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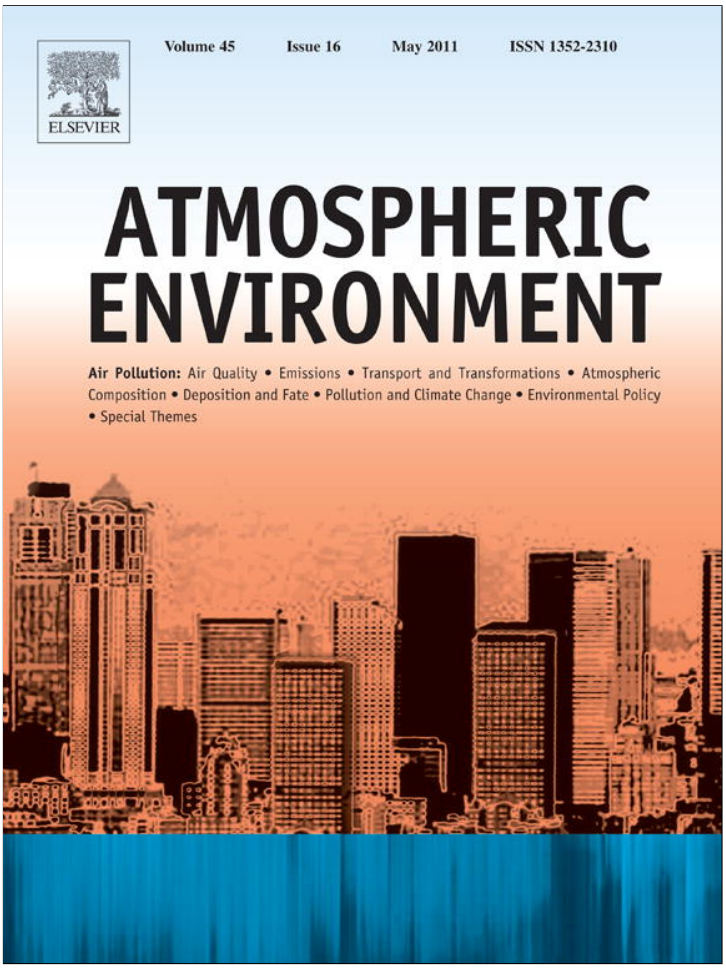

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Atmospheric Environment 45 (2011) 2675–2682

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Formaldehyde removal by common indoor plant species and various growing media

Ahu Aydogan [a,b], Lupita D. Montoya [b,c,*]

[a] School of Architecture, Built Ecologies Program, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[b] Center for Architecture Science and Ecology, School of Architecture, Rensselaer Polytechnic Institute and SOM, NY 10005, USA
[c] Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, 1111 Engineering Drive, ECOT 514, UCB 428, Boulder, CO 80305, USA

ARTICLE INFO

Article history:
Received 5 November 2010
Received in revised form
19 February 2011
Accepted 23 February 2011

Keywords:
Volatile organic compounds
Formaldehyde
Indoor air quality
Interior plants
Growing media

ABSTRACT

Three porous materials (growstone, expanded clay and activated carbon) were evaluated as hydroponic growing media and for their individual ability to remove the indoor volatile organic compound formaldehyde under three conditions: growing medium alone, dry medium in a pot, and wet medium in a pot. The total percent-reduction of formaldehyde by each growing media was evaluated over a 10-h period. In all cases, activated carbon achieved the highest removal under the three conditions studied with average percent reductions measured at about 98%. Four common interior plants: *Hedera helix* (English ivy), *Chrysanthemum morifolium* (pot mum), *Dieffenbachia compacta* (dump cane) and *Epipremnum aureum* (golden pathos) growing in growstone were then tested for their ability to remove formaldehyde. The removal capacity of the aerial plant parts (AP), the root zone (RZ) and the entire plant (EP) growing in growstone were determined by exposing the relevant parts to gaseous formaldehyde ($\sim$2000 μg m^{-3}) in a closed chamber over a 24-h period. The removal efficiency between species and plant parts were compared by determining the time interval required to decrease about 2/3 of the total formaldehyde concentration reduction, $T_{2/3}$. The $T_{2/3}$ measured were 23, 30, 34 and 56 min for EP of *C. morifolium, E. aureum, D. compacta and H. helix*, respectively. The formaldehyde removal by the root zone was found to be more rapid than the removal by the aerial plant parts.

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1. Introduction

Concerns about poor indoor air quality (IAQ) have steadily increased since the early 1950's when correlations between indoor air pollution, allergies and other chronic illnesses were first recognized (Randolph and Ralph, 1980; Weschler, 2009). Indoor air pollution (IAP) was further exacerbated by the energy crisis of 1973–74, when efforts to reduce energy consumption led to airtight buildings and the accumulation of indoor air (IA) pollutants. Over the past half century, poor IAQ has been attributed to factors including airtight buildings, changes in building materials and consumer products, poor ventilation and poor moisture control. Such factors have contributed to a renewed interest in green building practices (Harriman et al., 2001; Kibert, 2008; ASHRAE, 2009; Persily and Emmerich, 2010). In some metropolitan areas, IA has been found to be up to 100 times more polluted than outdoor air posing health threats and negative economical consequences (Brown, 1997; Orwell et al., 2004; Fisk, 2000). Given that people in industrialized nations spend an average of 80–90% of their time indoors (Robinson and Nelson, 1995; Klepeis et al., 2001; USEPA, 2002), the possible effects of IAP have become an issue of international concern (Samet, 1993; Fisk, 2000; Mølhave and Krzyzanowski, 2003). Poor IAQ has been linked to a number of health symptoms and between 65,000 and 150,000 deaths per year in the USA alone (Lomborj, 2002). The World Health Organization (WHO) has defined a combined group of symptoms as the Sick Building Syndrome (SBS), which include headache, nausea, dizziness, irritation of eyes, mucous membranes and the respiratory system, as well as drowsiness, fatigue, and general malaise (Kostiainen, 1995; Brasche et al., 1999). Additional impacts include decreases in work productivity and increases on medical expenses and the cost of poor indoor environmental quality has been estimated to be higher than space conditioning and ventilation energy costs (Seppanen and Fisk, 2006). An estimated average annual savings of 40–200 billion USD can be achieved by improving IAQ in the USA (Fisk, 2000).

