Efficacy of Indoor Plants for the Removal of Single and Mixed Volatile Organic Pollutants and Physiological Effects of the Volatiles on the Plants

Mung Hwa Yoo, Youn Jung Kwon, and Ki-Cheol Son¹

Department of Environmental Science, Konkuk University, Seoul 143-701, Korea

Stanley J. Kays

Department of Horticulture, Plant Sciences Building, University of Georgia, Athens, GA 30602-7273

ADDITIONAL INDEX WORDS. benzene, toluene, volatile organic compounds, stress, injury, indoor pollutants, phytoremediation, detoxification

ABSTRACT. Foliage plants of *Hedera helix* L. (english ivy), *Spathiphyllum wallisii* Regal (peace lily), *Syngonium podophyllum* Schott. (nephthytis), and *Cissus rhombifolia* Vahl. (grape ivy) were evaluated for their ability to remove two indoor volatile organic air pollutants, benzene and toluene. Removal was monitored when the aerial portion of plants was exposed singly to $1 \mu\text{L}\cdot\text{L}^{-1}$ or to $0.5 \mu\text{L}\cdot\text{L}^{-1}$ of each gas in a closed environment over 6-hour periods during the day and the night. Selected physiological processes were assessed before and immediately after treatment to determine the effect of the gases on the plants. The effectiveness of plants in the removal of air pollutant(s) varied with species, time of day, and whether the gases were present singly or as a mixture. When exposed to a single gas, *S. wallisii*, *S. podophyllum*, and *H. helix* displayed higher removal efficiencies ($\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$ leaf area) of either gas than *C. rhombifolia* during the day. The efficiency of removal changed when both gases were present; *H. helix* was substantially more effective in the removal of either benzene or toluene than the other species, with the removal of toluene more than double that of benzene. When exposed singly, the removal of both compounds was generally higher during the day than during the night for all species; however, when present simultaneously, *H. helix* removal efficiency during the night was similar to the day indicating that stomatal diffusion for english ivy was not a major factor. The results indicated an interaction between gases in uptake by the plant, the presence of different avenues for uptake, and the response of a single gas was not necessarily indicative of the response when other gases are present. Changes in the rates of photosynthesis, stomatal conductance, and transpiration before and after exposure indicated that the volatiles adversely affected the plants and the effects were not consistent across species and gases. Deleterious effects of volatile pollutants on indoor plants may be critical in their efficacy in improving indoor air quality and warrant further study.

Over the past century the shift away from a largely agrarian existence has resulted in a population influx into urban areas (Molina and Molina, 2004) where inhabitants spend increasingly more time indoors and air quality is often inferior to that outside (Jenkins et al., 1992; Snyder, 1990). The increased energy efficiency of newer buildings, with substantially reduced air exchange rates, often results in an increase in the concentration of indoor air pollutants. Indoor air in cities has been reported to be as much as 100 times more polluted than that outdoors (Brown, 1997; Brown et al., 1994; Godish, 1995; Ingrosso, 2002; Yang et al., 2004).

Over 300 volatile organic compounds have been identified as indoor contaminants, in addition to dust and inorganic gases (American Conference of Government and Industrial Hygienists, 1995). For example, the average formaldehyde concentration in occupied energy efficient homes was found to range from 40 to $2900 \mu\text{L}\cdot\text{m}^{-3}$ (National Research Council Committee on Air Pollutants, 1981). Indoor air pollutants originate from both living and inanimate objects within the dwelling and in some cases, diffuse into the building from the exterior. Volatile organic pollutants emanate from carpet, wood panels, paint, occupants, pets, and other sources. Benzene and toluene, for example, are emitted from household and consumer products, such as newspapers,

scientific journals, schoolbooks, electric shavers, portable compact disc players, liquid waxes, and certain adhesives (Salthammer, 1999). Collectively pollutants result in a significant reduction in indoor air quality that can affect the health and well-being of those exposed (Assimakopoulos, 2004; Jones, 1999; Wolverton, 1986; Wood et al., 2002; Yang et al., 2004).

Deterioration of indoor air quality can result in “multiple chemical sensitivity,” “new house syndrome,” and “sick building syndrome” (Ando, 2002; Shinohara et al., 2004) and a cross-section of physical symptoms for those exposed (e.g., allergies, frequent fatigue, asthma, headache, a feeling of uneasiness) that negatively affect their “quality of life” (Hayashi et al., 2004; Ingrosso, 2002; Jones, 1999; Kostianen, 1995).

Technology for improving indoor air quality continues to improve (e.g., electronic filtering systems); however, technological advances are often expensive and not widely used. In some instances the solution only replaces one pollutant with another (Snyder, 1995; Wolverton, 1997). Biological methods for improving indoor air quality, such as use of plants, are increasingly being tested (Darlington et al., 2001; Darrall, 1989; Lohr and Pearson-Mims, 1996; Shemel, 1980; Wolverton, 1986; Wood et al., 2002). Plants are known to absorb air pollutants via their stomata during normal gas exchange. Several pollutants have been shown to be sequestered or degraded in situ or after transfer to other locations in the plant (Schmitz et al., 2000; Shemel, 1980; Son et al., 2000). Some air pollutants are also removed by absorption or adsorption to the plant surface, microorganisms, or soil particles (Orwell et al., 2004; Son et al., 2000; Wolverton, 1986; Wolverton and Wolverton, 1993; Wood et al., 2002).

