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Efficiency of Volatile Formaldehyde Removal by Indoor Plants: Contribution of Aerial Plant Parts versus the Root Zone

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Abstract. **The contribution of aerial plant parts versus the root zone to the removal of volatile formaldehyde by potted *Fatsia japonica* Decne. & Planch. and *Ficus benjamina* L. plants was assessed during the day and night. The removal capacity of the entire plant, aerial plant parts, and root zone was determined by exposing the relevant parts to gaseous formaldehyde (2 $\mu L \cdot L^{-1}$) in airtight chambers (1.0 m^3) constructed of inert materials. The rate of formaldehyde removal was initially rapid but decreased as the internal concentration diminished in the chamber. To compare the removal efficiency between species and plant parts, the time interval required to reach 50% of the initial concentration was determined (96 and 123 min for entire plants of *F. japonica* and *F. benjamina*, respectively). In both species, the aerial plant parts reduced the formaldehyde concentration during the day but removed little during the night. However, the root zone eliminated a substantial amount of formaldehyde during the day and night. The ratio of formaldehyde removal by aerial plant parts versus the root zone was similar for both species, at ≈1:1 during the day and 1:11 at night. The effectiveness of the root zone in formaldehyde removal was due primarily to microorganisms and roots (≈90%); only about 10% was due to adsorption by the growing medium. The results indicate that the root zone is a major contributor to the removal of formaldehyde. A better understanding of formaldehyde metabolism by root zone microflora should facilitate maximizing the phytoremediation efficiency of indoor plants.**

Formaldehyde and a cross-section of volatile organic compounds (VOC) are major contaminants in indoor air, a problem that is exacerbated by the decreased air exchange in newer, more tightly constructed buildings. It has been estimated that over 30% of office workers in Germany have suffered from sick building syndrome (Brasche et al., 1999), a now widely recognized health problem (Carpenter, 1998; Carrer et al., 1999). For example, formaldehyde is emitted from particle board, plywood, carpet, curtains, paper product, tobacco smoke, and certain adhesives (Salthammer, 1999; Spengler and Sexton, 1983). Deterioration of indoor air quality can result in ''multiple chemical sensitivity'' and ''sick building syndrome'' (Shinohara et al., 2004) and a cross-section of physical symptoms for those exposed (e.g., allergies, asthma, and headache) (Jones, 1999; Kostiainen, 1995). Formaldehyde emission in new houses is several times higher than that in older homes (Marco et al., 1995). Due to its undesirable effect on health, 0.17 $\mu L \cdot L^{-1}$ has been established as the upper limit allowed in the indoor air of new houses in Korea (Ministry of Environment, Republic of Korea, 2006).

Plants are known to absorb and metabolize gaseous formaldehyde. Formaldehyde enters plant leaves through stomata and the cuticle, and is more readily absorbed by the abaxial surface and by younger leaves (Giese et al., 1994; Ugrekhelidze et al., 1997). Once absorbed by leaves, it generally enters the Calvin cycle after a two-step enzymatic oxidation to CO_2 (Schmitz, 1995). About 60% to 90% of radioactivity applied as ^{14}C-formaldehyde was recovered from the plants (Giese et al., 1994; Schmitz, 1995). Formaldehyde was assimilated about five times faster in the light than in the dark (Schmitz, 1995). Some of the formaldehyde is converted to S-methylmethionine and is translocated in the phloem to various organs (e.g., seeds and roots) (Hanson and Roje, 2001). Benzene and toluene also enter the Calvin cycle after ring cleavage and are typically converted to organic and amino acids (Ugrekhelidze et al., 1997).

Certain microorganisms found in the growing media of indoor potted plants are also involved in the removal of airborne VOC, as illustrated by the fact that when the plant(s) are removed from the media, the VOC continue to decrease (Godish and Guindon, 1989; Wolverton et al., 1989; Wood et al., 2002). Likewise, plants held in the dark also remove VOC (Orwell et al., 2004; Wolverton et al., 1984; Yoo et al., 2006), and their removal ability is improved when the plants were continuously exposed to air containing VOC (Orwell et al., 2006; Wolverton et al., 1989). A number of soil microorganisms are capable of degrading toxic chemicals (Darlington et al., 2000; Wolverton et al., 1989), although many of the microbes that are directly associated with VOC removal have not been identified.