* Corresponding author. Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, 1111 Engineering Drive, ECOT 514, UCB 428, Boulder, CO 80305, USA. Tel.: +1 303 492 7137; fax: +1 303 492 7317.
E-mail address: lupita.montoya@colorado.edu (L.D. Montoya).

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doi:10.1016/j.atmosenv.2011.02.062

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Volatile Organic Compounds (VOCs) are the most important class of contaminants in the indoor environment (Wolkoff, 2003). VOCs originate from both outdoor and indoor sources, and indoor levels can often be 10 times higher than outdoors (Brown, 1997; Rehwagen et al., 2003; Zuskin et al., 2009). A wide range (254–900) of VOCs has been identified in the IA in addition to particulate matter and inorganic gases (USEPA, 1989; Yu and Crump, 1998; Edwards et al., 2001; Sullivan et al., 2001). Some indoor VOCs are toxic at high levels and some, like benzene and formaldehyde, have been shown to be carcinogenic (Godish, 2001; IARC, 2006; ATSDR, 2007, Nielsen and Wolkoff, 2010). People are exposed to environmental formaldehyde from wood-based products, wall coverings, rubber, paint, adhesives, lubricants, cosmetics, electronic equipment, and combustion (Zhang et al., 2009; Salthammer et al., 2010). The levels of formaldehyde generally decrease with the product's age (Park and Ikeda, 2006; Chan et al., 2009) and in older homes, formaldehyde concentration levels have been found to be well below 0.125 mg m^{-3} (USEPA, 2007). These levels are close to the indoor limit of 0.1 mg m^{-3} (0.08 ppm) recommended by the World Health Organization (WHO-ROE, 2006). Unfortunately, the U.S. still lacks national IAQ standards and governmental guidelines regarding indoor ambient formaldehyde exposure. Consequently, formaldehyde levels in recently deployed Federal Emergency Management Agency (FEMA) trailers reached unsafe levels up to 1.2 ppm, resulting in sinus infections, burning sensation in the eyes, and a general feeling of illness (Babington, 2007; Hsu, 2008).

Over 35 years ago, the National Aeronautics and Space Administration (NASA) confronted health problems associated to poor IA in completely closed occupied systems in outer space, where more than 300 VOCs were detected within space vehicle environments. As a result, NASA researchers investigated the use of plants to reduce these indoor concentrations and maintain a safe and healthy personal breathing zone (Wolverton and Wolverton, 1993; Wolverton, 1996). Results from additional studies showed that plants effectively reduced levels of benzene, ammonia, formaldehyde, nitrogen oxides and particulate matter (Godish and Guidon, 1989; Wolverton and Wolverton, 1993; Giese et al., 1994; Lohr and Pearson-Mims, 1996). Plants have also been shown to increase indoor relative humidity by releasing moisture into the air thus increasing the comfort level in sealed environments. Others have linked the use of plants with improved productivity and wellbeing (Lohr et al., 1996) and observed that indoor plants are beneficial for mental health (Kim et al., 2010). Using plants offers the potential advantage of being less expensive than specialized technological approaches to remediate poor IAQ (Wolverton, 1986a,b; Darlington et al., 2001; Wood et al., 2002; NASA, 2007) and has been considered a feasible alternative to technology-based systems (Guieysse et al., 2008).

It has been previously demonstrated that formaldehyde (Kim et al., 2008) and other VOC (Wood et al., 2002; Orwell et al., 2004; Yoo et al., 2006) removal is due to biological action of plants and microorganisms. Plants have been shown to uptake air pollutants via their stomata during normal gas exchange (Schmitz et al., 2000) and various pollutants have been shown to be sequestered or degraded in situ or after transfer to other areas in the plant (Son et al., 2000). In addition to the stomata, the root zone has been shown to be an important contributor to the removal of VOCs (Yoo et al., 2006; Kim et al., 2008). Rhizosphere microorganisms, found in the growing media, have been identified as significant direct agents of VOCs removal (Wolverton and Wolverton, 1993; Wood et al., 2002; Orwell et al., 2004). Phytoremediation, defined as the use of plants to remove toxins from the air, water and soil, has been proposed as a cost effective and efficient way to improve IAQ (Liu et al., 2007). Kim et al., 2008 made simultaneous quantitative measurements of formaldehyde removal of *Fatsia japonica* and *Ficus benjamina* by the aerial plant parts and the root zone using potted plants. The only published study performed under hydroponic conditions examined benzene and n-hexane uptake of *Howea forsteriana, Spathiphyllum wallisii* and *Dracaena deremensis* using vermiculate as growing media (Wood et al., 2002).