Received for publication 1 Nov. 2005. Accepted for publication 1 May 2006. The authors would like to express their appreciation to the South Korean Ministry of Environment for funding the research through the “Eco-technopia 21 project” grant program.

¹Corresponding author. E-mail address: kcsn@konkuk.ac.kr

Several indoor plant species have been shown to remove gaseous benzene and toluene, two important indoor volatile pollutants (Ugrekheldidze et al., 1997; Wolverton et al., 1989; Wood et al., 2002). For example, *Spathiphyllum wallisii* Schott., *Dracaena deremensis* Engl. 'Janet Craig', and *Kalanchoe blossfeldiana* Poelln. effectively removed benzene while *Chrysanthemum lutescens* H. Wendl. and *Phoenix roebelenii* O'Brien readily removed toluene and xylene (Cornejo et al., 1999; Wolverton et al., 1989). *Howea forsteriana* (C. Moore & F. Muell.) Becc. was better than *S. wallisii* 'Petite' and *D. deremensis* 'Janet Craig' in the removal of *n*-hexane but not benzene (Wood et al., 2002); and the efficacy of *D. deremensis* 'Janet Craig' differed from that of *H. forsteriana* indicating individual species display different responses depending on the gas present. However, most studies assessed the removal of a single volatile organic compound, even though they are rarely found singly in the environment.

In addition to altering the concentration of volatile organic compounds, the plant may, in turn, be modulated by the gas, affecting a number of physiological responses. For example, the exposure of alfalfa (*Medicago sativa* L.) to 100 nL·L⁻¹ ozone (1 h) decreased photosynthesis; and a mixture of SO₂ and O₃ decreased photosynthesis more than when treated separately (Darrall, 1989). Since volatile organic compounds in indoor environments are a mixture of gases, assessment of the effect of plants on multiple gases and their physiological effect on the plants would be advantageous. We report the efficacy of four indoor plant species in the removal of benzene and toluene when treated separately and in combination. Physiological changes of the plants upon exposure were also assessed.

Material and Methods

PLANT MATERIAL. *Hedera helix*, *S. wallisii*, *S. podophyllum*, and *C. rhombifolia*, popular indoor plants, were obtained from a foliage plant grower in Gyeonggi province in Korea. Plants, individually planted in 18-cm-diameter pots containing a standard potting medium [Hydroball (6- to 9-mm-diameter circular clay pellets, volume 2160 cm³), Hanlim, Seoul, Korea] were acclimated in a shaded greenhouse (≈60% of the ambient light blocked) for >6 months. Acclimation conditions were: 100 ± 30 μmol·m⁻²·s⁻¹ photosynthetically active radiation (PAR); 25 ± 5 °C; and 50% ± 10% relative humidity (RH). The plants were watered as needed and fertilized every 2 weeks with 1000 mL/pot of a 0.2 g·L⁻¹ aqueous solution of Technigro (24N-3.1P-4.2K; SunGro Chemicals, Los Angeles). The age and leaf areas of the test plants are present in Table 1. Prior to gas exposure, the plants were further acclimated in a growth chamber (DF-95G-1485; Duri Science, Seoul, Korea) at 100 μmol·m⁻²·s⁻¹ PAR, 24 ± 1 °C, and 50% to 60% RH for 1 month. All plants were watered the day before the gas treatments.

GAS TREATMENTS AND SAMPLING. Individual plants were exposed to 1 μL·L⁻¹ of benzene or toluene or to a mixture of 0.5 μL·L⁻¹ each of benzene and toluene in a gas-tight chamber (0.55 m wide × 0.58 m long × 0.9 m high, 287.1 L) made of glass, stainless steel, and Teflon (sealant). Plants were placed in the chamber prior to introduction of the gas(es). The appropriate amount of benzene (vapor density in air = 2.8) and/or toluene (vapor density = 3.1) from premixed standard tanks (RiGAS, Seoul, Korea) was injected into the chamber. To minimize the effect of the pot, medium, and microorganisms present therein, the pot was enclosed within a Teflon bag with only the aerial plant parts exposed to the gas(es). Treatment durations were short enough to prevent

Table 1. Age and average leaf area of *Hedera helix*, *Cissus rhombifolia*, *Spathiphyllum wallisii*, and *Syngonium podophyllum*, test plants exposed to gaseous benzene, toluene, or benzene + toluene.

Plant species	Gas	Plant age (years)	Leaf area (cm ² /plant)
<i>H. helix</i>	Benzene	2	1736
	Toluene		1360
	Mixture		1352
<i>C. rhombifolia</i>	Benzene	2	3224
	Toluene		3328
	Mixture		3276
<i>S. wallisii</i>	Benzene	2	1522
	Toluene		1577
	Mixture		1705
<i>S. podophyllum</i>	Benzene	2	2100
	Toluene		1913
	Mixture		2625

a significant reduction in oxygen concentration in the root zone (tested previously).