Plants excrete into the root zone significant amounts of carbon that stimulates the development of microorganisms in

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the rhizosphere (Kraffczyk et al., 1984; Schwab et al., 1998). The phyllosphere is also colonized by a diverse array of microorganisms (Mercier and Lindow, 2000). Kempeneer et al. (2004) reported that inoculation of the leaf surface with microorganisms increased the rate of removal of volatile toluene. Therefore, rhizospheric and phyllospheric microorganisms, as well as stomate-mediated absorption, provide a means of biofiltration of VOC from the indoor air. As a consequence, air phytoremediation using indoor plants is seen as a potentially viable means of removing air pollutants in homes and offices (Darlington et al., 1998; Giese et al., 1994; Kempeneer et al., 2004; Salt et al., 1998; Wolverton et al., 1989; Wood et al., 2002). Initial screening of indoor plants for phytoremediation efficiency requires comparison of the purification capacity among species. The half-life of a contaminant (time required for 50% removal) is an indicator of the purification capacity of the plant and allows comparison of efficiency among species under standardized conditions (Orwell et al., 2006; Oyabu et al., 2003).

Research on phytoremediation of indoor air initially focused on stomatal uptake; however, it has become apparent that the root zone is an important contributor to VOC removal. We assessed the relative contribution of the aerial plant parts versus the root zone to the removal of volatile formaldehyde by two indoor ornamental species.

Materials and Methods

Plant materials. Two-year-old *Ficus benjamina* and *Fatsia japonica* plants were transplanted to 19- and 15-cm-diameter pots, respectively. These species were selected because each has a single main stem that allowed easy separation of the base of the plant from the aerial portion; additionally, both are popular indoor plants in Korea. Table 1 lists the characteristics of the plants and pots for the two test species. The growing medium was composed of Mix #4 (Sun Gro Horticulture, Bellevue, WA), bark-humus (Biocom. Co., Seoul, Korea), and sand at 5:1:1 (v/v/v). Mix #4 contains Canadian sphagnum peatmoss (55%–65% by volume), perlite, dolomitic lime, gypsum, and a wetting agent. The plants were acclimated to the indoor environment used for the experiment for more than 1 month at 23 °C ± 2 °C, 40% ± 5% relative humidity, and a light intensity of 20 ± 2 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with 12/12-h (day/night) photoperiod. The plants were thoroughly watered every 3 d and the excess water was allowed to drain. All plants were watered the day before the gas treatments.

Three treatments were imposed on the plants, which were placed in sealed chambers for 5 h during the day or the night. To determinate the formaldehyde removal capacity of aerial plant parts, the belowground portion of the plant below the medium surface was sealed with a Teflon bag. To determine the contribution of the root zone, the portion of the plant above the medium was surgically removed. The formaldehyde removal capacity of the root zone was calculated by dividing the plant leaf area before decapitation to correct for differences in plant size. Intact plants were also tested. Three pots of each species with about the same leaf areas were placed in a chamber. Three replicates (chambers) of both species were tested for each treatment. They were first treated in the day and then in the night. Control chambers without plants were used to determine losses that were not caused by the plants (e.g., leakage, absorption, and chemical reactions). The height and leaf area (LI-3100 area meter; LI-COR, Lincoln, NE) of the plants were measured at the end of the experiment.

A second set of *F. japonica* and *F. benjamina* plants (three per chamber) was used to investigate formaldehyde removal by rhizosphere microorganisms in the growing medium. The aerial plant parts were decapitated at the surface of the medium and the pot was tested as such or after the microorganisms and roots were killed by thermal sterilization. The pots were autoclaved (HS-196; Hanshin Medical Co., Seoul, Korea) at 120 °C ± 2 °C and 0.13 MPa pressure for 30 min.

Treatment system. The treatment system consisted of controlled environment rooms, test chambers, and a gas generator. The three controlled environment rooms in which the test chambers were placed had the temperature, light intensity, and relative humidity set as previously described. The test chambers were made of VOC inert materials (i.e., glass surfaces, stainless steel frame, and Teflon) and the doors of chambers were sealed using adhesive foam-tape and adjustable metal clips. The volume of each chamber was 1.0 m^3 (90 cm wide × 90 cm long × 123 cm high), equal to about one-half the volume of a personal breathing zone. Using a sealed external pump, the air was circulated (6 $L \cdot min^{-1}$) and released at the bottom of the chamber through a stainless steel tube (0.64 cm i.d.) with holes. The concentration of formaldehyde was determined on samples collected at three heights within the chambers (i.e., 12, 70, and 98 cm from a bottom of the chamber).

