Quantification of Carbon Assimilation in Interiorscape Plants

In Simulated and *In Situ* Environments

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INTRODUCTION

The word "sustainable" is exemplified by mainstream 'green' movements such as the Leadership in Energy and Environmental Design (LEED) certification. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality. LEED has become an important element in the building industry but it lacks an agricultural connection to indoor plants and their role in promoting human health by improving indoor air quality (IAQ).

Since the 1970s, a multitude of research has shown the positive direct (by removing air pollutants) and indirect impact (by reducing patient recovery time in hospitals) of plants on buildings. The University of Georgia and other leading academic institutions around the world (e.g. in Japan, Australia, Germany, Korea) have more recently engaged in expanding the scientific knowledge with regard to species, types of harmful indoor air pollutants, efficiency and mechanisms via which plants are able to neutralize such pollutants.

We have documented the efficiency of volatile formaldehyde removal by indoor plants and found that the root zone is a major contributor to the removal process (Kim et al, 2008). We have completed our screening of the efficiency of volatile organics removal by various indoor species, and submitted a manuscript to the Journal of American Society for Horticultural Sciences (p. 8, **Appendix**). Of the 28 species tested, *Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densiflorous* had the highest removal efficiencies for all pollutants; *Tradescantia pallida* displayed superior removal efficiency for 4 of the 5 VOCs (i.e., benzene, toluene, TCE, and α-pinene). The five species ranged in their removal efficiency from 26.08 to 44.04 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$ of the total VOCs. *Fittonia argyroneura* effectively removed benzene, toluene, and TCE; *Ficus benjamina*, octane and α-pinene; *Polyscias fruticosa*, octane. The variation in removal efficiency among species indicates that for maximum improvement of indoor air quality multiple species are needed and the number and type of plants tailored to the type of VOCs present and their rates of emanation at a specific indoor location.

Based on this and other studies, it is clear that plants have the potential to significantly improve the quality of indoor air with respect to harmful volatile organic compounds such as

benzene, toluene, octane, trichloroethylene (TCE), and α-pinene. Sustainable certification programs, therefore, could implement phytoremediation as part of a program for IAQ improvement.

One aspect of indoor air quality has received minimal attention to-date: the impact of plants on removal of carbon dioxide from indoor environments.

Light in the presence of water and carbon dioxide triggers internal mechanisms in chloroplasts (photosynthesis) that convert carbon dioxide and water into sugars and oxygen. The photoassimilates (sugars) are then used for new growth and maintenance of existing tissues and organs. As light is the driving force behind photosynthesis, generally, the higher the light level, the more sugars are produced. Indoors the most limiting factor for photosynthesis is light. The light levels in typical commercial interiorscape installations range from more than 250 foot-candles (fc) (rated as "good" level by interiorscapers), 200 – 150 fc ("medium" light), or 125 – 75 fc ("low" light). Under such conditions, plants sustain variable photosynthetic rates, mainly depending on the ambient light levels. It is important to note that temperature also has a significant impact on the production of photoassimilates, mainly due to its effect on respiration. In contrast to photosynthesis, respiration breaks down sugars (providing building blocks for plant growth and maintenance respiration) and releases carbon dioxide. Generally, indoor air temperatures (21 °C day/18 °C night) are not conducive to excessive respiration rates and thus carbon dioxide release from the plant.

Thus, the amount of carbon uptake and fixation in building interiors is directly related to light level, temperature and existing stored photosynthetic reserves (which in turn depend on production environment, level of acclimatization, etc).

While we have a plethora of data on photosynthetic performance of plants under various light regimes in simulated interior environments, we lack reliable knowledge of such performance *in situ* that is in a real-world interiorscape situation. Nor has there been a documented effort to systematically record photosynthetic rates of a number of plant species, at various canopy levels. Such quantitative data, correlated with data obtained under simulated environment, may enable us to extrapolate the amount of carbon dioxide assimilated under typical interiorscape conditions.

Lastly, we hope to be able to address the question: "If an interiorscape of certain size and plant species is implemented under typical light levels, how much carbon would be removed from the air over given period?"