To assess differences in the removal of the gas(es) between day and night periods, the gas concentration within the chamber was determined every 2 h for 6 h during day and night periods. Gas samples (0.5 mL) were removed from two locations in the chamber (toward the top and bottom) using gas-tight syringes (Hamilton Co., Reno, Nev.) and analyzed by capillary gas chromatography using a Shimadzu G-14 chromatograph (Shimadzu Corp., Seoul, Korea) containing a VB-624A 0.32 mm × 1.8 μm × 30 m column under the following conditions: oven temperature 100 °C; injector temperature 200 °C; detector temperature 270 °C; 2 mL·min⁻¹ N₂ flow rate. Data represent the mean of a sample taken at the top and bottom of the chamber at each measurement interval. To compensate for the loss of test gases within the chamber via adsorption, absorption, or leakage, the decline in concentration of the gases when present singly and in combination was monitored for each chamber (without plants) over a 24-h period. Appropriate corrections were made in the time course data when plants were included. In general, losses were very minor (i.e., <10% per day). All tests were replicated a minimum of three times.

To maintain constant conditions, the treatment chamber was placed in a controlled environment growth chamber. The interior of the chamber was maintained at 60% ± 5% RH using coiled stainless steel tubing within the chamber through which cold water was circulated from an external refrigeration system. Two small 10-cm-diameter internal fans, one each at the bottom and top, were used to facilitate air circulation and the uniformity of the gas concentration within the chamber.

MEASUREMENT OF PHYSIOLOGICAL RESPONSES. A portable Li-6400 photosynthetic analyzer (LI-COR, Lincoln, Nebr.) was used to ascertain changes in selected physiological processes before and after exposure to the gas(es) (e.g., rates of photosynthesis; respiration and transpiration; stomatal conductance; concentration of intercellular CO₂). Photosynthetic rate was measured at 24 ± 1 °C, 350 μL·L⁻¹ CO₂ and 100 μmol·m⁻² photosynthetic photon flux density (PPFD). Respiration was measured in the absence of light under the same conditions as the photosynthetic measurements. Measurements were for 5 min on each of five leaves per plant. Three replications per species were used for all tests.

DATA ANALYSIS. The internal concentration(s) determined by gas chromatography was corrected by compensating for the small amount of leakage from the chamber when empty. Gas concentrations were expressed as milligrams per cubic meter and the

data normalized to 24 ± 1 °C and 1 atmosphere pressure (Hines et al., 1993). To compensate for slight differences in initial gas concentrations among treatments, the initial concentration was normalized to 0 and the reduction in gas(es) within the chamber presented as a positive value. Individual data points represent the average of three replications with the standard error (SE) around the mean indicated. The amount of gas removed by an individual plant (A) and the rate of removal per unit area of leaf per hour (efficiency) (B) were calculated as follows:

$$(A) \quad (\text{mg} \cdot \text{m}^{-3} \cdot \text{cm}^{-2} \text{ leaf area}) = (P \times F \times CV)/L \quad [1]$$

$$(B) \quad (\text{mg} \cdot \text{m}^{-3} \cdot \text{h}^{-1} \cdot \text{cm}^{-2} \text{ leaf area}) = (P \times F \times CV)/(L \times T) \quad [2]$$

where:

P = the concentration of gas removed by the foliage ($\mu\text{L} \cdot \text{L}^{-1}$);
F = the extinction coefficient for the conversion from gas volume to mass;

CV = the volume of the chamber (L);

L = total leaf area (cm^2);

T = time exposed to the air pollutant(s) (h).

Data were analyzed by analysis of variance using standard statistical software (SAS Institute, Cary, N.C.) with the means separated using Duncan's test. Statistical differences in selected physiological responses before and after gas treatment were determined using a paired *t* test.

Results and Discussion

The removal of each gaseous pollutant by the plants varied depending upon the chemical, the plant species and whether it was during the day or night (Fig. 1–4). Although the species differed in their ability to remove benzene or toluene depending on whether it was day or night, each of the species was able to remove both chemicals.

When plants were exposed to a single gas, *S. wallisii*, *S. podophyllum*, and *H. helix* removed more than *C. rhombifolia* (Figs. 1–4). In contrast to *H. helix*, the three other species were more effective in removing gaseous pollutants during the day than the night. When exposed to the mixture of benzene and toluene, however, *H. helix* removed the largest amount of each of the gases during both the day and night periods; the other species were similar to each other in their ability to remove the volatiles (Figs. 1–4).

When the plants were exposed to both gases simultaneously, all four species showed a similar ability to remove benzene regardless of the time of day or night. In contrast, with the exception of *H. helix*, each of the species removed more toluene during the day than the night (Figs. 1–4). *H. helix* was equally effective in removing each gas when applied simultaneously whether during the day or the night (Fig. 4).

