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Variation in Formaldehyde Removal Efficiency among Indoor Plant Species

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Abstract. **The efficiency of volatile formaldehyde removal was assessed in 86 species of plants representing five general classes (ferns, woody foliage plants, herbaceous foliage plants, Korean native plants, and herbs). Phytoremediation potential was assessed by exposing the plants to gaseous formaldehyde (2.0 μL·L^{-1}) in airtight chambers (1.0 m^3) constructed of inert materials and measuring the rate of removal. *Osmunda japonica*, *Selaginella tamariscina*, *Davallia mariesii*, *Polypodium formosanum*, *Psidium guajava*, *Lavandula* spp., *Pteris dispar*, *Pteris multifida*, and *Pelargonium* spp. were the most effective species tested, removing more than 1.87 μg·m^{-3}·cm^{-2} over 5 h. Ferns had the highest formaldehyde removal efficiency of the classes of plants tested with *O. japonica* the most effective of the 86 species (i.e., 6.64 μg·m^{-3}·cm^{-2} leaf area over 5 h). The most effective species in individual classes were: ferns—*Osmunda japonica*, *Selaginella tamariscina*, and *Davallia mariesii*; woody foliage plants—*Psidium guajava*, *Rhapis excels*, and *Zamia pumila*; herbaceous foliage plants—*Chlorophytum bichetii*, *Dieffenbachia* 'Marianne', *Tillandsia cyanea*, and *Anthurium andraeanum*; Korean native plants—*Nandina domestica*; and herbs—*Lavandula* spp., *Pelargonium* spp., and *Rosmarinus officinalis*. The species were separated into three general groups based on their formaldehyde removal efficiency: excellent (greater than 1.2 μg·m^{-3} formaldehyde per cm^2 of leaf area over 5 h), intermediate (1.2 or less to 0.6), and poor (less than 0.6). Species classified as excellent are considered viable phytoremediation candidates for homes and offices where volatile formaldehyde is a concern.**

Formaldehyde is a major contaminant in indoor air that originates from particle board, plywood, carpet, curtain, paper products, tobacco smoke, certain adhesives, and other sources (Salthammer, 1999; Spengler and Sexton, 1983). Formaldehyde concentrations in new houses are often several times higher than that in older homes (Marco et al., 1995). Indoor volatile organic compounds (VOCs) such as formaldehyde can result in "multiple chemical sensitivity" and "sick building syndrome" (Shinohara et al., 2004) and several other physical symptoms for those exposed (e.g., allergies, asthma, headaches) (Jones, 1999; Kostiaineh, 1995). The World Health Organization estimates that undesirable indoor volatiles represent a serious health problem that is responsible for more than 1.6 million deaths per year and 2.7% of the global burden of disease (WHO, 2002). As a result of its undesirable effect on health, 0.1 μL·L^{-1} has been established as the upper limit for the concentration of formaldehyde 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. The volatile enters the leaves through stomata and the cuticle and is more readily absorbed by the abaxial surface and younger leaves (Giese et al., 1994; Ugrekhelidze et al., 1997). Once absorbed by the leaves, it generally enters the Calvin cycle after a two-step enzymatic oxidation to CO_2 (Schmitz, 1995). The amount of formaldehyde removed by indoor plants does not significantly increase with light intensities across the range commonly encountered within homes; however, there are considerable differences between light and dark conditions (Kil et al., 2008b). Approximately 60% to 90% of ^{14}C-formaldehyde was recovered from the plants (Giese et al., 1994; Schmitz, 1995) and it was assimilated approximately five times faster in the light than in the dark (Schmitz, 1995). Some of the formaldehyde is converted to S-methylmethionine and translocated in the phloem to various organs (e.g., seed, roots) (Hanson and Roje, 2001).

Assessing indoor plants for phytoremediation efficiency involves comparing the purification capacity among species under standard conditions. Comparing a cross-section of orchids, the formaldehyde removal efficiency of *Sedirea japonica* was the highest, whereas *Cymbidium* spp. was the lowest of the species tested (Kim and Lee, 2008). The half-life (time required for 50% removal) is considered a good indicator of the purification capacity of a plant and allows comparing the efficiency among species under standardized conditions (Kim et al., 2008; Orwell et al., 2006; Oyabu et al., 2003). Likewise, expression of VOC removal based on leaf area allows comparing plants of varying size (Kim and Kim, 2008) and is essential for determining the number of plants needed for specific indoor environments.

Certain microorganisms found in the growing media of indoor plants are also involved in the removal of VOCs as illustrated by the fact that when the plant(s) are removed from the media, the VOC concentration continues to decrease (Godish and Guindon, 1989; Wolverton et al., 1989; Wood et al., 2002). The root zone eliminates a substantial amount of formaldehyde during both the day and night. The ratio of removal by aerial plant parts versus the root-zone was ≈1:1 during the day and 1:11 at night (Kim et al., 2008). Likewise, the removal efficiency of the media increases (≈7% to 16%) with increased exposure frequency (Kil et al., 2008a) suggesting an apparent stimulation of the organism(s). A number of soil microorganisms are capable of degrading toxic chemicals (Darlington et al., 2000; Wolverton et al., 1989), although few of the microbes that are directly associated with formaldehyde removal has been identified.

Plants excrete into the root zone significant amounts of carbon that stimulate the development of microorganisms in 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). Therefore, rhizospheric and phyllospheric microorganisms as well as stomate-mediated absorption provide a means of biofiltration of VOCs from indoor air. As a consequence, phytoremediation of indoor air is seen as a potentially viable means of removing volatile pollutants in homes and offices (Darlington et al., 1998; Giese et al., 1994; Kempeneer et al., 2004; Kim et al., 2009; Salt et al., 1998; Wolverton et al., 1989; Wood et al., 2002). As a result of the importance of formaldehyde as an indoor air pollutant, we determined the formaldehyde removal efficiency of a diverse cross-section of indoor plants.