OBJECTIVE

      We propose a two-pronged research protocol aimed at addressing the questions posed above: first, a methodical assessment of photosynthetic rates of interiorscape plants *in situ*, and second, a quantification of carbon assimilation under simulated environment designed to replicate the light levels and temperatures of typical indoor environments.

MATERIALS AND METHODS

In Situ Environment. This phase of the research will be conducted in collaboration with Foliage Design Systems (Orlando, Fl). Three interiorscape accounts in the Metro Atlanta Area representing typical installations will serve as sampling sites. The locations, conditions, type of plant species are described below:

Interiorscape Sites:

Hospital Lobby – Good light – 250 fc +

1 – 21" Adonidia Palm at 10-12' height in center of room
4 – 6" Bromeliads at 1' around base of Palm
4 – 8" Pothos vining around base of Palm
6 – 10" Sanseveria at 2-3' heights in planter box
6 – 10" Variegated Arboricola at 2-3' heights in planter box
3 – 14" Ficus Trees at 5-6' heights along windows

Office Building Lobby – Medium light – 150-200 fc

1 – 17" Dracaena Marginata at 7-8' height in corner
4 – 14" Kentia Palms at 5-6' heights in wall recesses
16 – Vine Pothos around base of Palms (4 ea)
3 – 14" Spathiphyllum at 3-4' heights by doors

Lawyer Office – Low Light – 75-125 fc

1 – 14" Rhapis Palm at 5-6' height in corner
2 – 10" Janet Craigs at 2-3" heights in seating area
1 – 8" Aglaonema at 1' height on coffee table
1 – 6" Ctenanthe 'Tricolor' at 1' height on reception desk

Measurements

<u>Photosynthesis.</u> We will employ the use of CIRAS-1 (PP Systems), a portable infrared gas analyzer (CO_2 and H_2O) to assess net photosynthesis, light saturation point, and maximum light use efficiency. The procedure is briefly described as follows. A sample leaf is placed in a cuvette and exposed to progressively higher photosynthetic photon flux, *PPF* (approximately 0, 10, 20, 30, 40, 50, 100, 400, and 700 $\mu mol \cdot m^{-2} \cdot s^{-1}$, approximately 0 to 4000 footcandles). Leaf carbon dioxide is measured on the most-recently matured leaf, mid-way between the midrib and leaf edge, and mid-way between the petiole and leaf tip. Dark respiration (R_d), maximum light use efficiency (LUE), and light saturated gross photosynthesis (P_{gmax}) are estimated from a nonlinear regression (SigmaPlot software package; Systat Software):

$$P_n = (P_{gmax}) \; [1 - e^{(-LUE)(PPF)/ \; Pgmax}] + R_d$$

Where P_n is net photosynthetic rate, P_{gmax} is light-saturated gross photosynthetic rate, LUE is maximum light use efficiency, *PPF* is photosynthetic photon flux, and R_d is dark respiration (here expressed as a negative value, since it represents a CO_2 efflux from the plant). The light compensation point is determined by solving the above equation for *PPF* and a P_n of 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The light saturation point is determined as the *PPF* at which P_n was 95% of light-saturated net photosynthesis [$P_n = 0.95 \times (P_{gmax} + R_d)$]. The units for all parameters are $\mu mol \cdot m^{-2} \cdot s^{-1}$, with the exception of the unitless LUE, which is a measure of the efficiency with which plants can use light to fix carbon dioxide(the slope of the light response curve at a *PPF* of 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Ambient light levels at each location will be recorded. Photosynthetic measurements will be taken over a period of four weeks, once a week.

<u>Chlorophyll Analysis.</u> Relative chlorophyll content will be determined with a chlorophyll meter (SPAD-502, Minolta). Representative leaves of various species will be sampled in an effort to correlate chlorophyll content, net photosynthetic rate, and dry mass.