The efficiency of each species in the removal of benzene and toluene was determined by expressing the amount of gas ($\text{ng} \cdot \text{m}^{-3}$) removed per hour per unit leaf surface area (cm^2) (Table 2). When exposed only to benzene, *S. wallisii* had the highest removal efficiency ($174.5 \text{ ng} \cdot \text{m}^{-3} \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$); *S. podophyllum* and *H. helix* were similar to each other but less than *S. wallisii*; *C. rhombifolia* displayed the lowest efficiency of the four species ($50.3 \text{ ng} \cdot \text{m}^{-3} \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$). When the removal of toluene ($1 \mu\text{L} \cdot \text{L}^{-1}$) was assessed, *H. helix*, *S. podophyllum*, and *S. wallisii* were not significantly different from each other but were more ef-

Fig. 1. Accumulated removal of benzene and toluene by the above ground plant parts of *Spathiphyllum wallisii* over 6 h during the day (O) and night (●) when applied individually or together: (A) removal of benzene ($\mu\text{L} \cdot \text{L}^{-1}$); (B) removal of toluene ($1 \mu\text{L} \cdot \text{L}^{-1}$); (C) removal of benzene when exposed to benzene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$) and toluene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$); and (D) removal of toluene when exposed to benzene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$) and toluene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$). Vertical bars denote the SE.

Fig. 2. Accumulated removal of benzene and toluene by the above ground plant parts of *Cissus rhombifolia* over 6 h during the day (O) and night (●) when applied individually or together: (A) removal of benzene ($\mu\text{L} \cdot \text{L}^{-1}$); (B) removal of toluene ($1 \mu\text{L} \cdot \text{L}^{-1}$); (C) removal of benzene when exposed to benzene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$) and toluene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$); and (D) removal of toluene when exposed to benzene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$) and toluene ($0.5 \mu\text{L} \cdot \text{L}^{-1}$). Vertical bars denote the SE.

Fig. 3. Accumulated removal of benzene and toluene by the above ground plant parts of *Syngonium podophyllum* over 6 h during the day (O) and night (●) when applied individually or together: (A) removal of benzene ($1 \mu\text{L}\cdot\text{L}^{-1}$); (B) removal of toluene ($1 \mu\text{L}\cdot\text{L}^{-1}$); (C) removal of benzene when exposed to benzene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) and toluene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$); and (D) removal of toluene when exposed to benzene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) and toluene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$). Vertical bars denote the SE.

Fig. 4. Accumulated removal of benzene and toluene by the above ground plant parts of *Hedera helix* over 6 h during the day (O) and night (●) when applied individually or together: (A) removal of benzene (1 ppm); (B) removal of toluene ($1 \mu\text{L}\cdot\text{L}^{-1}$); (C) removal of benzene when exposed to benzene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) and toluene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$); and (D) removal of toluene when exposed to benzene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) and toluene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$). Vertical bars denote the SE.

Table 2. Comparison of the efficiency of the above ground plant parts of *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Cissus rhombifolia*, and *Hedera helix* in the removal of $1 \mu\text{L}\cdot\text{L}^{-1}$ of gaseous benzene ($3.21 \text{ mg}\cdot\text{m}^{-3}$) in a closed environment.

Species	Apparent removal efficiency of benzene ($\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$ leaf area)	
	Day	Night
<i>S. wallisii</i>	174.5 ± 3.8^z a	129.4 ± 39.5 a ^y
<i>S. podophyllum</i>	103.4 ± 6.9 b	67.6 ± 17.2 ab
<i>C. rhombifolia</i>	50.3 ± 7.0 c	26.6 ± 8.0 b
<i>H. helix</i>	102.8 ± 8.3 b	134.5 ± 13.7 a
Significance	***	*

^zMean $\pm$ SE of three plants.

^yMean separation within columns by Duncan's multiple range test at $P = 0.05$.

*, *** Significant at $P < 0.05$ or < 0.001 , respectively.

efficient than *C. rhombifolia*, which had the lowest efficiency ($85.7 \text{ ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$) (Table 3).

The effectiveness of the species in reducing the respective volatile during the day when the gases were presented simultaneously differed from when the gases were presented singly. The efficiency of *H. helix* in the removal of benzene with toluene present was the highest of the four species tested ($57.5 \text{ ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$) (Table 4). Even though *S. wallisii* and *S. podophyllum* had higher efficiencies when benzene was presented singly, their efficiency in removing benzene when both gases were present was relatively low (i.e., *S. wallisii* 37.0 and *S. podophyllum* 28.1 $\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$).

The removal efficiency of toluene by *H. helix* was substantially greater than *S. wallisii* and *S. podophyllum* (Table 5). The results indicate the efficiency of removing one volatile organic compound may not be indicative of the response when more than one volatile is present. The efficacy of gas removal, therefore, varies with the volatile, plant species, and time of day as well as other factors.

In general, when the gas removal efficiencies of plants during the day were high, they were also relatively high during the night. Three of the species displayed higher efficiencies during the day than the night, however, *H. helix* was similar between the day and the night and in some instances, more efficient during the night (Tables 2–5).