This paper presents results of original research that examines formaldehyde uptake by three growing media (growstone, expanded clay and activated carbon) and four common indoor plants: *Hedera helix*, *Chrysanthemum. morifolium*, *Dieffenbachia. compacta* and *Epipremnum. aureum*, under hydroponic conditions (using growstone). These are the first published measurements of HCHO removal for these four indoor plants under these conditions. The formaldehyde removal of individual plant (IP) parts (AP, RZ and EP) was also experimentally determined. In this study, formaldehyde was used as a model VOC contaminant but these methods can be applied to other VOCs. The goal of the present study was not to discriminate whether the removal of HCHO was due to a biological or physicochemical process, but to determine the overall rates of removal achieved by the four selected plant species and the growing media under specific conditions.

2. Materials and methods

2.1. Test chamber

A clear glass chamber with dimensions of 61 × 30.5 × 40.6 cm and a wall thickness of 0.46 cm was used in these experiments. The removable top cover was made from Lexan (Curbell Plastics, Orchard Park, NY) and adhesive foam-rubber insulation tape was used to provide airtight seal on the top. A 12V DC fan (273-243, Radio Shack, Fort Worth, TX) inside the chamber promoted complete mixing. Room temperature was kept at 21°C ± 1 °C. Artificial lighting was provided by two 24-inch fluorescent bulbs (model F20, General Electric, Cleveland, OH) placed outside the chamber, about 18 cm from the center of the plant. Lighting was provided in 12-h cycles (day/night). The lighting provided ~2000–5000 luxes of illumination intensity to the plant leaves.

2.2. Growing media

Hydroponic systems can be used to grow plants in different growing media without soil. The most important hydroponic growing media characteristics required for root formation are water-holding capacity and air-filled porosity. The development of microorganisms in the rhizosphere, are then stimulated by the carbon that plants excrete into the root zone (Kraffczyk et al., 1984; Schwab et al., 1998). Three growing media were used: 1) growstone (Growstone, 1/4 inch particle size, Santa Fe, NM), 2) expanded clay (Hydroton, 8/16 mm, Eschborn, Germany), and 3) activated carbon, (AC, 6 × 16 Granular, Carbon Activated Corp. Orchard Park, NY). Growstone is a porous material made from up to 99% recycled glass bottles commonly used for commercial and research purposes (Chen Lopez et al., 2008). Expanded clay is a lightweight gravel manufactured specifically for hydroponic cultivation and provides effective balance of aeration and moisture (Roberto, 2003). Activated carbon is a solid adsorbent material with a high surface area, often used to remove organic pollutants from liquid or gas streams (ASHRAE, 2004). Among these three media, activated carbon has been produced and used for the purpose of removing undesirable odor, color, taste and other organic and inorganic impurities from domestic and industrial wastewater, and air purification in diverse environments (Bansal and Goyal, 2005), whereas growstone and expanded clay have not. Further, activated carbon demonstrated superior performance in biofilters because of its higher absorptive

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capacity and capability as substrate for the microorganisms (Wani et al., 1997). The use of activated carbon with plants was also explored by NASA researchers (Wolverton, 1986a,b, 1988).

2.3. Plant materials

Four plant species (less than one-year-old) were used in these experiments: 1) *H. helix*, average height of 23 cm inside a 15 cm diameter pot; 2) *C. morifolium*, average height of 38 cm inside a 15 cm diameter pot; 3) *D. compacta*, average height of 39 cm inside a 16 cm diameter pot; and 4) *E. aureum*, average height of 27 cm inside a 16 cm diameter pot. Plants were obtained from commercial distributors. These species were selected because they are common indoor plants used internationally (Wolverton, 1993; Orwell et al., 2004). The plants were acclimated to the indoor environment used in these experiments for more than 2 weeks at 21°C ± 1 °C, and 45% ± 5% relative humidity and watered as needed. After each experiment, the dry weight (dwt) of shoots and roots of each plant was determined after drying the parts using a drying oven at 70 °C for 24 h. The plants were turned hydroponic before used in these experiments using published protocols (Wood et al., 2002) and then placed in individual beakers with 500 mL DI water and 1 drop (0.04 g) of plant food (Schultz, 10-15-10 Plant Food Plus). Plants were kept under hydroponic conditions for at least 48 h prior to testing.

2.4. Experimental setup

Fig. 1 shows the experimental setup for this study. The "contaminated" air was provided by a gas bubbler containing a 37% formaldehyde solution (Acros Organics., Belgium). The formaldehyde-laden air was introduced into the chamber through the top as shown. A pulse injection of formaldehyde (~0.3 L) was introduced to generate an initial concentration of ~1.63 ppm (~2000 μg m^{-3}) inside the chamber. Air was provided by a vacuum pump (0523-101Q-g582 DX, Gast, Benton Harbor, MI) and the flow rate was measured with an air flow meter (G69D, Laboratory Supplies, Hicksville, NY). The formaldehyde levels were measured with an HCHO monitor (HFX 105; Hal Technology, Rancho Cucamonga, CA), placed inside the chamber at a sampling rate of 3 min for 24 h. In each condition, the growing medium or the plant (parts) was placed in the middle of the chamber. A CO_2 monitor (Telaire 7001, General Electric, Goleta CA) with a HOBO RH Temp 2x External Sensor Logger (H08-007-02, Pocasset, MA) was also inside the chamber.