<u>Dry Mass Analysis.</u> To assess the amount of carbon fixed, leaf samples will be obtained from herbaceous species (e.g. pothos, Sanseveria) and total number of leaves will be counted. Leaves will be placed in a forced-air oven for 72 hr and weighed. Leaf samples will then be analyzed

for carbon content to precisely determine how much carbon has been sequestered in these plants. These data, along with number of leaves, will help quantify aerial plant dry mass as well as carbon removed by the plant and retained in its foliar tissues.

<u>Simulated Environment.</u> Representative plants of species and sizes similar to the ones in the *in situ* environment will be obtained from commercial sources. Plants will be grown in growth chambers with controlled conditions (i.e. light level, temperature, and photoperiod). The conditions will simulate the three respective interiorscape environments.
At experiment initiation a number of plants will be removed from their pots, soil washed from roots, and plant parts placed in a forced-air oven for 72 hrs and weighed to assess total dry mass and the amount of carbon in the plants before placing them in the simulated interiorscapes.

Plants will be grown for a minimum of 12 weeks. Any leaves abscised during the experiment will be collected, dried and weighed. Upon termination, plants will be removed from their pots, roots will be washed and plant parts dried, weighed, and analyzed for carbon content.
This phase of the research aims to quantify total plant dry mass and carbon removed by the plant and retained in its aerial and rhizomal tissues.

EXPECTED BENEFITS

1. Quantifying carbon assimilation of representative interiorscape species under representative interiorscape environments.
2. Further establishing the positive benefit of indoor plants on creating healthier indoor environments, and providing supporting data to substantiate the argument for using indoor plants as part of sustainable certification programs.

PROPOSED BUDGET

Travel	$5,000
Labor	$10,000
Operating	$10,000

Plant material, fertilizer, soilless mix, pots, analytical supplies, growth chambers, photosynthesis measuring system, and other miscellaneous equipment, etc.

Total requested from the NFF: $ 25,000

PROPOSED TIMETABLE

Both phases will be initiated simultaneously in January, 2009. An interim report will be sent July 1, 2009, and a final report to NFF will be sent November 1, 2009.

LITERATURE CITED

Kim, K.J., M.J. Kil, J.S. Song, and S.J. Kays. Efficiency of Volatile Formaldehyde Removal by Indoor Plants: Contribution of Aerial Plant Parts versus the Root Zone. J. Amer. Soc. Hort Sci. 133(4): 521-526. 2008.

APPENDIX

Screening Indoor Plants for Volatile Organic Pollutant Removal Efficiency

(manuscript submitted to the Journal of American Society for Horticultural Sciences)

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Abstract. A diverse cross-section of 28 ornamental species commonly used in indoor environments was screened for their ability to remove 5 representative volatile indoor pollutants with differing chemistries [benzene, toluene, octane, trichloroethylene (TCE), and α-pinene]. Removal efficiency was determined by monitoring the decline in concentration over 6 h within sealed glass containers after individual plants were exposed to 10 ppm of each pollutant. To determine removal by the plant, removal by other means (glass, plant pot, media) was subtracted. The removal efficiency expressed on a leaf area basis for each volatile organic compound (VOC) varied with plant species. Of the 28 species tested, *Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densiflorous* had the highest removal efficiencies for all pollutants; *Tradescantia pallida* displayed superior removal efficiency for 4 of the 5 VOCs (i.e., benzene, toluene, TCE, and α-pinene). The five species ranged in their removal efficiency from 26.08 to 44.04 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$ of the total VOCs. *Fittonia argyroneura* effectively removed benzene, toluene, and TCE; *Ficus benjamina*, octane and α-pinene; *Polyscias fruticosa*, octane. The variation in removal efficiency among species indicates that for maximum improvement of indoor air quality multiple species are needed and the number and type of plants tailored to the type of VOCs present and their rates of emanation at a specific indoor location.

INTRODUCTION

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

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

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

of the phytoremediation potential of a diverse range of indoor plants is needed. In the following study, a cross-section of indoor plants (28 species) was screened for their ability to remove 5 important VOC with differing chemistries (benzene, toluene, octane, TCE, and α-pinene).