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Materials and Methods

Plant material. The experiments were conducted between 2004 and 2008 at the Rural Development Administration, Suwon, Korea. The characteristics of 86 test species, classified into five general categories, are presented in Table 1. All plants were transplanted into 19- or 15-cm-diameter pots containing a uniform growing medium 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 contained Canadian sphagnum peat moss (55% to 65% by volume), perlite, dolomitic lime, gypsum, and a wetting agent. The plants were acclimated within the indoor environment used for the experiments for greater than 1 month (23 ± 2 °C, 40% ± 5% relative humidity). The light conditions were tailored to the plant type. Woody and herbaceous foliage plants and ferns were acclimated at a light intensity of 20 ± 2 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and the herbs and Korea native plants at 60 ± 3 $\mu mol \cdot m^{-2} \cdot s^{-1}$; the photoperiod for all species was 12/12 h (day/night).

The plants were watered every 3 d with the excess water allowed to drain. All plants were watered the day before the gas treatments. One to four pots of each species were placed in a chamber. Three replicates (chambers) of every

Table 1. Indoor plant species tested and their height, leaf area, and fresh weight.

Group	Scientific name	Common name	Plant ht (cm/pot)	Leaf area (cm^2/pot)	Fresh wt (g/pot)
Woody foliage plants	*Araucaria heterophylla* Franco	Norfork island pine	50.1 ± 0.1	2190.7 ± 146.6	182.2 ± 2.0
	Cupressus macrocarpa Hartweg 'Gold Crest'	Monterey cypress	66.7 ± 3.1	1362.9 ± 156.2	145.7 ± 14.1
	Cycas revoluta Thunb.	Sago palm	51.2 ± 3.8	3677.4 ± 210.9	229.2 ± 63.2
	Dizygotheca elegantissima R. Vig. & G.	False aralia	33.7 ± 1.7	1024.0 ± 130.6	44.8 ± 2.6
	Dracaena concinna Kunth	Red margined dracaena	59.1 ± 1.8	2682.6 ± 101.0	185.8 ± 14.8
	Dracaena deremensis N.E. Br. 'Warneckii'	Striped dracaena	80.6 ± 2.1	5529.2 ± 1553.4	542.8 ± 78.6
	Dracaena fragrans Ker. 'Massangeana'	Corn plant	63.2 ± 4.3	4568.9 ± 885.7	232.9 ± 5.2
	Eugenia myrtifolia 'Compacta'	Australian Brush-cherry	63.1 ± 2.7	1801.0 ± 305.7	193.2 ± 28.4
	Ficus benjamina L.	Weeping fig	27.8 ± 1.1	3525.8 ± 272.9	277.9 ± 17.6
	Ficus elastica Roxb. ex Horne.	Rubber fig	88.3 ± 8.2	2069.7 ± 224.7	214.6 ± 5.0
	Gardenia jasminoides Ellis	Cape jasmine	28.5 ± 1.0	1176.1 ± 41.8	54.8 ± 4.8
	Hedera helix L.	English ivy	15.5 ± 0.2	855.2 ± 15.1	38.5 ± 1.7
	Hoya carnosa (L.f.) R.Br.	Porcelain flower	13.8 ± 0.4	1096.4 ± 111.3	181.8 ± 11.1
	Pachira aquatica Aubl.	Guiana chestnut	58.6 ± 4.2	4107.5 ± 691.1	212.7 ± 22.0
	Polyscias balfouriana Bailey	Balfour aralia	72.8 ± 5.9	1804.2 ± 262.9	83.5 ± 4.6
	Psidium guajava 'Safeda'	Guava	60.0 ± 0.0	2201.1 ± 100.0	195.0 ± 0.0
	Rhapis excelsa Wendl.	Lady palm	29.2 ± 1.1	733.5 ± 71.7	37.5 ± 3.1
	Schefflera arboricola Hayata 'Hong Kong'	Umbrella tree	87.7 ± 3.1	8495.5 ± 2014.2	1191.7 ± 135.4
	Serissa foetida (L.f.) Lam.	Japanese serissa	23.9 ± 1.9	182.9 ± 39.6	14.5 ± 1.4
	Zamia pumila L.	Jamaica sago tree	52.8 ± 2.9	908.0 ± 130.9	55.6 ± 4.6
Herbaceous foliage plants	*Aglaonema modestum*	Silver evergreen	25.4 ± 0.7	859.0 ± 136.4	70.4 ± 5.4