Gas exposure and measurement. A gas generator converted a 35% formalin solution (Katayama Chemical Co., Hygro, Japan) to gaseous formaldehyde. The gaseous formaldehyde was collected in a sealed Teflon bag and 2.0 L was injected into the test chambers. To compensate for the differential in air pressure, 2.0 L air was removed from the chamber using a second air pump before gas injection. The injected formaldehyde gas was mixed for 30 min using the chamber air circulation system. The internal concentration was determined and adjusted as needed to ≈2.0 $\mu L \cdot L^{-1}$, a concentration that is ≈12 times higher than that allowed in new houses in Korea (i.e., 0.17 $\mu L \cdot L^{-1}$). There was a small amount of variation (e.g., 2.02–2.30 $\mu L \cdot L^{-1}$) in the initial concentration.

The concentration of formaldehyde in the gas phase was measured using a formaldehyde and data logging system (Z300-XP; Environmental Sensors Co., Boca Raton, FL) that was calibrated to a least detectable quantity of ≈0.01 $\mu L \cdot L^{-1}$. The instrument was connected to the sampling tube of a chamber, and after stabilization for 5 min, the concentration was determined every hour for 5 h during the day and the night. Control chambers were treated similarly to determine gas losses.

Data analysis. Gas concentrations were expressed as micrograms per cubic meter and the data were normalized to

Table 1. Characteristics of plants and pots used for *Fatsia japonica* and *Ficus benjamina* plants.

Species	Plant ht [mean ± se (cm)]	Leaf area [mean ± se (m^2/plant)]	Plant age [mean (yr)]	Pot diam [mean (cm)]	Medium vol [mean ± se (L/pot)]
F. japonica	41.7 ± 4.3	0.11 ± 0.03	2	15	1.6 ± 0.09
F. benjamina	55.6 ± 9.5	0.13 ± 0.02	2	19	1.9 ± 0.02

24 °C ± 1 °C and 1 atmosphere pressure (Hines et al., 1993; Yoo et al., 2006). Data were expressed as the average of three replicates with a standard error. The following formulas were used for a data analysis. The amount of formaldehyde removed per unit leaf area (A) (Yoo et al., 2006) and the percentage of formaldehyde remaining in the chamber (B) were calculated as follows:

$$(A)\ (\mu g \cdot m^{-3} \cdot cm^{-2}\ \text{leaf area}) = [(Pi - (Ci - C)) - P] \times (F \times CV)/L$$

$$(B)\ (\%) = (P \times F \times CV)/[(Pi - (Ci - C)) \times F \times CV] \times 100$$

where P equals the gas concentration measured in a chamber with plants ($\mu L \cdot L^{-1}$); Pi equals the initial gas concentration measured in a chamber with plants ($\mu L \cdot L^{-1}$); C equals the gas concentration measured in a chamber without plants ($\mu L \cdot L^{-1}$); Ci equals the initial gas concentration measured in a chamber without plants ($\mu L \cdot L^{-1}$); F equals a conversion factor from volume ($\mu L \cdot L^{-1}$) to mass ($mg \cdot m^{-3}$) of the gas; CV equals the volume of the chamber (m^3); and L equals total leaf area per chamber (cm^2).

As indicated in Table 1, the two species had almost the same leaf area. Therefore, formaldehyde remaining in the chamber (B) was calculated as a total leaf area per chamber without standardization. The time required to reach one-half of the initial concentration ($T_{50\%}$) was calculated from the standardization data. The loss of formaldehyde (Ci – C) not associated with the plant and medium was determined using empty chambers. Data were subjected to analysis of variance using standard statistical software (SAS Institute, Cary, NC) and Fisher's protected least significant difference at $\alpha = 0.05$.

Results and Discussion

Concentrations in control chambers (i.e., without plants) decreased by 7.3% during the day and 6.9% during the night for the 5 h after injection of the gas, apparently due to instability, adsorption on surfaces, or leakage. These losses are similar to those reported by Orwell et al. (2006) for several VOC.