2.5. Formaldehyde uptake by growing media

The combined chamber losses due to leakage, absorption, and chemical reactions were determined prior to the experiments with growing media and plants. The formaldehyde uptake of each growing medium was then determined under three (3) conditions: dry medium alone, dry medium inside a planting pot and wet medium inside a planting pot. Each experiment, done in triplicate, used 138 g of growing media, which translated into volumes of 780 mL, 340 mL and 280 mL, for growstone, expanded clay and activated carbon, respectively. An initial dose of formaldehyde (~2000 μg m^{-3} or 1.63 ppm) was pulse-injected into the chamber and monitoring continued for 10 h.

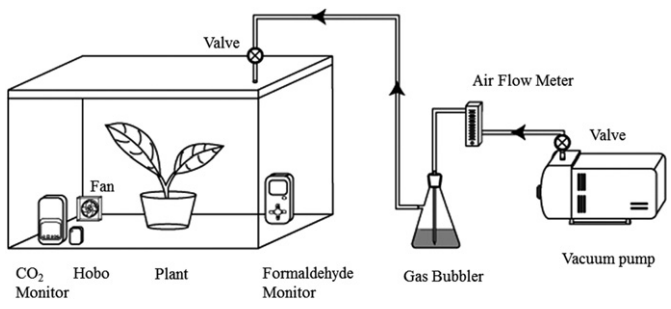

Fig. 1. Experimental setup for evaluating formaldehyde removal.

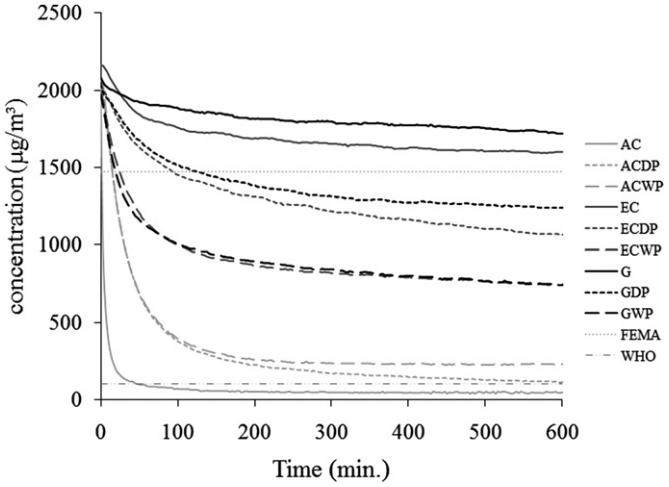

Fig. 2. Total reduction of gaseous formaldehyde achieved by three growing media in a 10-h period. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers. WHO: Indoor limit of formaldehyde recommended by WHO.

2.6. Leaf surface area

To facilitate comparisons, plant leaf surface area was determined using Image J 1.41°, a Java-basedimage processingprogram developed at the National Institutes of Health(http://rsbweb.nih.gov/ij/). The individual leaf area was determined by tracing the leaf on paper and then analyzing the traces with Image J. In the case of *E. aureum and D. compacta*, all the leaves were traced and then imaged. In the case of *H. helix* and *C. morifolium*, all plant leaves were counted and categorized as large, medium or small. Six sample leaves were then taken from each category and measured by Image J. The average surface area value for each category was then multiplied by the number of the leaves counted in each category and the total surface area was calculated by adding all the individual leaf areas.

2.7. Formaldehyde uptake by plants

For these experiments, done in triplicate, plants were subjected to a 12-h cycle of day/night illumination for 24 h. Formaldehyde was pulse-injected into the chamber (~1.63 ppm) and its concentration level was then monitored. The first set of experiments evaluated the formaldehyde removal capacities of the IP parts. Here, aerial plant (AP) parts were evaluated by sealing the roots and growstone inside a Teflon bag. The opening was sealed around the plant shoots with a wire tie. A similar technique was used by Yoo et al. (2006) and Kim et al., 2008. The plant then rested at least 24 h before starting the next experiment. Next, the contribution of the root zone (RZ) to the formaldehyde removal was determined by surgically removing the plant above the medium and repeating the experiment. In the second set of experiments, the removal capacity of the entire plant (EP) was evaluated by exposing

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the roots, growing media and the aerial plant leaves to contaminated air. A new set of plants for each of the four (4) species were used in these experiments to avoid confounding errors due to prior formaldehyde exposure.

2.8. Data analysis

Gas concentrations were expressed as micrograms per cubic meter ($\mu g/m^{-3}$). The percentage of removal efficiency in each case was evaluated using the initial and final gas concentrations within the chamber and was calculated as:

$$\frac{(C_0 - C_F)}{C_0} \times 100\%$$

The amount of gas removed per unit surface area of plant leaf was calculated as:

$$\mu g/m^3 cm^2 = \frac{(C_0 - C_F)}{A}$$

where C_0 is initial concentration ($\mu g/m^3$), C_F is final concentration ($\mu g/m^{-3}$), and A is total leaf area (cm^2). To compare the removal efficiency among species and plant parts, the time required to reach about 2/3 of a 24-h reduction in the concentration ($T_{2/3}$) was used. This parameter was used as a pseudo-characteristic time for each plant since the formaldehyde decrease did not exactly follow an exponential decay function.