	Anthurium andraeanum Linden	Flamingo flower	40.5 ± 1.0	1117.6 ± 28.1	114.2 ± 10.1
	Asplenium nidus L. 'avis'	Bird's nest fern	30.3 ± 1.3	2504.7 ± 345.7	118.2 ± 11.0
	Calathea makoyana E.Morr.	Brain plant	27.3 ± 3.9	2514.5 ± 301.9	120.7 ± 15.2
	Chlorophytum bichetii Backer	St. Bernard lily	17.2 ± 0.3	953.1 ± 53.6	46.8 ± 1.3
	Chrysalidocarpus lutescens H. Wendl.	Areca palm	96.0 ± 12.7	7966.6 ± 1142.4	4747.5 ± 991.5
	Clivia miniata Regal	Kaffir lily	39.2 ± 0.3	2193.6 ± 384.1	273.5 ± 20.4
	Dieffenbachia amoena 'Marianne'	Giant dumbcane	44.0 ± 1.0	1323.8 ± 114.4	197.6 ± 16.4
	Epipremnum aureum Bunt.	Pothos	19.9 ± 0.7	2820.2 ± 342.6	233.5 ± 18.3
	Haemaria discolor Lindl.	Jewel orchid	17.0 ± 1.6	452.1 ± 2.1	53.1 ± 4.5
	Howea belmoreana Becc.	Belmore palm	68.3 ± 4.0	2028.1 ± 77.1	131.0 ± 7.0
	Peperomia clusiifolia Hook.	Red edge peperomia	21.8 ± 2.3	1213.8 ± 191.0	167.9 ± 23.0
	Philodendron selloum C. Koch.	Lace tree philodendron	35.0 ± 3.1	2069.7 ± 183.4	231.0 ± 11.8
	Phoenix roebelenii O'Brien.	Pigmy date palm	69.0 ± 8.8	4139.2 ± 195.8	304.3 ± 49.2
	Saintpaulia ionantha H. Wendl	African violet	7.5 ± 0.3	364.9 ± 21.0	58.4 ± 6.0
	Sansevieria trifasciata Prain	Snake plant	71.4 ± 10.6	2860.4 ± 224.7	554.5 ± 113.3
	Spathiphyllum wallisii Regel	Peace lily	67.8 ± 2.3	4891.7 ± 282.3	134.5 ± 8.1
	Syngonium podophyllum Schott	Arrowhead vine	31.7 ± 1.6	1807.9 ± 125.8	138.5 ± 7.0
	Tillandsia cyanea Linden ex C. Koch	Pink quill	13.4 ± 0.9	736.2 ± 27.9	106.5 ± 1.9
	Zamioculcas zamiifolia	Aroid palm	57.9 ± 2.9	4031.3 ± 225.4	681.7 ± 86.9
Korean native plants	*Ardisia crenata* Sims.	Coralberry	33.0 ± 2.1	918.3 ± 262.4	99.2 ± 20.5
	Ardisia pusilla DC.	Japanese ardisia	25.4 ± 0.4	503.7 ± 28.3	77.3 ± 3.2
	Camellia japonica L.	Common camellia	69.0 ± 1.3	3621.4 ± 110.4	235.0 ± 25.7
	Camellia sinensis Kuntze	Tea plant	38.2 ± 2.9	4325.5 ± 530.0	144.0 ± 15.5
	Chamaecyparis obtusa Endl.	Hinoki false cypress	64.1 ± 3.9	5969.4 ± 593.8	443.3 ± 66.7
	Dendropanax morbifera Nakai	Korean dendropanax	110.0 ± 0.0	3479.5 ± 100.0	246.0 ± 0.0
	Elaeocarpus sylvestris var. *ellipticus* Hara	—	77.2 ± 1.4	2637.4 ± 477.3	87.8 ± 11.3
	Eurya emarginata (Thunb.) Makino	—	114.3 ± 5.1	4769.0 ± 651.8	556.8 ± 76.8
	Fatsia japonica Decne. et Planch.	Japanese fatsia	53.0 ± 5.0	1427.7 ± 279.4	80.8 ± 3.8
	Ilex crenata Thunb.	Box leaved holly	61.5 ± 3.0	2247.3 ± 329.4	227.7 ± 7.4
	Laurus nobilis L.	Bay tree	41.0 ± 5.7	517.2 ± 153.3	32.7 ± 7.5
	Ligustrum japonicum Thunb.	Wax leaf privet	92.7 ± 14.2	6630.8 ± 936.0	597.3 ± 84.7
	Nandina domestica Thunb.	Heavenly bamboo	35.1 ± 1.4	843.2 ± 160.2	20.2 ± 2.6
	Pittosporum tobira Ait.	Japanese pittosporum	55.7 ± 7.5	4291.7 ± 1126.2	481.6 ± 168.0
	Quercus acuta Thunb.	Japanese evergreen oak	83.7 ± 1.2	6501.2 ± 1171.6	373.5 ± 12.7
	Quercus glauca Thunb.	Ring-cupped oak	64.7 ± 3.0	2431.8 ± 186.2	122.3 ± 6.8
	Rhaphiolepis umbellata Makino	Yeddo hawthorn	54.0 ± 4.0	4096.7 ± 691.9	490.8 ± 94.5
	Stauntonia hexaphylla (Thunb.) Dence.	Japanese staunton vine	156.0 ± 20.0	4797.3 ± 480.0	268.3 ± 4.0
	Trachelospermum asiaticum Nakai	Chinese ivy	149.8 ± 25.4	1597.1 ± 129.0	75.3 ± 6.2
	Viburnum awabuki K. Koch	Sweet viburnum	65.0 ± 10.6	4521.0 ± 1084.8	372.0 ± 186.7