To examine the effect of the gases on the plants, we measured changes in the rates of photosynthesis, respiration and transpiration, and stomatal conductance and the concentration of intercellular CO_2 before and after exposure. The deleterious effect of the gases was evident in stomatal conductance and in the rates of photosynthesis and transpiration which were lower in all four plant species after exposure (Table 6). The response was even more pronounced when toluene and benzene were presented simultaneously. The results indicate a significant negative effect of the gases, whether presented singly or together, in the basic physiological processes operative within the plants. Changes in the respiratory rate and concentration of intercellular CO_2 differed depending upon species and whether the gases were applied singly or together.

It is evident from differences in the amount of volatile organic compounds removed during the day vs. night that more than one mechanism is operative (Cornejo et al., 1999). Air pollutants can be removed by plants in several ways. They may be taken into the plant during normal gas exchange, predominately through the stomata, and sequestered and/or metabolized; when this avenue is operative, the rate of removal declines appreciably during the dark

Table 3. Comparison of the efficiency of the above ground plant parts of *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Cissus rhombifolia*, and *Hedera helix* in the removal of $1 \mu\text{L}\cdot\text{L}^{-1}$ of gaseous toluene ($3.79 \text{ mg}\cdot\text{m}^{-3}$) in a closed environment.

Species	Apparent removal efficiency of toluene ($\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$ leaf area)	
	Day	Night
<i>S. wallisii</i>	$203.7 \pm 24.3^z \text{ a}^y$	128.9 ± 12.2
<i>S. podophyllum</i>	$161.6 \pm 19.2 \text{ a}$	60.2 ± 8.3
<i>C. rhombifolia</i>	$85.8 \pm 6.0 \text{ b}$	57.8 ± 15.1
<i>H. helix</i>	$220.2 \pm 31.8 \text{ a}$	142.1 ± 41.5
Significance	*	NS

^zMean $\pm$ SE of three plants.

^yMean separation within columns by Duncan's multiple range test at $P = 0.05$.

NS, *Nonsignificant or significant at $P < 0.05$, respectively.

Table 4. Comparison of the efficiency of the above ground plant parts of *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Cissus rhombifolia*, and *Hedera helix* in the removal of gaseous benzene when exposed to $0.5 \mu\text{L}\cdot\text{L}^{-1}$ of both gaseous benzene and toluene in a closed environment.

Species	Apparent removal efficiency of benzene ($\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$ leaf area)	
	Day	Night
<i>S. wallisii</i>	37.0 ± 10.0^z	30.4 ± 10.1
<i>S. podophyllum</i>	28.2 ± 5.2	18.8 ± 8.5
<i>C. rhombifolia</i>	33.0 ± 5.7	28.0 ± 4.2
<i>H. helix</i>	57.5 ± 4.6	50.6 ± 12.9
Significance	NS	NS

^zMean $\pm$ SE of three plants.

^yMean separation within columns by Duncan's multiple range test at $P = 0.05$.

NS Nonsignificant.

period when the stomata are closed. Volatiles may also undergo adsorption to plant surfaces (e.g., leaves, stems, flowers, fruits), absorption to the growing medium and water molecules, and degradation by microorganisms in the root zone (Orwell et al., 2004; Son et al., 2000; Wolverton and Wolverton, 1993; Wood et al., 2002), the latter of which are extremely important in the removal of volatile air pollutants. By isolating the root system in this study, however, we focused on the role of above ground plant parts in the removal of benzene and toluene. Therefore, uptake with sequestering and/or metabolism of the molecules and adsorption of the gas molecules to the aerial plant surface were the primary mechanisms operative.

Much of the work published on the removal of volatile pollutants by plants has viewed stomatal entry as the primary avenue for absorption (Darrall, 1989; Wolverton, 1986; Wolverton et al., 1989). For example, the uptake of ozone is reduced by elevated CO_2 due to its effect on stomatal aperture (Fiscus et al., 1997). When day time removal rates are substantially higher than night (stomata closed), stomatal uptake of the gas(es) would appear to be a major avenue, the assumption being that the rate of adsorption is similar between the day and night. In general, we found the removal of benzene and toluene during the day was significantly higher than during the night, pointing toward the importance of a stomatal entry. However, if stomatal access is rate limiting for benzene and toluene removal, then the removal efficiency for each volatile should be fairly closely related to day time stomatal conductance. This was not the case. While the average stomatal conductance of *S. podophyllum* ($0.0243 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was equal

Table 5. Comparison of the efficiency of the above ground plant parts of *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Cissus rhombifolia*, and *Hedera helix* in the removal of gaseous toluene when exposed to $0.5 \mu\text{L}\cdot\text{L}^{-1}$ of both gaseous benzene and toluene in a closed environment.

Species	Apparent removal efficiency of toluene ($\text{ng}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$ leaf area)	
	Day	Night
<i>S. wallisii</i>	$61.2 \pm 6.3^z \text{ b}^y$	27.1 ± 3.9
<i>S. podophyllum</i>	$61.5 \pm 11.3 \text{ b}$	33.5 ± 28.0
<i>C. rhombifolia</i>	$77.4 \pm 17.1 \text{ ab}$	44.3 ± 14.2
<i>H. helix</i>	$112.2 \pm 4.1 \text{ a}$	86.6 ± 35.2
Significance	*	NS

^zMean $\pm$ SE of three plants.