3. Results and discussion

The chamber's combined losses due to leakage, absorption, and chemical reactions with the chamber surfaces starting from an initial formaldehyde concentration of about 2000 $\mu g\ m^{-3}$, were 9% and 13% for the first 5 and 10-h periods respectively. Kim et al. (2008) reported similar values for a 5-h period.

3.1. Formaldehyde uptake by growing media

Table 1 lists the initial (C_0), final (C_F) concentrations measured after 10 h and the total percent reduction achieved by growstone, expanded clay and activated carbon. The average percent reductions measured were 97.6%, 94.1% and 88.9% for dry activated carbon alone (AC), dry activated carbon in a pot (ACDP), and wet activated carbon in a pot (ACWP), respectively. AC and ACDP had the same surface area of activated carbon, where AC was spread out in the testing chamber and ACDP was kept inside the pot. Even though AC had the same surface area as ACDP, more of its surface area was directly exposed to the formaldehyde and therefore, displayed a higher formaldehyde absorption capacity (Fig. 2).

Table 1
Total reduction of gaseous formaldehyde achieved by three growing media in a 10-h period. C_0: initial concentration, C_F: final concentration.

	Concentration ($\mu g\ m^{-3}$) in 10 h		
	C_0	C_F	Total % reduction
Activated Carbon (AC)	2012 ± 32	49 ± 25	97.6 ± 3
Activated Carbon dry in pot (ACDP)	2033 ± 90	119 ± 37	94.1 ± 2
Activated Carbon w/water in pot (ACWP)	2065 ± 37	229 ± 14	88.9 ± 1
Expanded Clay (EC)	2164 ± 169	1599 ± 237	26.4 ± 5
Expanded Clay dry in pot (ECDP)	2033 ± 26	1067 ± 77	47.5 ± 4
Expanded Clay w/water in pot (ECWP)	2033 ± 26	1067 ± 77	62.6 ± 6
Growstone (GA)	2086 ± 32	1722 ± 7.08	17.4 ± 1
Growstone Dry in pot (GDP)	2041 ± 50	1239 ± 68	39.3 ± 3
Growstone w/water in pot (GWP)	1971 ± 14	744 ± 227	62.3 ± 11

Table 2
Entire plant characteristics of plant species studied. Data represent Mean ± SD ($n = 3$), dwt: dry weight, A_{OL}: leaf area used leaf only experiments, A_{EP}: leaf area used in entire plant experiments.

Species	Plant characteristics			
	Leaf area (cm^2)		Shoot dwt (g)	Root dwt (g)
	A_{EP}	A_{OL}		
Hedera helix	2751 ± 107	2576 ± 163	9.57 ± 1.53	2.86 ± 0.39
Chrysanthemum morifolium	2762 ± 143	2870 ± 122	13.81 ± 0.77	2.38 ± 0.15
Dieffenbachia compacta	3718 ± 321	2664 ± 93	7.42 ± 1.46	4.36 ± 0.93
Epipremnum aurenum	3506 ± 281	2516 ± 212	6.62 ± 1.10	5.21 ± 0.59

Although ACWP displayed higher formaldehyde uptake, previous experiments revealed that as a growing media, it did not properly sustain long-term plant growth. Further experiments of formaldehyde uptake by plants employed growstone as the hydroponic growing media because it provided the best growth conditions for the plants.

3.2. Leaf surface area

Table 2 shows the total leaf area (A_{TL}) determined for the four plant species included in this study. These values were determined for the cases involving the first set (leaf-only, A_{OL}) and second set (entire plant, A_{EP}) of experiments. The coefficient of variation (CV) for the A_{OL} was 6% for *H. helix*, 4% for *C. morifolium*, 3% for *D compacta* and 8% for *E. aurenum*. The CV of A_{EP} for *H. helix*, *C. morifolium*, *D. compacta* and *E. aurenum* were 3%, 5%, 8% and 8%, respectively.

3.3. Formaldehyde uptake by plants

Key plant characteristics (leaf area, shoot dry weight and root dry weight) were evaluated to provide comparisons among plant species and are shown in Table 2. The formaldehyde absorption capacity of each plant was evaluated, in triplicate, under three conditions: 1) AP parts, 2) RZ, and 3) EP (entire plant -aerial plant parts and root zone). Table 3 summarizes the results of these experiments. The combined removal achieved by the AP parts and by the RZ in 24 h was slightly greater than that of the EP. These

Table 3
Total reduction of gaseous formaldehyde achieved by AP parts, RZ and EP of four plant species in a 24-h period. C_0: initial concentration, C_F: final concentration AP: aerial plant parts, RZ: root zone, EP: entire plant, $T_{2/3}$: the time interval required to achieve 2/3 of the total formaldehyde reduction.