(Continued on next page)

Table 1. (Continued) Indoor plant species tested and their height, leaf area, and fresh weight.

Group	Scientific name	Common name	Plant ht (cm/pot)	Leaf area (cm²/pot)	Fresh wt (g/pot)
Ferns	*Adiantum capillus-veneris*	Southern maiden hair	24.4 ± 1.9	811.4 ± 33.2	16.8 ± 8.4
	Arachniodes aristata (G. Forst.) Tindale	Pricky shield fern	31.9 ± 3.9	1551.8 ± 132.8	52.1 ± 6.0
	Botrychium ternatum (Thunb.) Swartz.	Hammock fern	16.7 ± 1.3	536.5 ± 336.1	13.0 ± 0.8
	Coniogramme japonica (Thunb.) Diels	Bamboo fern	19.1 ± 2.1	987.8 ± 42.7	24.3 ± 1.0
	Cyrtomium caryotideum Nakai 'coreanum'	—	20.3 ± 0.5	1997.2 ± 250.6	70.3 ± 8.6
	Cyrtomium falcatum (L.f.) Presl.	Holly fern	50.7 ± 6.7	1107.6 ± 69.2	102.3 ± 3.9
	Davallia mariesii Moore ex Baker	Hare's-foot fern	13.6 ± 2.3	148.9 ± 28.1	13.6 ± 2.3
	Dryopteris nipponensis Koidz.	—	16.9 ± 1.1	734.1 ± 41.8	18.6 ± 0.4
	Microlepia strigosa (Thunb.) Presl.	Lace fern	12.6 ± 0.1	452.9 ± 62.2	11.4 ± 1.2
	Osmunda japonica Thunb.	Japanese royal fern	9.7 ± 0.3	95.9 ± 14.7	1.7 ± 0.0
	Polypodium formosanum Baker	—	7.4 ± 0.5	154.9 ± 3.7	4.2 ± 0.2
	Polystichum tripteron (Kunze) Presl.	—	23.4 ± 0.8	825.8 ± 235.2	22.9 ± 0.8
	Pteris dispar Kunze.	—	11.4 ± 0.3	323.6 ± 10.5	11.4 ± 0.3
	Pteris ensiformis Burm. 'victoriae'	Silver leaf fern	17.8 ± 1.9	739.8 ± 32.3	18.7 ± 1.5
	Pteris multifida Poir.	Spider fern	34.7 ± 1.9	1338.9 ± 225.5	37.6 ± 6.2
	Selaginella tamariscina Spring	Spikemoss	7.9 ± 0.8	143.6 ± 21.2	8.1 ± 0.7
	Thelypteris acuminata (Houtt.) Morton	—	28.8 ± 1.2	1467.3 ± 436.4	30.9 ± 2.2
	Thelypteris decursive-pinnata Ching	—	33.8 ± 0.4	1662.6 ± 255.4	35.8 ± 2.7
	Thelypteris esquirolii K. Iwats. var. *glabrata*	—	23.1 ± 2.6	917.7 ± 217.5	17.3 ± 2.8
	Thelypteris torresiana K. Iwats. var. *calvata*	—	34.6 ± 1.7	1954.2 ± 681.6	46.7 ± 8.3
Herbs	*Jasminum polyanthum* Franchet	White jasmine	113.6 ± 6.6	2216.5 ± 343.9	101.7 ± 3.2
	Jasminum sambac (L.) Aiton	Arabian jasmine	22.1 ± 1.4	1206.6 ± 234.2	96.2 ± 4.8
	Lavandula spp.	Sweet lavender	17.4 ± 1.6	442.7 ± 28.8	149.8 ± 9.6
	Mentha suaveolens 'applemint'	Apple mint	18.9 ± 1.2	928.2 ± 30.5	30.8 ± 0.2
	Pelargonium spp.	Geranium	38.7 ± 3.6	820.1 ± 76.3	77.8 ± 7.0
	Rosmarinus officinalis L.	Rosemary	26.8 ± 1.0	678.7 ± 38.7	56.9 ± 7.1

Data are means ± SE (n = 9).

species were tested. Control chambers without plants were used to determine formaldehyde losses not resulting from the plants (e.g., leakage, adsorption, chemical reactions). Plant height and leaf area (LI-3100 area meter; LI-COR Inc., Lincoln, NE) were determined at the end of the experiment (Table 1).

Treatment system. The treatment system consisted of controlled environment rooms, test chambers, and a gas generator. The environment rooms in which the test chambers were placed controlled the temperature, light intensity, and relative humidity. The test chambers were made of inert materials (i.e., glass surfaces, stainless steel frame, and Teflon) that were impermeable to VOCs. The chamber doors were sealed using an adhesive foam tape and adjustable metal clips (Fig. 1). The volume of each chamber was 1.0 m³ (90 cm wide × 90 cm long × 123 cm high), equal to approximately half the volume of a personal breathing zone. Using a sealed external pump, the interior air was circulated (6 L·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).

Fig. 1. Schematic diagram of one of the test chambers that were made of inert materials (i.e., glass surfaces, stainless steel frame, and Teflon) that were impermeable to volatile organic compounds (VOCs). The chamber doors were sealed using an adhesive foam-tape and adjustable metal clips. The volume of each chamber was 1.0 m³ (90 cm wide × 90 cm long × 123 cm high). Using a sealed external pump, air was circulated (6 L·min⁻¹) and released at the bottom of the chamber through a perforated stainless steel tube (0.64 cm i.d.). Gas samples were collected at three heights within the chambers (i.e., 12, 70, and 98 cm from the bottom of the chamber).

Gas exposure and measurement. We developed a gas generator that converted a 35% formalin solution (Katayama Chemical Co., Hygro, Japan) to gaseous formaldehyde. The gaseous formaldehyde was generated as air passed through headspace. The gaseous formaldehyde was collected in a sealed Teflon bag and ≈2.0 L was introduced into each test chamber by a quantitative pump (MP-Σ; Sibata Co., Tokyo, Japan). To compensate for the differential in air pressure, 2.0 L of air was removed from the chamber using a second air pump before gas injection. The formaldehyde gas was mixed with the chamber atmosphere for 30 min using the chamber air circulation system. The internal concentration was determined and corrected to ≈2.0 μL·L⁻¹, a concentration that is ≈12 × higher than that allowed in new houses in Korea (i.e., 0.17 μL·L⁻¹). There was a small amount of variation (e.g., 2.02 to 2.30 μL·L⁻¹) in the initial concentration.

The concentration of formaldehyde in the gas phase was measured using a Formaldehyde & Data Logging System (Z300-XP; Environmental Sensors Co., Boca Raton, FL) that was calibrated to a least detectable quantity of ≈0.01 μL·L⁻¹. The instrument was connected to the chamber sampling tube and after stabilization for 5 min, the concentration was determined at every hour for 5 h during the test. Control chambers, devoid of plants, were treated similarly to determine gas losses. The plants were exposed to the light intensity used for acclimatization during the tests.

Data analysis. Gas concentrations were expressed as μg·m⁻³ and the data were normalized to 24 ± 1 °C and 100 kPa (Hines et al., 1993). Data were expressed as the average of three replicates. The amount of formaldehyde removed per unit leaf area was calculated (Kim et al., 2008; Kim and Kim, 2008) as:

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

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

The loss of formaldehyde (Ci – C) not resulting from the plant and media was determined using empty chambers. Data were subjected to analysis of variance using standard statistical software (SAS Institute Inc., Cary, NC) and Fisher's protected least significant difference ($\alpha \leq 0.05$).

Results and Discussion

Among the 86 species tested, nine (*Osmunda japonica*, *Selaginella tamariscina*, *Davallia mariesii*, *Polypodium formosanum*, *Psidium guajava*, *Lavandula* spp., *Pteris dispar*, *Pteris multifida*, and *Pelargonium* spp.) displayed excellent formaldehyde removal characteristics (e.g., 1.87 $\mu g \cdot m^{-3} \cdot cm^{-2}$ or greater leaf area over 5 h). In contrast, the average formaldehyde removal among all of the species tested was only 1.00 $\mu g \cdot m^{-3} \cdot cm^{-2}$ leaf area over 5 h or 0.20 $\mu g \cdot m^{-3} \cdot h^{-1} \cdot cm^{-2}$ (Fig. 2).