^yMean separation within columns by Duncan's multiple range test at $P = 0.05$.

NS, **Nonsignificant or significant at $P < 0.05$, respectively.

to *C. rhombifolia*, both were higher than *H. helix* (0.0163) and substantially higher than *S. wallisii* (0.0140). The relationship between the removal efficiency for each volatile was not consistent with stomatal conductivity (Tables 2 and 6). Therefore, stomatal conductivity does not appear to be rate limiting in the removal of benzene and toluene in the species tested. This finding is supported by data of Cornejo et al. (1999) in which stomatal density (stomata/ cm^2) and stomata area per unit leaf mass ($\text{cm}^2\cdot\text{g}^{-1}$) of *Chlorophytum comosum* L., *Pelargonium xdomesticum* L.H. Bailey, *Ficus elastica* Roxb., and *K. blossfeldiana* were not directly related to the removal efficiency of benzene or by ^{14}C -formaldehyde removal by leaves of *Epipremnum aureum* (Linden ex André) G.S. Bunting and *F. benjamin* L. (Schmitz et al., 2000).

The efficiency of removal when the plants were challenged with both benzene and toluene decreased, in contrast to exposure singly, suggesting that the gases had a synergistic deleterious effect on the stomata and/or sequestering or metabolism within the plant (Tables 2–5). An accentuated adverse effect is supported by the fact that key physiological processes were less affected by either gas presented singly than together (Table 6). Interestingly, *H. helix* displayed a similar or better efficiency during the night than the day. Degradation by microorganism in the rhizosphere has been considered the major avenue for night-time removal of pollutants; however, isolation of the rhizosphere in the current study has indicated the importance of other mechanisms. The efficiency was also higher when *H. helix* was exposed to the mixture compared to the gases singly even though the physiological activities decreased more than *S. podophyllum* (Tables 2–5). These results suggest that volatile removal by *H. helix* was achieved mainly by adhesion of the gaseous molecules or via processes other than stomatal uptake (e.g., cuticular absorption).

Previous work demonstrated that a number of species (i.e., *C. comosum*, *D. deremensis*, *D. marginata* Lam., *F. elastica*, *H. helix*, *K. blossfeldiana*, *P. xdomesticum*, and *S. wallisii*) were able to remove volatile benzene (Cornejo et al., 1999; Orwell et al., 2004; Wolverton et al., 1989; Wood et al., 2002). We found that *S. wallisii* also efficiently removed benzene, in addition to toluene, during the day when applied individually. Most of the species we tested were able to more effectively remove toluene than benzene when exposed to the gases simultaneously. The results differ markedly from those with *K. blossfeldiana* where benzene but not toluene was removed when both gases were applied simultaneously (Cornejo et al., 1999). It would appear, therefore, that the ability to remove a particular gas varies among plant species and the method of exposure (single vs. multiple

Table 6. Changes in selected physiological responses of *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Cissus rhombifolia*, and *Hedera helix* before and after exposure to gaseous benzene ($1 \mu\text{L}\cdot\text{L}^{-1}$), toluene ($1 \mu\text{L}\cdot\text{L}^{-1}$), or benzene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) + toluene ($0.5 \mu\text{L}\cdot\text{L}^{-1}$) in a closed environment.

