 °C for 0.5 min and then programmed at 10 °C/min to 90 °C and held for 1 min. Mass spectroscopy conditions were: ion source 230 °C; electron energy 70 eV; multiplier voltage 1247 V; GC-MS interface zone 280 °C; and a scan range of 35 to 350 mass units. For quantifying absolute concentrations of each compound, standard curves for each compound were determined using analytical standards. Solutions of 0.5, 1, 2, 5, 10, 20, 50, and 100 $\mu L \cdot L^{-1}$ in hexane of each compound were prepared. Each standard solution (1.0 μL, three replications) was injected directly into the GC-MS using a microsyringe. The concentration of VOCs removed by a plant was calculated as (Yoo et al., 2006):

$$\text{(A) VOC removal efficiency} = [C - (S - M)]/(L \times T) \quad [1]$$

$$\text{(B) Accumulated removal concentration of VOC} = [C - (S - M)]/L \quad [2]$$

where:

C = the concentration of VOC in the control jar ($\mu g \cdot m^{-3}$)
S = the concentration of VOC in the sample jar ($\mu g \cdot m^{-3}$)

Table 2. Accumulated removal concentration of volatile organic compounds (VOCs) by plastic pot (10 cm, 500 cc) containing soilless media without plant 3 h and 6 h after introduction of five representative VOCs [benzene, toluene, octane, trichloroethylene (TCE), and α-pinene].

	Accumulated removal concn by plastic pot containing media ($\mu g \cdot m^{-3}$)	
VOC	3 h	6 h
Benzene	0.34 ± 0.06	0.38 ± 0.05
Toluene	1.13 ± 0.06	1.21 ± 0.04
Octane	0.35 ± 0.08	0.47 ± 0.07
TCE	1.00 ± 0.17	1.10 ± 0.08
α-Pinene	1.03 ± 0.17	1.13 ± 0.07

Data are means ± SEM (n = 3).

M = the concentration of VOC in the jar containing only the plastic pot and media ($\mu g \cdot m^{-3}$) (Table 2)
L = total leaf area (m^2)
T = VOC exposure time (h)

Statistical analysis. Analysis of variance and Duncan's multiple range test were carried out by using the SAS system for Windows v8 (SAS Institute, Cary, NC).

Results and Discussion

The initial concentrations of benzene, toluene, octane, TCE, and α-pinene within the container were 9.66 ± 0.03 (30.9), 9.66 ± 0.07 (59.1), 9.49 ± 0.06 (36.4), 11.00 ± 0.07 (44.3), and 9.82 ± 0.20 (54.7) ppm ($mg \cdot m^{-3}$), respectively. The concentration of each VOC, after subtraction of the concentration of VOC in jars containing the pot and media without a plant (Table 2) from that in the sample jar with plant, decreased with exposure duration, indicating VOC removal by the plants (Fig. 1). Because the test plants varied in size and foliar surface area, the removal efficiency for each VOC was expressed on a leaf area basis to allow identification of species with superior removal efficiency. VOC removal represents the effect of the plant and subterranean micro-organisms associated with the plant in the potting media, the latter of which is known to be an important contributor (Wood et al., 2002).

The removal efficiency varied substantially among the species tested: benzene (0.03 to 5.54 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), toluene (1.54 to 9.63), octane (0 to 5.58), TCE (1.48 to 11.08), α-pinene (2.33 to 12.21), and total VOC (5.55 to 44.04) (Table 3). The results demonstrate the rate of removal varies depending on the VOC in question and the plant species present.

Benzene. Six species with superior benzene removal efficiency were identified: *Hemigraphis alternata* (5.54 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *Tradescantia pallida* (3.86), *Hedera helix* (3.63), *Fittonia argyroneura* (2.74), *Asparagus densiflorus* (2.65), and *Hoya carnosa* (2.21) (Table 3; Fig. 1A). *H. alternata* had the highest removal efficiency and the highest accumulated removal of benzene at 3 h and 6 h. At 3 h, five species classified as having high removal efficiency were not statistically significant in their accumulated removal concentrations; however, by 6 h, there were significant differences (Fig. 1A). *Sansevieria trifasciata* (1.76), *Ficus benjamina* (1.66), *Polyscias fruticosa* (1.53), *Guzmania* sp. (1.46), *Anthurium andreanum* (1.31), and *Peperomia clusiifolia* (1.20) were classified as having an intermediate benzene removal efficiency; the remainder had very low benzene removal efficiencies (Table 3).