The combined amount of removal measured separately by the aerial plant parts and by the root zone was slightly greater than that by the entire plant, indicating the probability of competition for gaseous formaldehyde between aerial plant parts and root zone as the concentration within the chambers was declining (Fig. 1). Removal of formaldehyde by the aerial plant parts was greater during the day than at night; the opposite was true for the root zone when formaldehyde removal is expressed on a leaf area basis (i.e., micrograms of formaldehyde removed per cubic meter of air per square centimeter of leaf area). In *F. japonica*, the aerial plant parts removed 0.01 $\mu g \cdot m^{-3} \cdot cm^{-2}$ and the root zone removed 0.53 $\mu g \cdot m^{-3} \cdot cm^{-2}$ of formaldehyde during the 5-h night period. The sum of two values was similar to the amount of formaldehyde removed by the entire plant (0.51 $\mu g \cdot m^{-3} \cdot cm^{-2}$). Similar removal rates were found for *F. benjamina*.

The amount of formaldehyde removed by the aerial plant parts during the day was substantially greater than in the night when the stomata were closed (Fig. 1). The aerial plant parts of *F. japonica* removed 0.50 $\mu g \cdot m^{-3} \cdot cm^{-2}$, whereas the root zone removed only 0.32 $\mu g \cdot m^{-3} \cdot cm^{-2}$ during the day. *Ficus benjamina* displayed a similar trend. The declining rate of formaldehyde removal with time appears to be due to the reduced concentration of the material available for metabolism. Intact plants removed ≈80% of the formaldehyde within 4 h, thus impeding the rate of subsequent removal. A similar removal pattern was reported by Orwell et al. (2006) for toluene and xylene.

The aerial plant parts had a significant impact during the day, whereas only a small effect during the night on the removal of