Species	Gas		Photosynthetic rate ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Respiration rate ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Stomatal conductance ($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Intercellular CO_2 concn ($\mu\text{mol}\cdot\text{mol}^{-1}$)	Transpiration rate ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
<i>S. wallisii</i>	B ^z	before	1.57 ± 0.11	-0.16 ± 0.03	0.0156 ± 0.0014	174 ± 4	0.271 ± 0.032
		after	$0.87 \pm 0.10^*$	$-0.18 \pm 0.01^{\text{NS}}$	$0.0086 \pm 0.0009^*$	$171 \pm 15^{\text{NS}}$	$0.158 \pm 0.016^*$
	T	before	1.51 ± 0.11	-0.25 ± 0.03	0.0146 ± 0.0013	169 ± 6	0.259 ± 0.022
		after	$0.62 \pm 0.11^*$	$-0.21 \pm 0.02^*$	$0.0081 \pm 0.0009^*$	$225 \pm 10^*$	$0.140 \pm 0.016^*$
	B+T	before	1.40 ± 0.08	-0.26 ± 0.02	0.0119 ± 0.0007	148 ± 7	0.213 ± 0.016
		after	$0.51 \pm 0.08^*$	$-0.19 \pm 0.01^*$	$0.0048 \pm 0.0006^*$	$537 \pm 311^{\text{NS}}$	$0.090 \pm 0.013^*$
<i>S. podophyllum</i>	B	before	2.34 ± 0.09	-0.12 ± 0.01	0.0291 ± 0.0025	199 ± 8	0.417 ± 0.032
		after	$0.79 \pm 0.14^*$	$-0.23 \pm 0.02^*$	$0.0073 \pm 0.0017^*$	$127 \pm 22^*$	$0.101 \pm 0.021^*$
	T	before	1.93 ± 0.11	-0.29 ± 0.05	0.0213 ± 0.0015	189 ± 6	0.320 ± 0.019
		after	$0.96 \pm 0.14^*$	$-0.25 \pm 0.02^{\text{NS}}$	$0.0089 \pm 0.0017^*$	$151 \pm 10^*$	$0.127 \pm 0.021^*$
	B+T	before	2.00 ± 0.18	-0.12 ± 0.01	0.0224 ± 0.0026	173 ± 14	0.334 ± 0.035
		after	$0.48 \pm 0.06^*$	$-0.23 \pm 0.02^*$	$0.0041 \pm 0.0004^*$	$156 \pm 11^{\text{NS}}$	$0.070 \pm 0.007^*$
<i>C. rhombifolia</i>	B	before	1.83 ± 0.09	-0.28 ± 0.03	0.0226 ± 0.0019	201 ± 8	0.341 ± 0.029
		after	$1.15 \pm 0.14^*$	$-0.25 \pm 0.02^{\text{NS}}$	$0.0116 \pm 0.0018^*$	$167 \pm 8^*$	$0.200 \pm 0.030^*$
	T	before	1.61 ± 0.08	-0.26 ± 0.03	0.0191 ± 0.0011	203 ± 4	0.320 ± 0.022
		after	$0.95 \pm 0.08^*$	$-0.22 \pm 0.01^{\text{NS}}$	$0.0092 \pm 0.0007^*$	$175 \pm 6^*$	$0.160 \pm 0.012^*$
	B+T	before	1.95 ± 0.13	-0.32 ± 0.04	0.0312 ± 0.0052	214 ± 10	0.492 ± 0.069
		after	$0.94 \pm 0.19^*$	$-0.22 \pm 0.02^*$	$0.0099 \pm 0.0024^*$	$191 \pm 14^{\text{NS}}$	$0.165 \pm 0.036^*$
<i>H. helix</i>	B	before	1.87 ± 0.14	-0.24 ± 0.03	0.0203 ± 0.0021	180 ± 8	0.318 ± 0.033
		after	$1.37 \pm 0.17^*$	$-0.25 \pm 0.01^{\text{NS}}$	$0.0151 \pm 0.0024^{\text{NS}}$	$181 \pm 9^{\text{NS}}$	$0.236 \pm 0.035^{\text{NS}}$
	T	before	1.46 ± 0.11	-0.24 ± 0.01	0.0150 ± 0.0015	176 ± 8	0.230 ± 0.021
		after	$0.60 \pm 0.33^*$	$-0.23 \pm 0.01^{\text{NS}}$	$0.0082 \pm 0.0017^*$	$64 \pm 116^{\text{NS}}$	$0.147 \pm 0.029^*$
	B+T	before	1.37 ± 0.17	-0.28 ± 0.02	0.0135 ± 0.0023	157 ± 10	0.173 ± 0.026
		after	$0.49 \pm 0.17^*$	$-0.23 \pm 0.01^*$	$0.0058 \pm 0.0016^*$	$244 \pm 17^*$	$0.080 \pm 0.018^*$

^zB = benzene, T = toluene, B+T = mixture of benzene and toluene.

^{NS}, *Nonsignificant or significant at $P = 0.05$, respectively, by paired t test between before and after exposure of gas.

gases). Whether the differential in removal among pollutants is totally a function of their individual chemistries in relation to the plants or there is a synergism/antagonism among specific compounds that alters their interaction within the plant, is not currently known.

The decrease in photosynthesis in each of the species tested indicates a deleterious effect of the volatile(s) on the basic metabolism of the plant. Though during the relatively short-time interval tested there was not a decline in uptake, it is probable that extended exposure would result in a significant change, decreasing the plants effectiveness in the removal of undesirable volatiles. Currently little is known about possible transient recovery from pollution mediated damage to the plant or recovery mechanisms operative. Thus, the relationship between the ability to remove a volatile and undesirable physiological changes has not been adequately assessed and based on our results, warrants further study. In addition, a better understanding of the relative contribution of each avenue of removal for individual volatiles would be of considerable value in developing plant/media systems for maximizing phytoremediation of indoor air. In that indoor plants generally are present as a cross-section of species, the interrelationship among species with regard to phytomediation represents potentially an important topic for study.

Literature Cited

American Conference of Government and Industrial Hygienists. 1995. Threshold limit values for chemical substances and physical agents and biological exposure indices. ACGIH 1994-5. Amer. Conf. of Govt. and Industrial Hygienists, Cincinnati, Ohio.

Ando, M. 2002. Indoor air and human health. Sick-house syndrome and multiple chemical sensitivity. Kokuritsu Iyakuin Shokuhin Eisei Kenkyusho Hokoku 120:6-38.

Assimakopoulos, V.D. and C.G. Helmis. 2004. On the study of a sick building: The case of Athens air traffic control tower. Energy Buildings 36:15-22.

Brown, S. 1997. Volatile organic compounds in indoor air: Sources and control. Chem. Australia 64:10-13.

Brown, S.K., M.R. Sim, M.J. Abramson, and C.N. Gray. 1994. Concentrations of volatile organic compounds in indoor air—A review. Indoor Air 4(2):123-134.