P. guajava, *Rhapis excelsa*, *Zamia pumila*, *Dizygotheca elegantissima*, *Ficus elastica*, and *Gardenia jasminoides* were among the most effective formaldehyde-removing woody foliage plants (Table 2). *P. guajava* was the highest, whereas *Dracaena deremensis* 'Warneckii' was the lowest in removal efficiency. *P. guajava* removed 2.39 $\mu g \cdot m^{-3} \cdot cm^{-2}$ leaf area, 18× greater than *D. deremensis* (0.13 $\mu g \cdot m^{-3} \cdot cm^{-2}$ leaf area). Of the herbaceous foliage plants tested, *Chlorophytum bichetii*, *Dieffenbachia* 'Marianne', *Tillandsia cyanea*, *Anthurium andraeanum*, *Syngonium podophyllum*, and *Peperomia clusiifolia* were the most effective in removing formaldehyde, whereas *Sansevieria trifasciata*, *Zamioculcas zamiifolia*, and *Calathea makoyana* were the least (Table 3). Consequently, *P. guajava*, *R. excelsa*, *Z. pumila*, *C. bichetii*, *Dieffenbachia* 'Marianne', *T. cyanea*, and *A. andraeanum* were in the top 15% of the 40 woody and herbaceous foliage plants tested (Tables 2 and 3).

Nandina domestica was the most effective of the Korean native plants tested in removing formaldehyde followed by *Dendropanax morbifera*, *Ardisia crenata*, *Laurus nobilis*, *Trachelospermum asiaticum*, and *Stauntonia hexaphylla*, whereas *Elaeocarpus sylvestris* was the least (Table 4). Of the fern species, *O. japonica*, *S. tamariscina*, *D. mariesii*

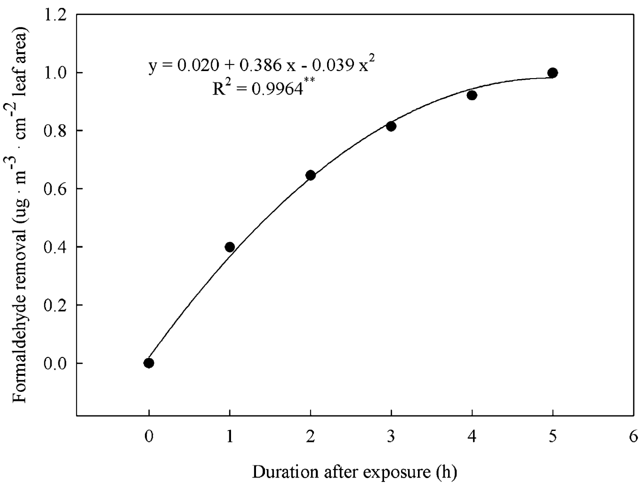

Fig. 2. Mean formaldehyde removal during a 5-h exposure for 86 species of indoor plants (initial concentration 2 $\mu L \cdot L^{-1}$).

Table 2. Formaldehyde removal by woody foliage plants when exposed to 2 $\mu L \cdot L^{-1}$ formaldehyde in sealed chambers for 1 to 5 h.

	Formaldehyde removal ($\mu g \cdot m^{-3} \cdot cm^{-2}$ leaf area)				
	Duration after exposure (h)				
Scientific name	1	2	3	4	5
Psidium guajava 'Safeda'	0.53 ab[z]	1.17 a	1.69 a	2.10 a	2.39 a
Rhapis excelsa Wendl.	0.60 a	0.88 b	1.17 b	1.43 b	1.67 b
Zamia pumila L.	0.46 bc	0.83 b	1.09 b	1.23 c	1.32 c
Dizygotheca elegantissima R. Vig. & G.	0.37 cd	0.67 c	0.87 c	1.03 d	1.13 d
Ficus elastica Roxb. ex Horne.	0.20 fgh	0.37 defg	0.56 de	0.69 ef	0.82 e
Gardenia jasminoides Ellis	0.33 de	0.65 c	0.75 cd	0.79 e	0.80 e
Serissa foetida (L.f.) Lam.	0.24 efg	0.43 efg	0.56 de	0.64 efg	0.68 ef
Eugenia myrtifolia 'Compacta'	0.32 de	0.52 cd	0.60 de	0.63 efg	0.64 f
Polyscias balfouriana Bailey	0.26 ef	0.45 de	0.53 e	0.60 fg	0.62 f
Hedera helix L.	0.25 ef	0.42 def	0.53 e	0.59 fg	0.62 f
Dracaena concinna Kunth	0.13 ghij	0.28 efghi	0.43 ef	0.53 fg	0.61 f
Cycas revoluta Thunb.	0.18 fghi	0.30 efghi	0.44 ef	0.52 fgh	0.61 f
Ficus benjamina L.	0.19 fghi	0.32 efgh	0.44 ef	0.52 fgh	0.55 f
Cupressus macrocarpa Hartweg 'Gold Crest'	0.20 fgh	0.32 efgh	0.44 ef	0.49 ghi	0.52 fg
Pachira aquatica Aubl.	0.12 hij	0.23 ghij	0.29 fgh	0.35 hij	0.40 gh
Hoya carnosa (L.f.) R.Br.	0.13 ghij	0.20 hij	0.27 fgh	0.33 ij	0.37 gh
Araucaria heterophylla Franco	0.19 fghi	0.28 efghi	0.33 fg	0.35 ij	0.35 h
Schefflera arboricola Hayata 'Hong Kong'	0.15 fghij	0.27 fghij	0.29 fgh	0.29 jk	0.29 hi
Dracaena fragrans Ker. 'Massangeana'	0.08 ij	0.14 ij	0.16 gh	0.17 kl	0.17 ij
Dracaena deremensis N.E. Br. 'Warneckii'	0.07 j	0.13 j	0.13 h	0.13 l	0.13 j

[z]Mean separation with columns by least significant difference test at $P \leq 0.05$.