Materials and Methods

PLANT MATERIAL. Twenty-eight species of indoor ornamental plants representing 26 genera and 15 botanical families (Table 1) were obtained from commercial sources. After the media was washed from the roots, the plants were repotted in 10-cm pots using a growing media (Fafard 3B; Fafard, Anderson, SC), and grown in a shade house for 8 weeks prior to acclimatization for 12 weeks under indoor conditions, 22 ± 1 °C, 50% RH and 5.45 μmol·m^{-2}·s^{-1} *PAR* (LI-COR LI-189 light meter with a line quantum sensor, LI-COR, Lincoln, NE). At the end of the experiment, the leaf areas were determined using a LI-3100c leaf area meter (LI-COR, Lincoln, NE) to allow expressing the removal efficiency on a leaf area basis.

INTRODUCTION OF VOLATILE ORGANIC COMPOUNDS. Plants were placed in 10.5 L gas-tight glass jars (1 plant/jar) with the lid fitted with welded stainless steel tubing inlet and outlet ports. To facilitate a uniform distribution of the gases in the jar, the inlet tubing extended downward within the jar, following the contour of the side of the jar, three quarters of the distance to the base. The lids were sealed using specially constructed 11.8 cm o.d. × 9.8 cm i.d. gaskets in which a 4.2 mm thick EPDM rubber gasket was sealed within a Teflon envelope (Phelps Industrial Products, Elkridge, MD). The inlet port was connected to a charcoal filter (Alltech Assoc. Inc., Deerfield, IL) [Pyrex glass tube (10 cm × 1 cm i.d.) with 7 cm of 2.5 g of charcoal] such that purified air was introduced into the jar at 150 ml·min^{-1}. The plants were placed in the jars 24 h prior to treatment. Just prior to the introduction of the VOCs, the inlet and outlet ports were closed using gas tight Swagelok fittings (Georgia Valve & Fitting, Co., Alpharetta, GA). The exit port was configured with Swagelok fittings holding a gas tight GC septum which was capped to prevent leakage. The cap was briefly removed when a gas sample was removed for analysis. The individual plants were exposed to ~10 ppm of high purity analytical grade benzene, TCE, toluene, octane, and α-pinene (Table 2), respectively, in the gas-tight glass jars. Through preliminary tests, concentration of 9.66, 11.00, 9.66, 9.49, and 9.82 ppm of each compound were created by introducing 2.0, 2.7, 2.4, 4.0, and 4.0 μL of benzene, TCE, toluene, octane, and α-pinene, respectively, into the jar using a microsyringe

(Agilent Technologies, Wilmington, DE) and calibrating the amount of each compound adsorbed onto the inner surface of the jar. A small 4 cm dia. 6V DC brushless fan (RadioShack, Fort Worth, TX) was placed near the top of each jar to ensure adequate mixing of the volatiles. The gas concentration within the jar was determined after 3 and 6 h during the day. Three replications of each species were tested at a setting with a fourth jar used as a control without a plant to measure the concentration of airborne VOCs within the jar. Leak tests were carried out on the empty jar before every 4th experiment; no leakage was found during the 6 h test period.

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

(A) VOC removal efficiency = [C - (S - M)] / (L × T)   [1]

(B) Accumulated removal concentration of VOC = [C - (S - M)] / L   [2]

where:

C = the concentration of VOC in the control jar (μg·m^{-3})

S = the concentration of VOC in the sample jar (μg·m^{-3})

M = the concentration of VOC in the jar containing only the plastic pot and media (μg·m^{-3}) (Table 2)

L = total leaf area (m^2)

T = VOC exposure time (h)

STATISTICAL ANAYSIS. Analysis of variance (ANOVA) and Duncan's multiple range test were carried out by using the SAS system for Windows v8.