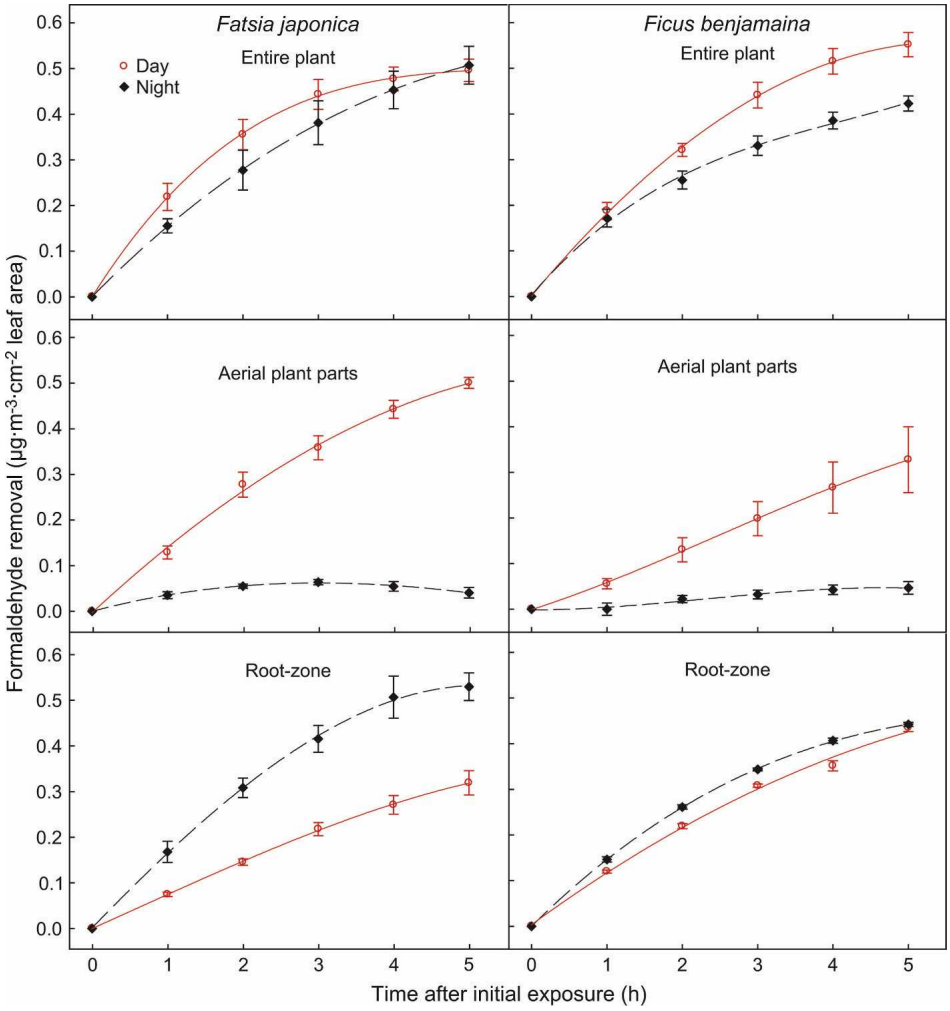

Fig. 1. Formaldehyde removal by potted *Fatsia japonica* and *Ficus benjamina* plants when exposed to formaldehyde gas (2 $\mu L \cdot L^{-1}$) for 5 h during the day (○) and night (◆): entire potted plant (top); aerial plant parts (middle); and the root-zone (bottom). Vertical bars denote the SE.

gaseous formaldehyde. The results indicate that stomatal uptake facilitates the removal of the formaldehyde that is metabolized in the leaves. Formaldehyde is thought to couple with nucleophiles, such as glutathione, to form *S*-hydroxymethylglutathione, which is subsequently converted to *S*-formylglutathione (Haslam et al., 2002). Absorption and metabolism of formaldehyde by the rhizosphere also appears to be operative.

The relatively small amount of formaldehyde removed by the aerial plant parts during the night when the stomata are closed may occur via cuticular absorption (Fig. 1). Previous work has indicated that the uptake of VOC is primarily by diffusion through the stomata in the light and through the cuticle in the dark (Giese et al., 1994; Jen et al., 1995; Schmitz et al., 2000; Ugrekhelidze et al., 1997).

When the aerial plant parts were removed, formaldehyde removal was greater during the night than during the day by *F. japonica* (Fig. 1). Removal by *F. benjamina* was nearly the same between the day and night, with the latter being only slightly greater. Similar results were reported by Godish and Guindon (1989); i.e., greater reductions of formaldehyde were observed when plants were defoliated first by 50% and then 100%. In addition, plants were known to excrete up to 45% of their net photosynthate, mainly translocated to roots during night, which nourishes specific rhizosphere microorganisms (Kraffczyk et al., 1984; Schwab et al., 1998). Thus, the higher removal during the night may be due to microbial utilization of formaldehyde as a carbon source in addition to root exudates. Collectively, the results indicate that microorganisms/roots in the rhizosphere are crucial contributors to the removal of formaldehyde, a phenomenon that has been demonstrated for several other VOC (Godish and Guindon, 1989; Orwell et al., 2004; Wolverton et al., 1984; 1989; Wood et al., 2002; Yoo et al., 2006).

The percentage of formaldehyde removed by the root zone of *F. japonica* and *F. benjamina* was 39% and 57% during the day and 98% and 94% during the night, respectively (Table 2). The ratio of formaldehyde removal by aerial plant parts versus the root zone was similar for both species, ≈1:1 during the day and 1:11 at night. The greater percentage of formaldehyde removal by the root zone of *F. benjamina* than that of *F. japonica* during the day may be because the former was planted in larger pots with a greater medium volume. Although some air pollutants are removed by absorption or adsorption to the growing medium and microorganisms (Orwell et al., 2004, 2006), removal effects of air pollutants due to the volume of growing media have not been reported. Thus, a more precise removal ratio needs to be determined for individual plant species growing in different sizes of pots.

Table 2. Comparison of the removal of gaseous formaldehyde (2 $\mu L \cdot L^{-1}$) between the aerial plant parts and root zone by *Fatsia japonica* and *Ficus benjamina* during the day and night.

	Removal ratio of formaldehyde [aerial plant parts:root zone (%)][z]	
Species	Day	Night
F. japonica	61 : 39	2 : 98
F. benjamina	43 : 57	6 : 94

[z]Based upon the amount of gaseous formaldehyde removed by aerial plant part (A) and root zone (R) measured after 5 h of the day and night (i.e., A or R/(A + R) × 100%). Removal by aerial plant parts was determined by sealing the root zone using a gas-impermeable plastic bag during the treatment period. Root zone measurements were made using pots with growing medium and root system immediately after the aerial plant parts were decapitated at the medium surface and removed.