Table 3. Formaldehyde removal by herbaceous foliage plants when exposed to 2 $\mu L \cdot L^{-1}$ formaldehyde in sealed chambers for 1 to 5 h.

	Formaldehyde removal ($\mu g \cdot m^{-3} \cdot cm^{-2}$ leaf area)				
	Duration after exposure (h)				
Scientific name	1	2	3	4	5
Chlorophytum bichetii Backer	0.29 de	0.55 cd	0.85 ab	1.05 a	1.25 a
Dieffenbachia amoena 'Marianne'	0.36 cd	0.68 ab	0.88 ab	1.08 a	1.24 a
Tillandsia cyanea Linden ex C. Koch	0.48 a	0.73 a	0.95 a	1.11 a	1.23 a
Anthurium andraeanum Linden	0.32 cd	0.61 bc	0.90 ab	1.06 a	1.22 a
Syngonium podophyllum Schott	0.23 ef	0.49 de	0.74 cd	0.93 b	1.06 b
Peperomia clusiifolia Hook.	0.43 ab	0.62 bc	0.79 bc	0.89 bc	0.94 bc
Haemaria discolor Lindl.	0.34 cd	0.59 cd	0.70 cde	0.80 cd	0.85 cd
Asplenium nidus L.	0.35 cd	0.53 cde	0.69 cde	0.76 cd	0.83 cd
Saintpaulia ionantha H. Wendl	0.24 ef	0.44 ef	0.60 e	0.72 d	0.81 cd
Aglaonema modestum	0.30 cde	0.50 de	0.65 de	0.75 d	0.78 d
Philodendron selloum C. Koch.	0.37 bc[z]	0.53 cde	0.64 de	0.70 d	0.76 d
Chrysalidocarpus lutescens H. Wendl	0.21 f	0.37 fg	0.47 f	0.55 e	0.61 e
Howea belmoreana Becc.	0.22 f	0.31 gh	0.43 f	0.49 e	0.53 e
Phoenix roebelenii O'Brien.	0.21 f	0.34 g	0.42 f	0.48 e	0.51 e
Epipremnum aureum Bunt.	0.21 f	0.34 g	0.40 g	0.44 f	0.44 ef
Spathiphyllum wallisii Regal	0.13 gh	0.21 ij	0.28 g	0.31 f	0.37 f
Clivia miniata Regal	0.14 gh	0.24 hi	0.30 g	0.33 f	0.34 fg
Calathea makoyana E. Morr.	0.12 gh	0.20 ij	0.26 g	0.27 f	0.29 fg
Zamioculcas zamiifolia	0.12 gh	0.19 ij	0.24 g	0.27 f	0.29 fg
Sansevieria trifasciata Prain	0.08 h	0.14 j	0.18 g	0.21 f	0.23 fg

[z]Mean separation with columns by least significant difference test at $P \leq 0.05$.

Polypodium formosanum, *Pteris dispar*, and *Pteris multifida* were highly effective in removing formaldehyde (Table 5). For example, *O. japonica* removed 6.64 μg·m^{-3} of formaldehyde/cm^{2} of leaf area over 5 h and was the most effective of the 86 species tested. In contrast, *D. deremensis* was the least effective. Of the herbs, *Lavandula* spp., *Pelargonium* spp., and *Rosmarinus officinalis* were the most effective in removing formaldehyde (Table 6).

Wolverton (1997) reported that *Nephrolepis exaltata*, *Chrysanthemum morifolium*, *Gerbera jamesonii*, *Phoenix roebelenii*, *Dracaena deremensis*, *Chamaedorea seifrizii*, and *Nephrolepis obliterata* ranked highest among 50 test species in removing formaldehyde with the ferns *N. exaltata* and *N. obliterata* being in the top 15% of the plants tested. Although we also found the ferns to effectively remove formaldehyde, there were distinct differences between tests. Wolverton (1986) found that with exposure to 10 μL·L^{-1} formaldehyde for 6 h, *Philodendron*, *Chlorophytum*, *Aloe vera*, and *Scindapsus aureus* removed greater than 2.2 μg·m^{-3}·cm^{-2} leaf area, whereas *S. wallisii* and *S. trifasciata* removed relatively little formaldehyde (1.05 and 0.76 μg·m^{-3}·cm^{-2} leaf area, respectively). Our results were lower for *S. wallisii* (0.37 μg·m^{-3}·cm^{-2} leaf area) and *S. trifasciata* (0.23 μg·m^{-3}·cm^{-2} leaf area) (Table 3), which appeared to be the result of the significantly lower initial formaldehyde concentration (10 versus 2 μL·L^{-1}) and to a lesser extent the shorter time interval (6 versus 5 h).

When comparing the five general classes of plants, ferns were the most effective in removing formaldehyde followed by herbs (Fig. 3). There were major differences in formaldehyde removal efficiency among species within the ferns as indicated by the higher SE values. There were no significant differences between the woody and herbaceous foliage plants and the Korean native plants classes in the removal of formaldehyde. Figure 4 illustrates formaldehyde removal by the 86 species based on a total leaf area per chamber. Formaldehyde removal decreased slightly with increasing total leaf area in the chamber. Although formaldehyde is absorbed and metabolized by both the leaves and the rhizosphere microorganisms (Godish and Guindon, 1989; Kim et al., 2008; Wolverton et al., 1989; Wood et al., 2002), the efficiency of formaldehyde removal is generally expressed on a unit leaf area basis (Kim and Lee, 2008; Orwell et al., 2006; Wolverton et al., 1989; Wood et al., 2002; Yoo et al., 2006). Thus, the calculated efficiency of formaldehyde removal was lower at higher total leaf areas in the chamber when comparing different sizes of plants with the same media volume (Kim and Kim, 2008) because the effect of rhizosphere microorganisms is not considered in calculating the efficiency.