Toluene. H. alternata had the highest toluene removal efficiency (9.63 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$) followed by *T. pallida* (9.10), *H. helix* (8.25), *A. densiflorus* (7.44), *H. carnosa* (5.81), *F. argyroneura* (5.09), and *F. benjamina* (5.06) (Table 3; Fig. 1B). The plants were much more effective in removing toluene than benzene, a finding corroborated by Yoo et al. (2006). The rate of toluene removal during the initial 3-h exposure was more rapid compared with the second 3 h of exposure. Toluene removal occurs through adsorption to the plant

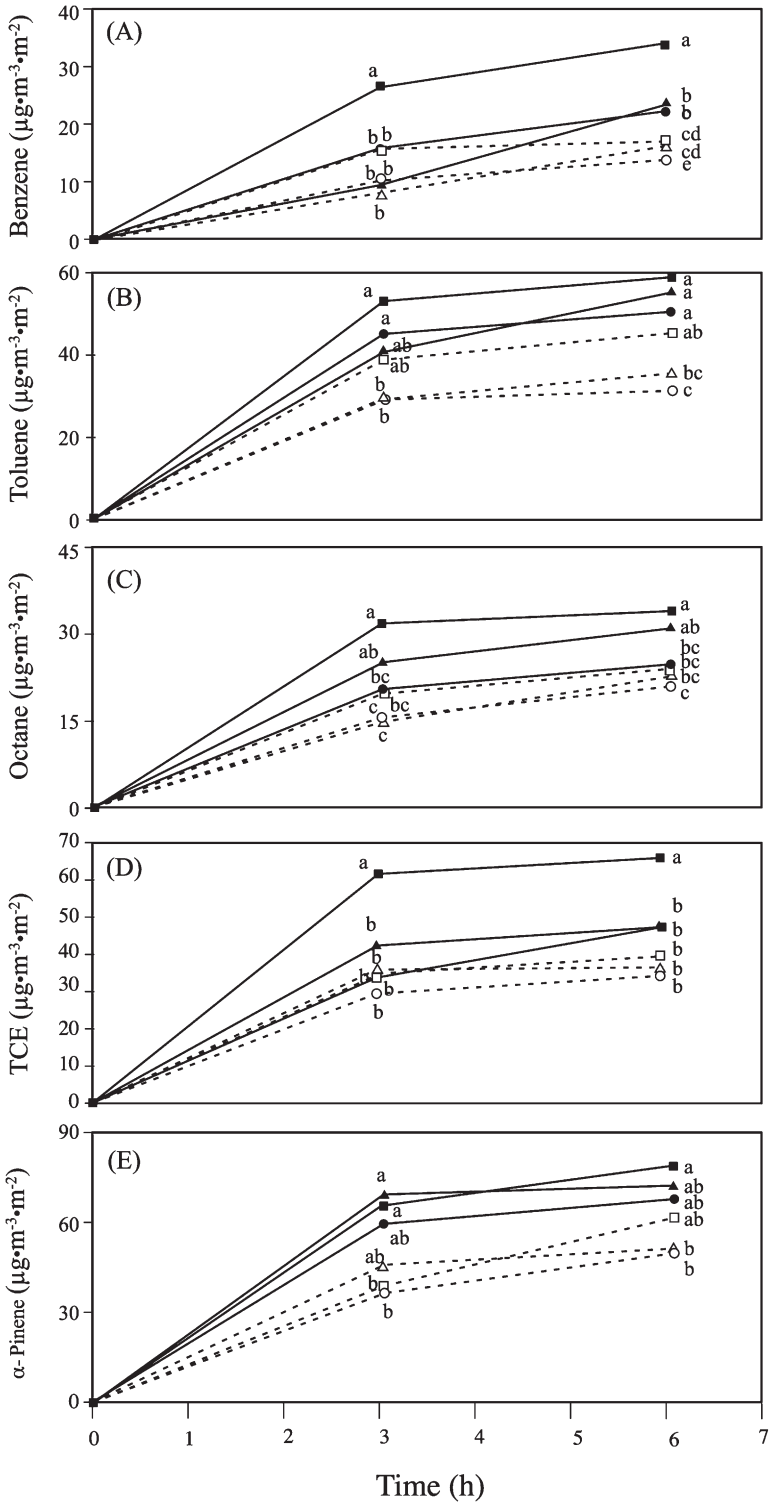

Fig. 1. Accumulated removal of (**A**) benzene, (**B**) toluene, (**C**) octane, (**D**) trichloroethylene, and (**E**) α-pinene by plants with superior volatile organic compound removal efficiency over 6 h during the day. Plots with different letters at the same time are significantly different by Duncan's multiple range test ($P < 0.05$). The solid squares, solid triangles, solid circles, open squares, open triangles, and open circles represent the following species in sequence: (**A**) *Hemigraphis alternata*, *Tradescantia pallida*, *Hedera helix*, *Fittonia argyroneura*, *Asparagus densiflorus*, and *Hoya carnosa*; (**B**) *H. alternata*, *T. pallida*, *H. helix*, *A. densiflorus*, *H. carnosa*, and *F. argyroneura*; (**C**) *H. alternata*, *H. helix*, *Ficus benjamina*, *H. carnosa*, *A. densiflorus*, and *Polyscias fruticosa*; (**D**) *H. alternata*, *H. helix*, *T. pallida*, *A. densiflorus*, *F. argyroneura*, and *H. carnosa*; and (**E**) *H. helix*, *H. alternata*, *A. densiflorus*, *T. pallida*, *F. benjamina*, and *H. carnosa*.

Table 3. Removal efficiency based on leaf area of five representative volatile organic compounds (VOCs) [benzene, toluene, octane, trichloroethylene (TCE), and α-pinene] of 28 indoor plants over 6 h during the day.

Plant	VOC removal efficiency ($\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$)					
	Benzene	Toluene	Octane	TCE	α-Pinene	Total
Superior removal efficiency						
Hemigraphis alternata	5.54 ± 0.29	9.63 ± 0.94	5.58 ± 0.68	11.08 ± 0.99	12.21 ± 1.61	44.04 ± 2.98
Hedera helix	3.63 ± 0.33	8.25 ± 0.64	5.10 ± 0.49	8.07 ± 0.77	13.28 ± 0.95	38.33 ± 3.17
Tradescantia pallida	3.86 ± 0.58	9.10 ± 1.17	2.76 ± 1.08	7.95 ± 1.20	10.45 ± 1.78	34.12 ± 5.52