	Concentration ($\mu g\ m^{-3}$) in 24-h			$T_{2/3}$ (min.)	Total leaf area (cm^2)
	C_0	C_F	Total change %		
Hedera Helix					
AP	2012 ± 65	384 ± 167	81 ± 7	105	2576 ± 179
RZ	2004 ± 28	295 ± 63	85 ± 2	98	–
EP	1971 ± 28	241 ± 46	88 ± 2	56	2751 ± 107
Chrysanthemum morifolium					
AP	1980 ± 28	115 ± 49	92 ± 2	44	2870 ± 91
RZ	1971 ± 14	233 ± 12	88 ± 1	66	–
EP	1992 ± 39	323 ± 14	84 ± 1	23	2762 ± 143
Dieffenbachia compacta					
AP	1967 ± 7	160 ± 12	92 ± 1	85	2663 ± 94
RZ	1959 ± 7	160 ± 24	92 ± 1	59	–
EP	1984 ± 26	73.62 ± 0	96 ± 0	34	3718 ± 321
Epipremnum aurenum					
AP	1992 ± 7	102 ± 19	95 ± 1	63	2516 ± 212
RZ	1955 ± 7	131 ± 14	93 ± 1	36	–
EP	1963 ± 12	119 ± 19	94 ± 2	30	3506 ± 281

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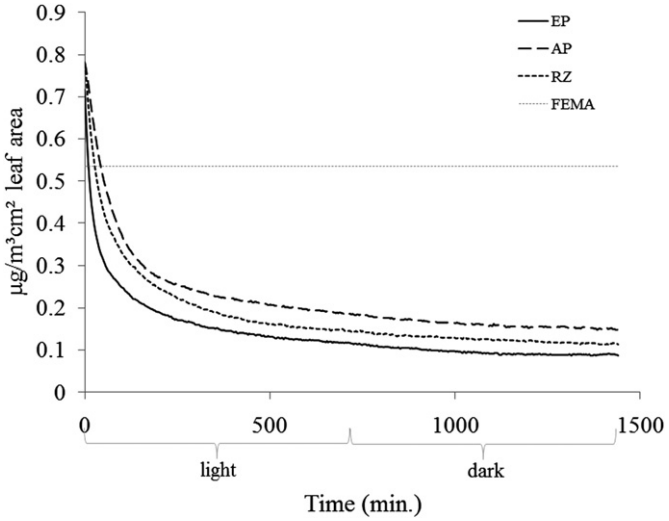

Fig. 3. Formaldehyde removal by EP, AP parts and RZ of *H. helix*. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

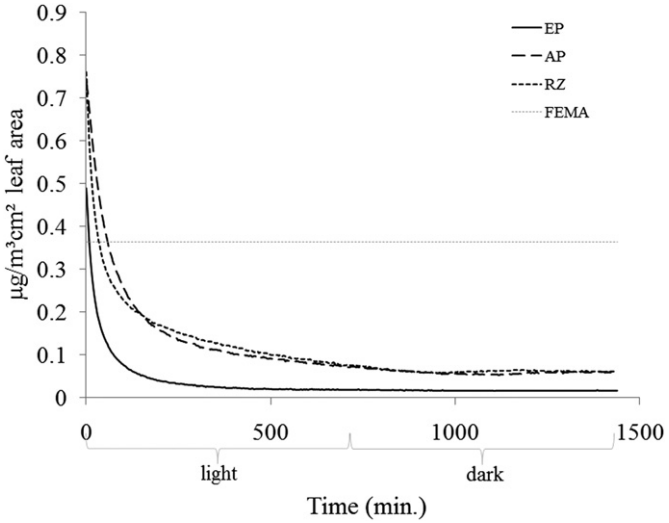

Fig. 5. Formaldehyde removal by EP, AP parts and RZ of *D. compacta*. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

results signaled the probability of competition between AP and RZ with declining formaldehyde concentration. Kim et al. (2008) reported similar findings for a different set of plants. The contribution of the combined chamber losses was not deducted from the reported results. The formaldehyde removal by the AP parts reported here represent the values that can be achieved without the growing media contribution. The formaldehyde reduction of watered growing media was found to be 57%; however, this reduction cannot be additive to the contribution of RZ and EP experiments due to the competition between different plant parts. This study did not determine how much each part of the plant and the growing media contributed individually to the overall reduction; however, the contributions from the plants and the growing media can be roughly compared. It is also expected that a small amount of water was lost from the media and the plant during the course of the experiments and that a small portion of this water ended up condensing on the walls of the test chamber and on the surfaces of the leaves of some species. Ultimately, a fraction of the extracted formaldehyde may end up ultimately in dew; however, the intent of this study was to demonstrate that formaldehyde could be removed from the air irrespective of the mechanism. The formaldehyde removal values reported here include the contribution by combined chamber losses including the small fraction that may end up in dew.

Fig. 3 shows the formaldehyde reductions achieved by the EP, AP parts and RZ of *H. helix* in a 24-h period. The $T_{2/3}$ of EP, AP and RZ parts were 56 min, 105 min., and 98 min, respectively (Table 3). The higher uptake by the RZ may be due to the presence of microorganisms in the RZ, as previously determined (Wolverton and Wolverton, 1993; Wood et al., 2002; Orwell et al., 2004). Fig. 4 shows the formaldehyde reductions achieved by *C. morifolium* in a similar period. The EP *C. morifolium* achieved a $T_{2/3}$ of 23 min

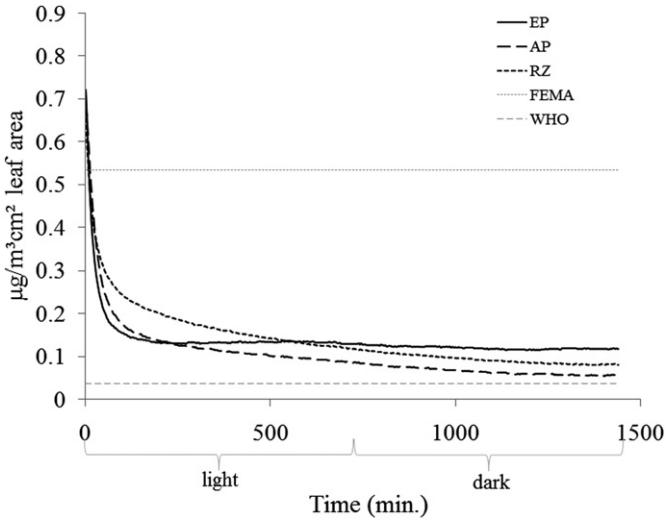

Fig. 4. Formaldehyde removal by EP, AP parts and RZ of *C. morifolium*. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers. WHO: Indoor limit of formaldehyde recommended by WHO.