Differences in ranking between Wolverton's data (Wolverton, 1986, 1997) and the current study appear to be largely the result of differences in methods (e.g., concentration, test chambers, cultivars). The test concentration of formaldehyde is known to be critical because the rate of VOC removal decreases as the internal concentration declines (Kim et al., 2008). Wolverton (1986) used various initial formaldehyde concentrations ranging from 1 μL·L^{-1} to 22 μL·L^{-1}. The current results are based on an initial formaldehyde concentration of 2 μL·L^{-1}, which was selected based on the maximum acceptable concentration in homes and offices (Ministry of Environment, Republic of Korea, 2006) and was used over the entire 5-year test period for each of the 86 species.

Table 4. Formaldehyde removal by Korean native plants when exposed to 2 μL·L^{-1} formaldehyde in sealed chambers for 1 to 5 h.

Scientific name	Formaldehyde removal (μg·m^{-3}·cm^{-2} leaf area)				
	Duration after exposure (h)				
	1	2	3	4	5
Nandina domestica Thunb.	0.28 defg	0.72 bc	1.05 b	1.35 a	1.58 a
Dendropanax morbifera Nakai	0.34 cdef	0.70 c	1.03 b	1.30 a	1.50 ab
Ardisia crenata Sims.	0.62 a	1.04 a	1.27 a	1.40 a	1.46 ab
Laurus nobilis L.	0.45 b	0.83 b	1.11 b	1.28 a	1.40 ab
Trachelospermum asiaticum Nakai	0.28 defg	0.54 d	0.81 c	0.92 b	1.03 c
Stauntonia hexaphylla (Thunb.) Dence.	0.08 j	0.25 hi	0.40 efgh	0.54 cde	0.66 d
Rhaphiolepis umbellata Makino	0.42 bc	0.56 d	0.59 d	0.59 c	0.59 de
Viburnum awabuki K. Koch	0.46 b	0.55 d	0.55 de	0.55 cde	0.55 def
Quercus glauca Thunb.	0.36 cde	0.52 def	0.55 de	0.55 cde	0.55 def
Ilex crenata Thunb.	0.36 cde	0.46 efg	0.50 def	0.51 cdef	0.51 defg
Chamaecyparis obtusa Endl.	0.26 efgh	0.38 fgh	0.43 efgh	0.47 cdefg	0.50 defg
Fatsia japonica Decne. et Planch.	0.22 ghi[z]	0.36 fgh	0.44 defg	0.48 cdefg	0.50 defg
Eurya emarginata (Thunb.) Makino	0.28 defg	0.42 efg	0.46 defg	0.46 cdefg	0.47 efg
Pittosporum tobira Ait.	0.25 efgh	0.34 fgh	0.39 fg	0.41 de	0.44 ef
Camellia sinensis Kuntz.	0.16 hij	0.29 ghi	0.36 fghi	0.40 defg	0.43 fg
Ardisia pusilla DC.	0.14 ij	0.26 hi	0.33 ghi	0.38 efgh	0.43 fg
Ligustrum japonicum Thunb.	0.28 defg	0.35 fgh	0.36 fghi	0.36 fgh	0.36 gh
Quercus acuta Thunb.	0.26 efgh	0.32 fgh	0.36 fghi	0.36 fgh	0.36 gh
Camellia japonica L.	0.16 hij	0.26 hi	0.30 hi	0.32 gh	0.33 gh
Elaeocarpus sylvestris var. *ellipticus* Hara	0.14 ij	0.19 i	0.21 i	0.22 h	0.23 h

[z]Mean separation with columns by least significant difference test at $P \le 0.05$.

Table 5. Formaldehyde removal by ferns when exposed to 2 μL·L^{-1} formaldehyde in sealed chambers for 1 to 5 h.

Scientific name	Formaldehyde removal (μg·m^{-3}·cm^{-2} leaf area)				
	Duration after exposure (h)				
	1	2	3	4	5
Osmunda japonica Thunb.	2.82 a[z]	4.42 a	5.42 a	6.19 a	6.64 a
Selaginella tamariscina Spring	2.22 b	3.48 b	4.16 b	4.60 b	4.84 b
Davallia mariesii Moore ex Baker	1.34 c	2.37 c	3.16 c	3.74 c	4.15 c
Polypodium formosanum Baker	1.20 c	2.09 c	2.69 d	3.21 d	3.62 c
Pteris dispar Kunze.	0.89 d	1.40 d	1.70 e	1.86 e	1.95 d
Pteris multifida Poir.	0.82 de	1.34 d	1.64 e	1.76 e	1.92 d
Microlepia strigosa (Thunb.) Presl.	0.66 def	1.07 de	1.29 ef	1.42 ef	1.49 de
Botrychium ternatum (Thunb.) Swartz.	0.68 def	1.06 de	1.26 ef	1.38 ef	1.42 def
Cyrtomium caryotideum Nakai 'Coreanum'	0.59 efg	0.78 ef	0.92 fg	1.00 fgh	1.09 efg
Pteris ensiformis Burm. 'Victoriae'	0.53 fgh	0.78 ef	0.91 fg	0.97 fgh	1.01 efgh
Polystichum tripteron (Kunze) Presl.	0.36 ghi	0.61 fg	0.78 gh	0.88 ghi	0.92 efgh
Dryopteris nipponensis Koidz.	0.43 fghi	0.64 fg	0.76 gh	0.85 ghi	0.91 efgh
Adiantum capillus-veneris L.	0.35 ghi	0.58 fg	0.72 gh	0.81 hi	0.86 fgh
Thelypteris esquirolii var. *glabrata* K. Iwats.	0.43 fghi	0.66 fg	0.77 gh	0.82 hi	0.84 fgh
Coniogramme japonica (Thunb.) Diels	0.44 fghi	0.61 fg	0.70 gh	0.74 hi	0.76 gh
Cyrtomium falcatum (L.f.) Presl.	0.39 ghi	0.58 fg	0.67 gh	0.67 hi	0.67 gh
Thelypteris acuminata (Houtt.) Morton	0.33 hi	0.46 fg	0.49 gh	0.50 hi	0.51 gh
Arachniodes aristata (G. Forst.) Tindale	0.30 hi	0.27 g	0.47 gh	0.49 hi	0.49 gh
Thelypteris decursive-pinnata Ching	0.27 hi	0.41 fg	0.45 gh	0.47 hi	0.47 gh
Thelypteris torresiana 'Calvata' K. Iwats.	0.24 i	0.33 g	0.37 h	0.39 i	0.40 h

[z]Mean separation with columns by least significant difference test at $P \le 0.05$.