Asparagus densiflorus	2.65 ± 0.24	7.44 ± 0.28	3.76 ± 0.64	6.69 ± 0.49	11.40 ± 0.78	31.94 ± 2.40
Hoya carnosa	2.21 ± 0.21	5.81 ± 0.67	3.80 ± 0.62	5.79 ± 0.75	8.48 ± 1.17	26.08 ± 3.40
Intermediate removal efficiency						
Ficus benjamina	1.66 ± 0.07	5.06 ± 0.19	3.98 ± 0.19	4.74 ± 0.15	8.68 ± 0.40	24.13 ± 0.86
Polyscias fruticosa	1.53 ± 0.08	4.29 ± 0.04	3.43 ± 0.08	3.98 ± 0.16	8.30 ± 0.12	21.53 ± 0.42
Fittonia argyroneura	2.74 ± 0.28	5.09 ± 0.23	1.77 ± 0.25	6.15 ± 0.36	4.30 ± 0.39	20.05 ± 1.46
Sansevieria trifasciata	1.76 ± 0.48	4.97 ± 0.70	2.73 ± 0.50	4.61 ± 0.81	5.49 ± 1.31	19.56 ± 3.68
Guzmania sp.	1.46 ± 0.25	4.04 ± 0.56	2.07 ± 0.24	4.01 ± 0.49	6.43 ± 0.55	18.01 ± 1.77
Anthurium andreanum	1.31 ± 0.12	3.60 ± 0.37	2.45 ± 0.24	3.58 ± 0.35	5.85 ± 0.54	16.78 ± 1.59
Schefflera elegantissima[z]	0.66 ± 0.19	4.94 ± 0.37	0.65 ± 0.46	3.87 ± 0.10	7.33 ± 0.36	17.46 ± 0.81
Poor removal efficiency						
Peperomia clusiifolia	1.20 ± 0.10	2.75 ± 0.11	2.03 ± 0.01	2.40 ± 0.13	4.61 ± 0.14	12.98 ± 0.39
Chlorophytum comosum	0.75 ± 0.11	3.18 ± 0.14	1.70 ± 0.08	2.86 ± 0.13	4.17 ± 0.21	12.66 ± 0.54
Howea belmoreana	0.80 ± 0.10	2.95 ± 0.32	1.81 ± 0.28	2.71 ± 0.28	4.25 ± 0.67	12.52 ± 1.64
Spathiphyllum wallisii	0.75 ± 0.11	2.52 ± 0.13	1.55 ± 0.21	2.25 ± 0.19	4.09 ± 0.21	11.15 ± 0.83
Schefflera arboricola	0.44 ± 0.07	2.25 ± 0.23	1.75 ± 0.13	1.78 ± 0.17	4.18 ± 0.34	10.40 ± 0.84
Codiaeum variegatum	0.89 ± 0.04	2.28 ± 0.08	1.21 ± 0.03	2.34 ± 0.10	3.61 ± 0.09	10.33 ± 0.31
Calathea roseopicta	0.94 ± 0.18	2.70 ± 0.38	0.83 ± 0.14	2.32 ± 0.40	3.25 ± 0.58	10.04 ± 1.62
Aspidistra elatior	0.53 ± 0.08	2.22 ± 0.24	1.22 ± 0.17	2.00 ± 0.20	3.17 ± 0.40	9.14 ± 1.06
Maranta leuconeura	0.74 ± 0.19	2.67 ± 0.28	0.51 ± 0.19	2.35 ± 0.40	2.76 ± 0.67	9.03 ± 1.68
Dracaena fragrans	0.55 ± 0.01	2.01 ± 0.08	1.18 ± 0.08	1.90 ± 0.09	3.31 ± 0.19	8.95 ± 0.44
Ficus elastica	0.38 ± 0.07	2.29 ± 0.11	1.20 ± 0.13	1.75 ± 0.19	2.66 ± 0.12	8.28 ± 0.56
Dieffenbachia seguine[y]	0.18 ± 0.04	2.03 ± 0.10	1.01 ± 0.10	1.83 ± 0.07	2.99 ± 0.20	8.05 ± 0.39
Philodendron scandens ssp. *oxycardium*	0.49 ± 0.08	1.80 ± 0.11	0.98 ± 0.06	1.66 ± 0.16	2.33 ± 0.12	7.26 ± 0.52
Syngonium podophyllum	0.03 ± 0.02	1.84 ± 0.15	0.76 ± 0.16	1.67 ± 0.22	2.75 ± 0.17	7.04 ± 0.70
Epipremnum aureum[x]	0.44 ± 0.05	1.54 ± 0.15	0.86 ± 0.09	1.52 ± 0.16	2.34 ± 0.21	6.71 ± 0.64
Pelargonium graveolens	0.03 ± 0.02	1.67 ± 0.29	0.00 ± 0.00	1.48 ± 0.44	2.37 ± 0.26	5.55 ± 0.99