With a removal ratio of ≈1:1 during the day between the aerial plant parts and the root zone, formaldehyde removal by the aerial plant parts must be substantially greater during the day than the night because the aerial plant parts accounted for very little removal during the night (Fig. 1). However, the actual differential in the amount of removal by the intact plant between the day and night was essentially the same in *F. benjamina* and nearly the same in *F. japonica* (Fig. 1). Previous reports (Godish and Guindon, 1989; Wood et al., 2002) have suggested that the aerial plant parts play only very minor role in formaldehyde metabolism because there was little difference between the day and night in removal. However, the aerial plant parts obviously removed formaldehyde during the day (Fig. 1 aerial plant parts) even though there is little difference between the day and night by the entire plant (Fig. 1, entire potted plant).

The fact that the formaldehyde removal by the aerial plant parts was less than 10% (2% in *F. japonica* and 10% in *F. benjamina*) during the night implies that most of the formaldehyde was removed by the root zone. Figure 2 illustrates the differences in formaldehyde removal by the root zone before and after the microorganisms and roots were killed by sterilization. Formaldehyde removal by the microorganisms and roots was ≈90% of the total; only about 10% of the total occurred after sterilizing. The microorganisms and roots accounted for the removal of about 0.27 $\mu g \cdot m^{-3} \cdot mL^{-1}$ of formaldehyde in both species. The sterilized pots removed only around 0.03 $\mu g \cdot m^{-3} \cdot mL^{-1,}$ and although only a minor contribution to the overall removal, it indicates that the medium has the potential to adsorb or absorb formaldehyde, as proposed by Wood et al. (2002). Therefore, the removal of formaldehyde during the night is due to biotic and abiotic factors (Fig. 2). The decline in gaseous formaldehyde mediated by *F. japonica* and *F. benjamina* plants was similar during the day and night (Fig. 3), although in both instances, the decline was greater during the day than the night.

The decline in gaseous formaldehyde tended to decrease with time. For example, during the day, 38.7% and 28.8% were

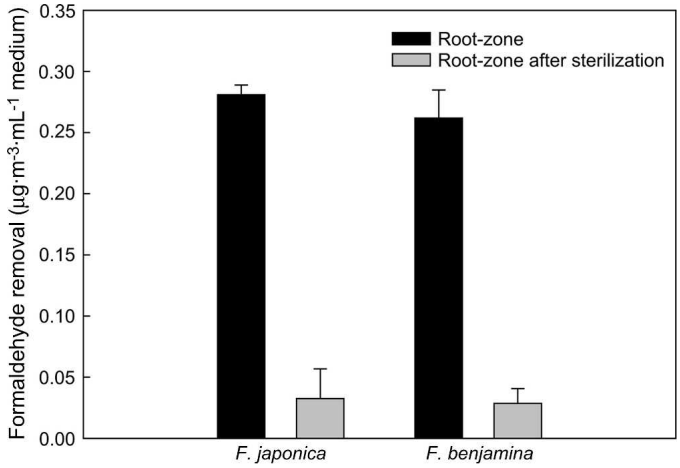

Fig. 2. Formaldehyde removal by the root zone of *Fatsia japonica* and *Ficus benjamina* after the aerial parts of the plants were decapitated at the medium surface, with and without sterilization. The initial concentration of gaseous formaldehyde was 2 $\mu L \cdot L^{-1}$ and the containers were exposed for 5 h in sealed chambers at a light intensity of 20 ± 2 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Vertical bars denote the SE.