Cornejo, J.J., F.G. Munoz, C.Y. Ma, and A.J. Stewart. 1999. Studies on the decontamination of air by plants. Ecotoxicology 8:311-320.

Darlington, A.B., J.F. Dat, and M.A. Dixon. 2001. The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. Environ. Sci. Technol. 35:240-246.

Darrall, N.M. 1989. The effect of air pollutants on physiological processes in plants. Plant Cell Environ. 12:1-30.

Fiscus, E.L., C.D. Reid, J.E. Miller, and A.S. Heagle. 1997. Elevated CO_2 reduces O_3 flux and O_3 -induced yield losses in soybeans: Possible implications for elevated CO_2 studies. J. Expt. Bot. 48:307-313.

Godish, T. 1995. Sick building: Definition, diagnosis, and mitigation. Lewis Publishers, Boca Raton, Fla.

Hayashi, H., N. Kunugita, K. Arashidani, H. Fujimaki, and M. Ichikawa. 2004. Long-term exposure to low levels of formaldehyde increases the number of tyrosine hydroxylase-immunopositive periglomerular cells in mouse main olfactory bulb. Brain Res. 1007:192-197.

Hines, A.L., T.K. Ghosh, S.K. Loylka, and R.C. Warder, Jr. 1993. Indoor air: Quality and control. Prentice Hall, Englewood Cliffs, N.J.

Ingrasso G. 2002. Free radical chemistry and its concern with indoor air quality: An open problem. Microchemistry J. 73:221-236.

Jenkins, P.L., T.J. Phillips, E.J. Mulberg, and S.P. Hui. 1992. Activity

- patterns of Californians: Use of and proximity to indoor pollutant sources. *Atmospheric Environ.* 26:2141–2148.
- Jones, A.P. 1999. Indoor air quality and health. *Atmospheric Environ.* 33:4535–4564.
- Kostiainen, R. 1995. Volatile organic compounds in the indoor air of normal and sick houses. *Atmospheric Environ.* 29:693–702.
- Lohr, V.I. and C.H. Pearson-Mims. 1996. Particulate matter accumulation on horizontal surfaces in interiors: Influence of foliage plants. *Atmospheric Environ.* 30:2565–2568.
- Molina, L.T. and M.J. Molina. 2004. Improving air quality in megacities: Mexico City case study. *Ann. New York Acad. Sci.* 1023:142–158.
- National Research Council Committee on Air Pollutants. 1981. Indoor pollutants. Nat. Acad. Press, Washington, D.C.
- Orwell, R.L., R.L. Wood, J. Tarran, F. Torpy, and M.D. Burchett. 2004. Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water Air Soil Pollution* 157:193–207.
- Salthammer, T. 1999. Organic indoor air pollutant: occurrence-measurement-evaluation. Wiley, New York.
- Schmitz, H., U. Hilgers, and M. Weidner. 2000. Assimilation and metabolism of formaldehyde by leaves appear unlikely to be of value for indoor air purification. *New Phytol.* 147:307–315.
- Shemel, G.A. 1980. Particle and gas deposition. *Atmospheric Environ.* 14:983–1011.
- Shinohara, N., A. Mizukoshi, and Y. Yanagisawa. 2004. Identification of responsible volatile chemicals that induce hypersensitive reactions to multiple chemical sensitivity patients. *J. Exposure Anal. Environ. Epidemiol.* 14:84–91.
- Snyder, S.D. 1990. Building interior, plants and automation. Prentice Hall, Englewood Cliffs, N.J.
- Snyder, S.D. 1995. Environmental interiorscape. Whitney Library of Design, New York.
- Son, K.C., S.H. Lee, S.G. Seo, and J.E. Song. 2000. Effects of foliage plants and potting soil on the absorption and adsorption of indoor air pollutants. *J. Korean Soc. Hort. Sci.* 41:305–310.
- Ugrekheldze, D., F. Korte, and G. Kvesitadze. 1997. Uptake and transformation of benzene and toluene by plant leaves. *Ecotoxicology Environ. Safety* 37:24–29.
- Wolverton, B.C. 1986. Houseplants, indoor air pollutants and allergic reactions, Natl. Space Technol. Laboratories, NASA, Stennis Space Ctr., Miss.
- Wolverton, B.C. 1997. How to grow fresh air: 50 house plants that purify your home or office. Penguin Books, East Rutherford, N.J.
- Wolverton, B.C., A. Johnson, and K. Bounds. 1989. Interior landscape plants for indoor air pollution abatement. Final Rpt., NASA, Stennis Space Center, Miss.
- Wolverton, B.C. and J.D. Wolverton. 1993. Plants and soil microorganism: Removal of formaldehyde, xylene, and ammonia from the indoor environment. *J. Mississippi Acad. Sci.* 38:11–15.
- Wood, R.A., R.L. Orwell, J. Tarran, F. Torpy, and M. Burchett. 2002. Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. *J. Hort. Sci. Biotechnol.* 77:120–129.
- Yang, X., J. Srebric, X. Li, and G. He. 2004. Performance of three air distribution systems in VOC removal from an area source. *Building Environ.* 39:1289–1299.