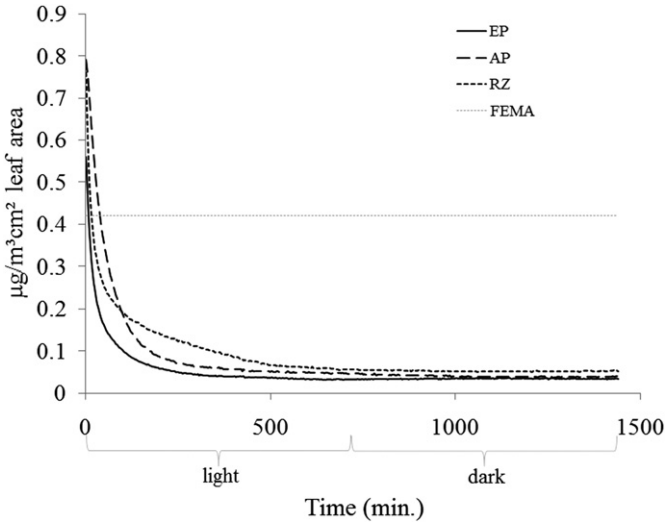

Fig. 6. Formaldehyde removal EP, AP parts and RZ of *E. aurenum*. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

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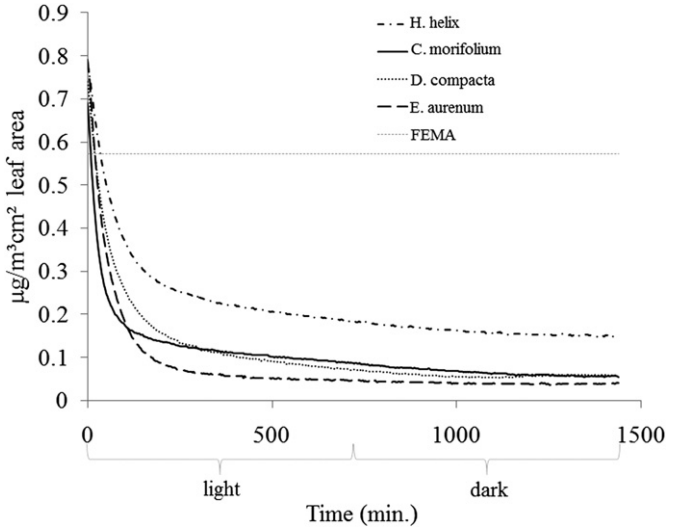

Fig. 7. Formaldehyde removal by AP parts of four plant species. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

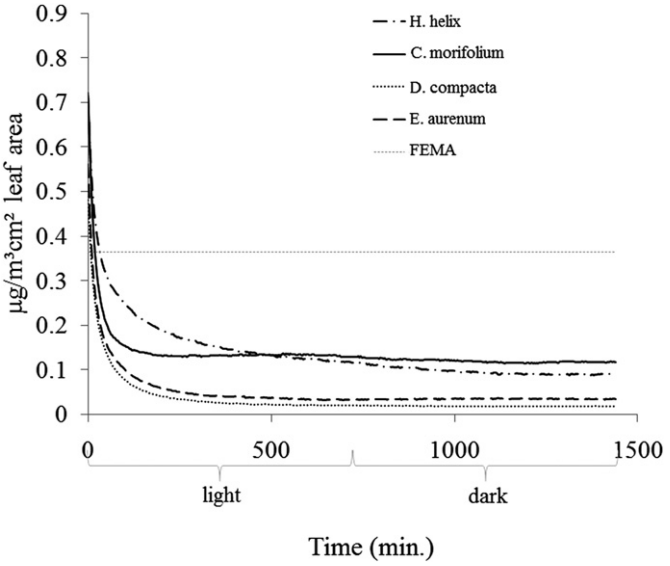

Fig. 9. Formaldehyde removal by EP of four plant species. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

Fig. 5 shows reductions achieved by the EP, AP parts and RZ of *D. compacta*. Although the AP parts and the RZ for *D. compacta* showed similar total reductions in a 24-h period, the RZ had a $T_{2/3}$ of 59 min while AP had a $T_{2/3}$ of 85 min (Table 3). Fig. 6 shows reductions achieved by EP, AP parts and RZ of *E. aurenum*.

Fig. 7–9 show the individual formaldehyde removal by the IP parts per surface area and compare the four plant species studied. Fig. 7 shows the AP removal of formaldehyde by all four species. In this case, the AP of *C. morifolium* showed the quickest initial removal ($T_{2/3}$ = 44 min), evidenced by the steepest initial slope; however, the maximum AP total removal (95%) in 24 h was achieved by AP of *E. aurenum*. These results demonstrate that plant species have a significant but variable effect on removal of formaldehyde. Fig. 8 shows the formaldehyde removal of the RZ by all four species. Results are shown per leaf area (A_{OL}) in order to compare with AP parts and EP.The RZ of *E. aurenum* showed both the quickest initial removal ($T_{2/3}$ = 36 min) and the maximum total removal (93%) in 24 h Fig. 9 shows EP formaldehyde removal by all four species. In this case, the EP of *C. morifolium* showed the smallest $T_{2/3}$ (23 min); however, the maximum total removal (96%) in 24 h was achieved by EP of *D. compacta*.