Table 6. Formaldehyde removal by herbs when exposed to 2 μL·L^{-1} formaldehyde in sealed chambers for 1 to 5 h.

Scientific name	Formaldehyde removal (μg·m^{-3}·cm^{-2} leaf area)				
	Duration after exposure (h)				
	1	2	3	4	5
Lavandula spp.	1.35 a[z]	1.80 a	1.97 a	2.06 a	2.12 a
Pelargonium spp.	0.58 b	1.00 b	1.44 b	1.66 b	1.87 b
Rosmarinus officinalis L.	0.75 b	0.96 b	1.03 b	1.05 b	1.05 b
Mentha suaveolens 'Applemint'	0.22 c	0.41 c	0.61 cd	0.73 c	0.89 c
Jasminum polyanthum Franchet	0.29 c	0.53 c	0.70 c	0.78 c	0.84 c
Jasminum sambac (L.) Aiton	0.18 c	0.30 c	0.36 d	0.38 d	0.42 d

[z]Mean separation with columns by least significant difference test at $P \le 0.05$.

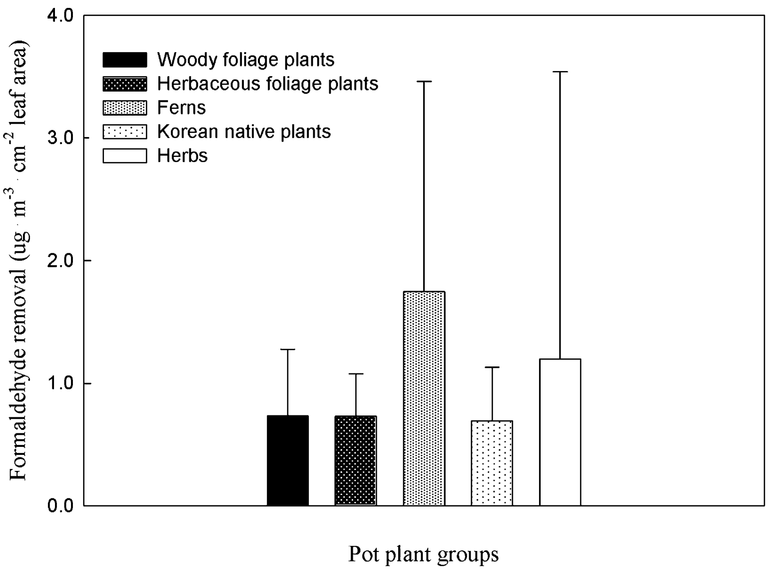

Fig. 3. Mean formaldehyde removal by indoor plants, grouped into five general categories based on the type of plant when exposed to 2 μL·L^{-1} formaldehyde for 5 h. Vertical bars (SE) denote variation among species within groups.

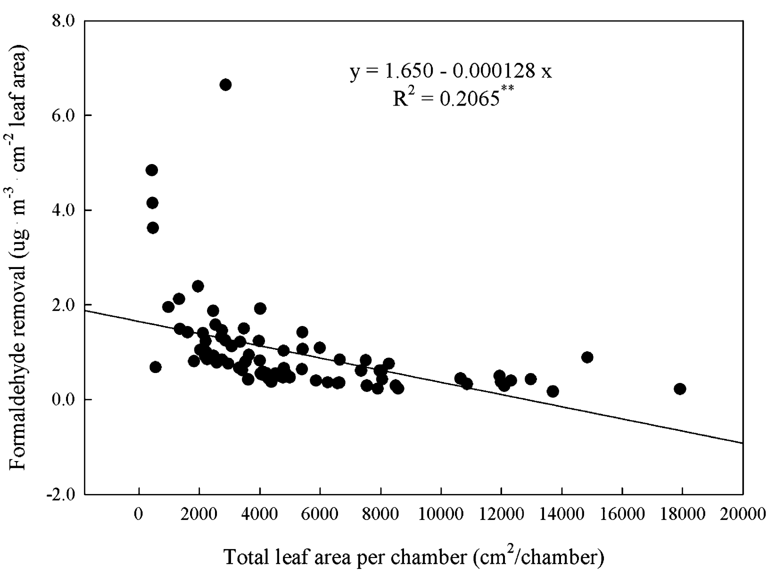

Fig. 4. The effect of total leaf area per chamber for 86 indoor species on the efficiency of formaldehyde removal during a 5-h exposure (initial concentration 2 μL·L^{-1}).

The most effective species for removing formaldehyde (*O. japonica*) was 50 times more effective than the least (*D. deremensis*), indicating the extensive range found among the plants. Based on this diversity, we separated the species into three general groups based on formaldehyde removal efficiency: excellent (greater than 1.2 μg·m^{-3} formaldehyde per cm^2 of leaf area over 5 h), intermediate (1.2 or less to 0.6), and poor (less than 0.6). The species classified as excellent are considered desirable for use in homes and offices where the formaldehyde concentration in the air is of concern. The species tested were predominantly indoor ornamentals. However, there are likely other species within the plant kingdom that may be equal or more effective than *O. japonica*. A better understanding of the effect of concentration, duration of exposure, and presence of other VOCs (Yang et al., 2009) on the health and VOC removal efficiency of interior plants needs to be ascertained. It is evident from our results that certain species have the potential to improve interior environments and, in so doing, the health and well-being of the inhabitants.

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