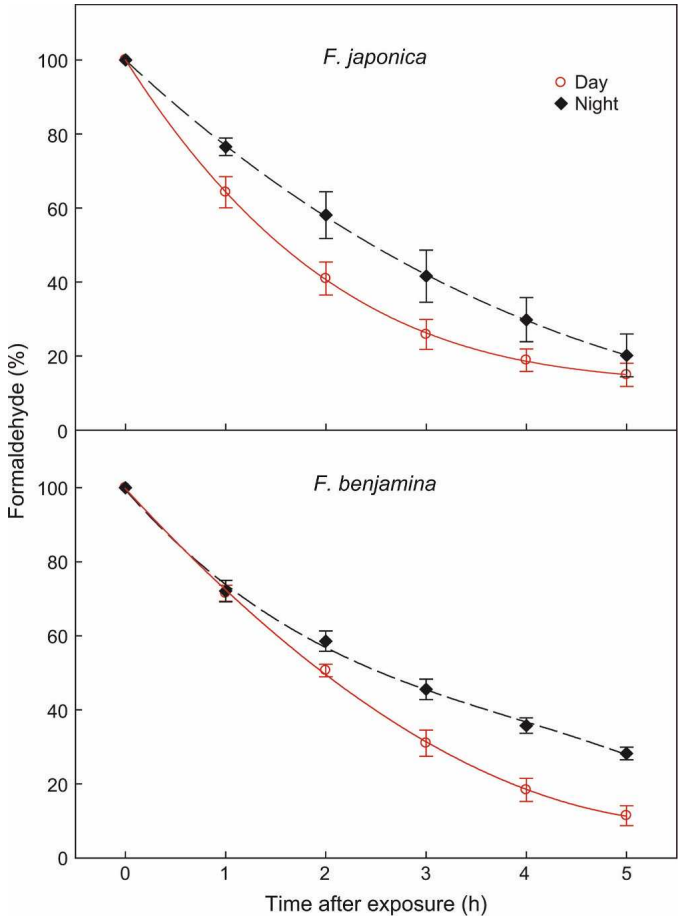

Fig. 3. Decline in gaseous formaldehyde, expressed as a percentage of initial concentration (2 μL·L^{-1}), caused by potted *Fatsia japonica* and *Ficus benjamina* plants in closed chambers (1.0 m^{-3}) for 5 h during the day (○) and night (◆). Vertical bars denote the SE.

removed at 0 to 1 h and 4.2% and 7.0% at 4 to 5 h in *F. japonica* and *F. benjamina*, respectively. In contrast, during the night, 25.6% and 28.1% were removed at 0 to 1 h and 10.4% and 7.5% at 4 to 5 h in *F. japonica* and *F. benjamina*, respectively. The declining rate appears to reflect the progressive decline in the concentration of the formaldehyde available to react. Similar results (i.e., initially rapid loss followed by a more gradually decline as the concentration decreased) have been demonstrated for other VOC (Kempeneer et al., 2004; Orwell et al., 2006; Oyabu et al., 2003; Wolverton et al., 1989) (Fig. 3).

To make comparisons among species, the time required to reach one-half ($T_{50\%}$) the initial concentration of gaseous formaldehyde was calculated (Table 3). $T_{50\%}$ for intact *F. japonica* plants was significantly different between the day and the night, although the formaldehyde removal with *F. japonica* plants was not different between the day and night at 5 h after exposure (Fig. 1). $T_{50\%}$ by *F. japonica* plants was reached faster than by *F. benjamina* plants except for the root zone during the day. As a result, potted *F. japonica* plants were more efficient than potted *F. benjamina* plants in the phytoremediation of formaldehyde.

The aerial plant parts and the root zone of potted *F. japonica* and *F. benjamina* plants effectively removed gaseous formaldehyde from the air. The aerial plant parts of the plants readily

Table 3. Effect of entire plants, aerial plant parts, and the root zone of *Fatsia japonica* and *Ficus benjamina* plants on the time required to reach one-half ($T_{50\%}$) of the initial concentration (2 μL·L^{-1}) in closed chambers. The $T_{50\%}$ (min) was calculated on the basis of a leaf area of 0.4 m^2.

		$T_{50\%}$ [mean ± SE (min)]	
Species	Plant part	Day	Night
F. japonica	Entire plant	96 ± 11[z]	150 ± 24
	Aerial plant parts[y]	149 ± 36	—[x]
	Root zone[w]	299 ± 18	117 ± 11
F. benjamina	Entire plant	123 ± 5	160 ± 13
	Aerial plant parts	296 ± 57	–
	Root zone	206 ± 16	174 ± 6

[z]Mean ± SE of three chambers with plants.
[y]Removal by aerial plant parts was determined by sealing the root zone using a gas-impermeable plastic bag during the treatment period.
[x]The $T_{50\%}$ did not reach one-half of the initial concentration for 5 h during the treatment period.
[w]Root zone measurements were made using pots with growing medium and root system immediately after the aerial plant parts were decapitated at the medium surface and removed.

metabolized formaldehyde during the day; the root zone was a major contributor to the removal, especially during the night when the stomata were closed. Removal by the root zone occurred largely via biotic means. Due to the importance of the root zone, a better understanding of the critical organisms and factors modulating their ability to metabolize gaseous formaldehyde would help in maximizing the phytoremediation potential of the two species.

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