Results and Discussion

Twenty-eight species of indoor plants (Table 1) were exposed to 5 VOCs for 6 h [i.e., aromatic hydrocarbons (benzene and toluene), aliphatic hydrocarbon (octane), halogenated hydrocarbon (trichloroethylene), terpene (α-pinene)]. The initial concentrations of benzene, toluene, octane, TCE, and α-pinene within the container were 9.66 (0.03), 9.66 (0.07), 9.49 (0.06), 11.00 (0.07), and 9.82 (0.20) ppm (standard error of mean), respectively. The concentration of each VOC, after subtraction of changes in control jars containing the pot and media without a plant (Table 2), decreased with exposure duration, indicating VOC removal by the plants (Table 3). Since the test plants varied in size and foliar surface area, the removal efficiency for each VOC was expressed on a leaf area basis to allow identification of species with superior removal efficiency. VOC removal represents the effect of the plant and aerial and subterranean microorganisms, the latter of which is known to be an important contributor (Wood et al., 2002).

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

Benzene. Six species with superior benzene removal efficiency were identified: *H. alternata* (5.54 µg·m^{-3}·m^{-2}·h^{-1}), *T. pallida* (3.86), *H. helix* (3.63), *F. argyroneura* (2.74), *A. densiflorous* (2.65), and *H. carnosa* (2.21) (Table 3, Fig. 1A). *H. alternata* had the highest removal efficiency and the highest accumulated removal of benzene at 3 h and 6 h. At 3 h, 5 species classified as having high removal efficiency were not statistically significant in their accumulated removal concentrations, however, by 6 h there were significant differences (Fig. 1A). *S. trifasciata* (1.76), *F. benjamina* (1.66), *P. fruticosa* (1.53), *Guzmania* sp. (1.46), *A. andreanum* (1.31), and *P. clusiifolia* (1.20) were classified as having an intermediate benzene removal efficiency; the remainder had very low benzene removal efficiencies (Table 3).

Toluene. *H. alternata* had the highest toluene removal efficiency (9.63 µg·m^{-3}·m^{-2}·h^{-1}) followed by *T. pallida* (9.10), *H. helix* (8.25), *A. densiflorous* (7.44), *H. carnosa* (5.81), *F. argyroneura* (5.09), and *F. benjamina* (5.06) (Table 3, Fig. 1B). The plants were considerably much more effectively in removing toluene than benzene, a finding corroborated by Yoo et al.

(2006). The rate of toluene removal during the initial 3 h exposure was more rapid compared to the second 3 h of exposure. Toluene removal occurs via adsorption to plant surface and absorption via stomatal uptake; the removal rate depending on the number of stomata and cuticular structure (Jen et al., 1995; Ugrekhelidze et al, 1997).

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

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

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

Based on the total VOC removal efficiency, the plants were classified into superior, intermediate, and poor categories (Table 3). Five species (i.e., *H. alternata, H. helix, T. pallida, A. densiflorous,* and *H. carnosa*) with superior phytoremediation potential, were identified. Their total VOC removal ranged from 26.08 to 44.04 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$ and they effectively removed each of the test compounds. In contrast, the total VOC removal efficiency of the 7 plants classified as having an intermediate phytoremediation potential ranged from 17.46 to 24.13 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$ while those with poor efficiencies ranged from 5.55 to 12.98 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$.

There were no discernible trends in VOC removal potential based on taxonomical relatedness. However, the Araceae family [e.g., *E. pinnatum* (6.71 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *S. podophyllum* (7.04), *P. scandens* var. *oxycardium* (7.26), *D. seguine* (8.05), *S. wallisii*

(11.15)] generally had poor phytoremediation potential, while representatives of the Araliaceae family had, in general, a far better removal potential [e.g., *H. helix* (38.33 $\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), *P. fruticosa* (21.53), and *S. elegantissima* (17.46)].

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

While a diverse cross-section of plants was capable of removing the VOCs tested (Table 3), removal efficiency varied within a single species due to differences in the chemical properties of the individual compounds (e.g., polarity, vapor pressure, molecular weight, solubility, dissociation), an effect previously noted by Yoo et al., 2006. The fate of VOCs (e.g., accumulation, adsorption, absorption, penetration, transportation, metabolism), therefore, depends on the chemical characteristics of each volatile (Deinum et al., 1995; Korte et al., 2000; Cape, 2003) and the physical and chemical characteristics of the plants. Lipophilic compounds more readily penetrate the cuticular surface of plants, expediting uptake in contrast to compounds that are largely restricted to stomatal penetration (Deinum et al., 1995; Schmitz et al., 2000). In addition, the ability to metabolize VOCs varies widely among species and volatiles (Deinum et al., 1995; Jen et al., 1995; Cape, 2003; Beattie and Seibel, 2007). Therefore, a better understanding of the basic physical and chemical factors modulating the phytoremediation processes in the most efficient species is needed.