Data are means ± SEM (n = 3).
[z]Syn. *Dizygotheca elegantissima* (Veitch) R.Vig. and Guillaumin.
[y]Syn. *Diffenbachia amoena* Hort. and Bull.
[x]Syn. *Scindapsus aureus* Engl. f.

surface and absorption through stomatal uptake; the removal rate depends on the number of stomata and the cuticular structure (Jen et al., 1995; Ugrekhelidze et al., 1997).

Octane. H. alternata had the highest octane removal efficiency (5.58 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$) followed by *H. helix* (5.10), *F. benjamina* (3.98), *H. carnosa* (3.80), *A. densiflorus* (3.76), and *P. fruticosa* (3.43) (Table 3; Fig. 1C). *Pelargonium graveolens* had no effect on octane concentration, whereas *Maranta leuconeura* (0.51 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *Schefflera elegantissima* (0.65), *Syngonium podophyllum* (0.76), *Calathea roseopicta* (0.83), and *Epipremnum aureum* (0.86) had very low octane removal efficiencies. The removal of octane, an aliphatic hydrocarbon, by indoor plants has not been reported; however, hexane, also an aliphatic hydrocarbon, was removed by *Dracaena deremensis* and *Spathiphyllum wallisii* (Wood et al., 2002).

Trichloroethylene. The six species that effectively removed toluene also had superior TCE removal efficiencies: *H. alternata* (11.08 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *H. helix* (8.07), *T. pallida* (7.95), *A. densiflorus* (6.69), *F. argyroneura* (6.15), and *H. carnosa* (5.79) (Table 3; Fig. 1D). Similar to toluene, the highest rate of TCE removal was during the initial 3 h, declining subsequently with the exception of *T. pallida* in which the rate remained fairly consistent. *Chlorophytum comosum,* which was previously reported to remove TCE (Cornejo et al., 1999), had an intermediate TCE removal efficiency (2.86 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$).