Conclusions and Summary
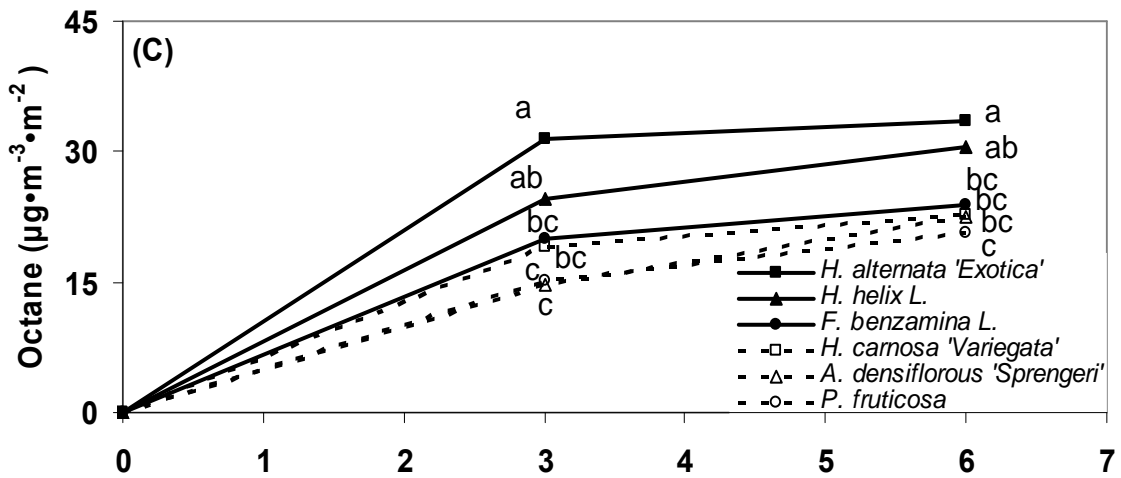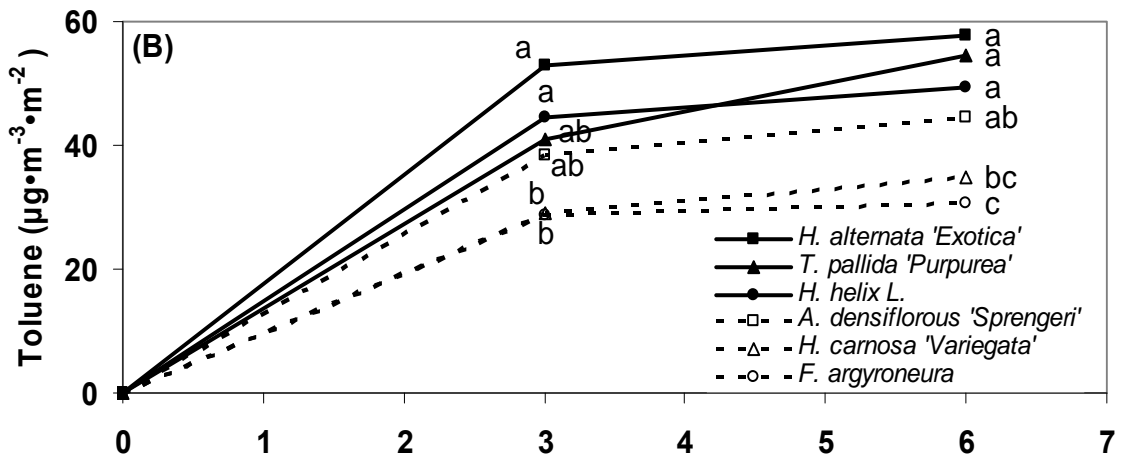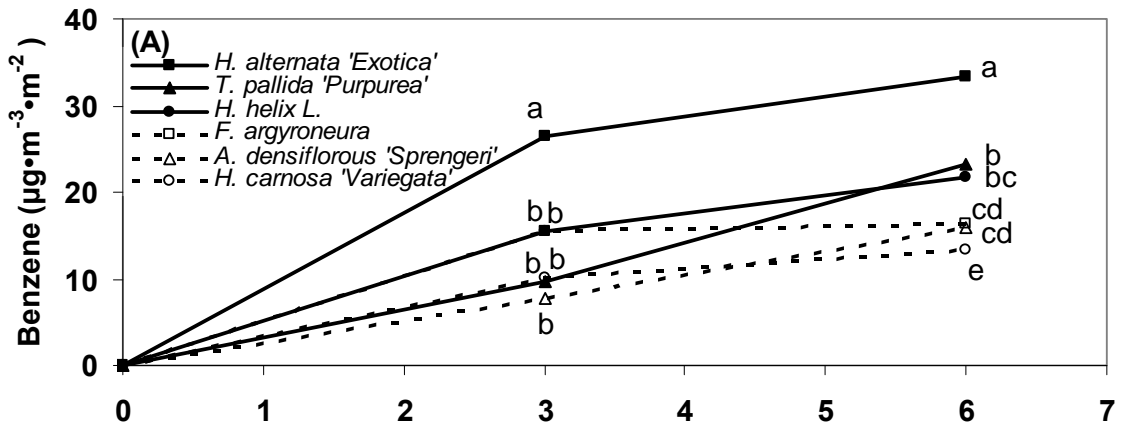
Of the 28 species tested, *H. alternata*, *H. helix*, *H. carnosa*, and *A. densiflorous* had superior removal efficiencies for each of the test compounds (i.e., benzene, toluene, octane, TCE, and α-pinene). Likewise, *T. pallida* had superior removal efficiencies for 4 of the compounds (i.e., benzene, toluene, TCE, and α-pinene). *H. alternata*, in particular, had the

highest removal efficiency for 4 of the compounds (benzene, toluene, octane, and TCE). Indoor plants are known to confer significant psychological and physical benefits to individuals living/working in environments where they are present [e.g., reduced stress, increased task performance, and decreased symptoms of ill health (Son, 2004; Bringslimark et al., 2007)]. Based on this and other studies, plants also have the potential to significantly improve the quality of indoor air. Their increased use in both "green" and traditional buildings could have a tremendous positive impact on the ornamental industry by increasing customer demand and volume of sales. Further studies focusing on screening additional plant species for superior VOC removal efficiencies are warranted.

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(A)

Benzene (μg•m⁻³•m⁻²)

- H. alternata 'Exotica'
- T. pallida 'Purpurea'
- H. helix L.
- F. argyroneura
- A. densiflorous 'Sprengeri'
- H. carnosa 'Variegata'

(B)

Toluene (μg•m⁻³•m⁻²)

- H. alternata 'Exotica'
- T. pallida 'Purpurea'
- H. helix L.
- A. densiflorous 'Sprengeri'
- H. carnosa 'Variegata'
- F. argyroneura

(C)

Octane (μg•m⁻³•m⁻²)

- H. alternata 'Exotica'
- H. helix L.
- F. benzamina L.
- H. carnosa 'Variegata'
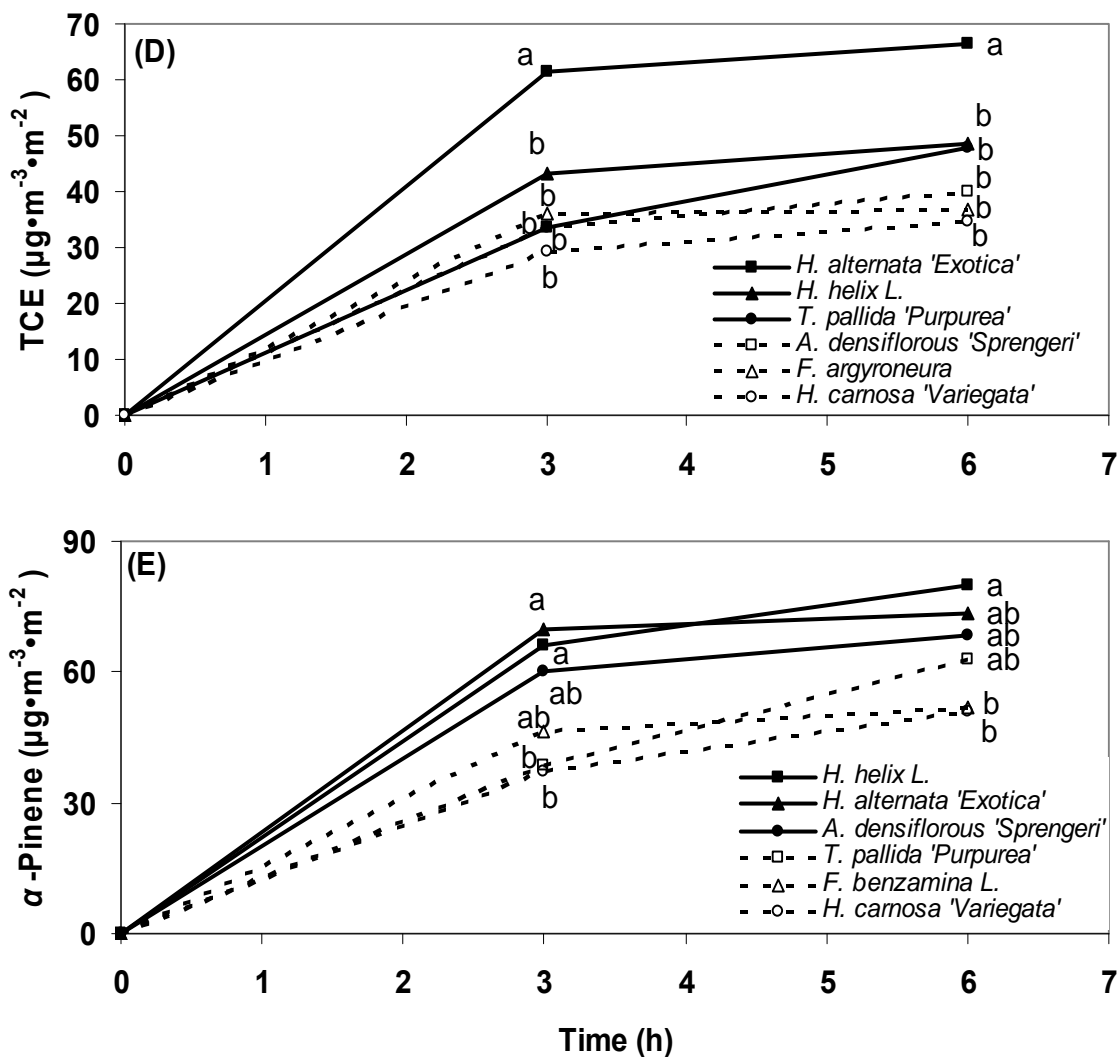- A. densiflorous 'Sprengeri'
- P. fruticosa

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

Table 1. Test plants and corresponding leaf areas.

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

Data are means ± S.E.M. (n=3).
[z] syn. *Diffenbachia amoena* Hort. & Bull.
[y] syn. *Scindapsus aureus* Engl.
[x] syn. *Dizygotheca elegantissima* (Veitch) R.Vig. & Guillaumin

Table 2. Accumulated removal concentration of VOCs by plastic pot containing soil-less media.

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

Data are means $\pm$ S.E.M. (n=3).

Table 3. Removal efficiency based on leaf area of 5 representative volatile organic compounds (benzene, toluene, octane, TCE, and α-pinene) of 28 indoor plants.

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

Data are means ± S.E.M. (n=3).
[z] syn. *Dizygotheca elegantissima* (Veitch) R.Vig. & Guillaumin
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