α-Pinene. H. helix had the highest α-pinene removal efficiency (13.28 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$) of the 28 species tested followed by *H. alternata* (12.21), *A. densiflorus* (11.40), *T. pallida* (10.45), *F. benjamina* (8.68), *H. carnosa* (8.48), and *P. fruticosa* (8.30) (Table 3; Fig. 1E).

Based on the total VOC removal efficiency, the plants were classified into superior, intermediate, and poor categories (Table 3). Five species (i.e., *H. alternata*, *H. helix, T. pallida, A. densiflorus,* and *H. carnosa*) with superior phytoremediation potential were identified. Their total VOC removal ranged from 26.08 to 44.04 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$ and they effectively removed each of the test compounds. In contrast, the total VOC removal efficiency of the six plants classified as having an intermediate phytoremediation potential ranged from 17.46 to 24.13 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$, whereas those with poor efficiencies ranged from 5.55 to 12.98 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$.

There were no discernible trends in VOC removal potential based on taxonomical relatedness. However, the Araceae family [e.g., *E. aureum* (6.71 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *S. podophyllum* (7.04), *P. scandens* ssp. *oxycardium* (7.26), *Dieffencachia seguine* (8.05), *S. wallisii* (11.15)] generally had poor phytoremediation potential, whereas representatives of the Araliaceae family had, in general, a far better removal potential [e.g., *H. helix* (38.33 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *P. fruticosa* (21.53), and *S. elegantissima* (17.46)].

The volatiles tested in this study are commonly found in buildings. They can adversely affect indoor air quality and have a potential to seriously compromise the health of exposed individuals (Mitchell et al., 2007; Suh et al., 2000; Zabiegała, 2006). Benzene and toluene are known to originate from petroleum-based indoor coatings, cleaning solutions, plastics, environmental tobacco smoke, and exterior exhaust fumes emanating into the building; octane from paint, adhesives, and building materials; TCE from tap water, cleaning agents, insecticides, and plastic products; and α-pinene from synthetic paints and odorants. Some of the common indoor VOCs are known carcinogens (Jones, 1999; Newman et al., 1997) and at sufficiently high concentrations, a number of VOCs are harmful to plants (Cape, 2003). Visible injury to plants in this study was not observed.

Although a diverse cross-section of plants was capable of removing the VOCs tested (Table 3), removal efficiency varied within a single species as a result of differences in the chemical properties of the individual compounds (e.g., polarity, vapor pressure, molecular weight, solubility, dissociation), an effect previously noted by Yoo et al. (2006). The fate of VOCs (e.g., accumulation,

adsorption, absorption, penetration, transportation, metabolism), therefore, depends on the chemical characteristics of each volatile (Cape, 2003; Deinum et al., 1995; Korte et al., 2000) and the physical and chemical characteristics of the plants. Lipophilic compounds more readily penetrate the cuticular surface of plants, expediting uptake in contrast to compounds that are largely restricted to stomatal penetration (Deinum et al., 1995; Schmitz et al., 2000). In addition, the ability to metabolize VOCs varies widely among species and volatiles (Beattie and Seibel, 2007; Cape, 2003; Deinum et al., 1995; Jen et al., 1995). Therefore, a better understanding of the basic physical and chemical factors modulating the phytoremediation processes in the most efficient species is needed.

Conclusions and Summary

Of the 28 species tested, *H. alternata*, *H. helix*, *H. carnosa*, and *A. densiflorus* had superior removal efficiencies for each of the test compounds (i.e., benzene, toluene, octane, TCE, and α-pinene). Likewise, *T. pallida* had superior removal efficiencies for four of the compounds (i.e., benzene, toluene, TCE, and α-pinene). *H. alternata*, in particular, had the highest removal efficiency for four of the compounds (benzene, toluene, octane, and TCE). Indoor plants are known to confer significant psychological and physical benefits to individuals living/working in environments where they are present [e.g., reduced stress, increased task performance, and decreased symptoms of ill health (Bringslimark et al., 2007; Son, 2004)]. Based on this and other studies, plants also have the potential to significantly improve the quality of indoor air. Their increased use in both "green" and traditional buildings could have a tremendous positive impact on the ornamental industry by increasing customer demand and volume of sales. Further studies focusing on screening additional plant species for superior VOC removal efficiencies are warranted.

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