In order to compare rates of removal under light versus dark conditions, additional experiments were conducted. The first set of experiments were performed for 24 h, with an initial 12-h period under light conditions followed by a 12-h period under dark conditions. All four species showed similar percent reductions in the first 12 h (under light conditions) and the results did not show any discontinuities in the data during the transition from light to dark. Another set of experiments was conducted where initial dark conditions were tested for 12 h for all plant species at an initial formaldehyde concentration of ~2000 µg m^{-3} Fig. 10 shows the results for the RZ experiments. The present study showed similar results to those obtained by Kim et al. (2008) under potted

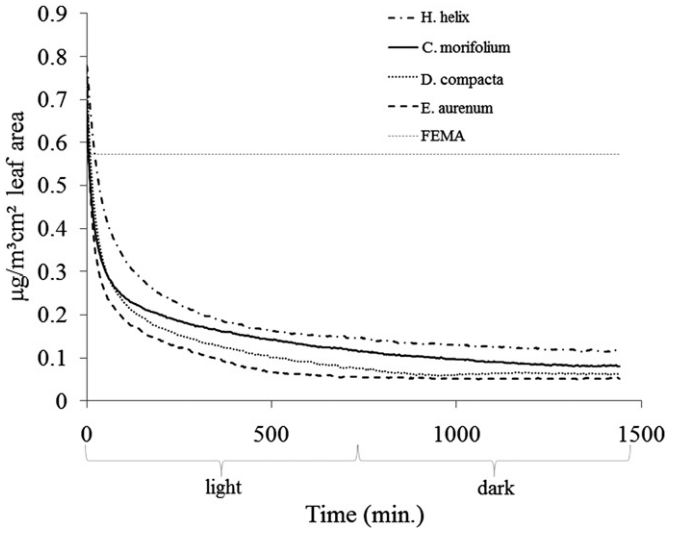

Fig. 8. Formaldehyde removal by RZ of four plant species. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

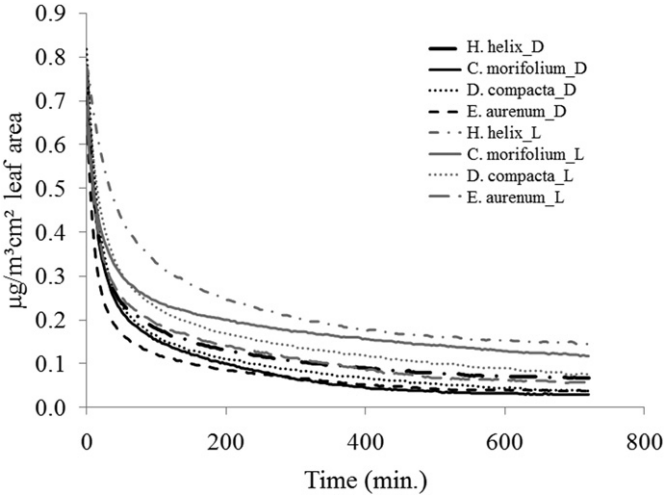

Fig. 10. Formaldehyde removal by RZ of four plant species. *Initial* formaldehyde concentration was ~2000 µg m^{-3} and exposure was for 24 h. FEMA: Formaldehyde levels found in bedrooms of FEMA Trailers.

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conditions. In this study, the AP parts formaldehyde removal for *H. helix* in 5 h under light conditions were similar to those displayed by *F. japonica* and *F. benjamaine* (0.50 and 0.32 $\mu g\ m^{-3}\ cm^2$ leaf area, respectively) in that study. The higher removals in the present study compared to those from Kim et al. (2008) may be due to an improved growth zone created by the hydroponic medium, which allowed the plant roots to live and stimulate the development of microorganisms in the rhizosphere. Ultimately, there were significant differences in formaldehyde removal between the two studies under dark conditions.

4. Conclusions

Of the three growing media studied, activated carbon alone (AC) showed the highest formaldehyde removal at about 98% for a period of 10 h and exhibited a $T_{2/3}$ of 6 min. The formaldehyde reductions for a 10-h period achieved by expanded clay and growstone in a pot under wet conditions, the better substrates for plant growth, were 62.6% and 62.3%, respectively. Their $T_{2/3}$ for the same time period were estimated at 58 min and 53 min, respectively. The four plant species studied demonstrated similar abilities to remove formaldehyde (around 90%) for a 24-h period; however, the $T_{2/3}$ determined for each species was significantly different. The EP of *C. morifolium* was found to provide the fastest uptake (23 min), whereas *H. helix* under all conditions provided the slowest uptake of formaldehyde among the four plant species. In a 12-h period, excluding the AP parts of *D. compacta* and *E. aurenum*, all four plants species under all conditions demonstrated quicker uptake of formaldehyde under dark versus light conditions.

Acknowledgments

The authors would like to thank Ilgaz Akseli, Zhicheng Wei, Michael P. Allard, David Rangel, Philippe Baveye and Don VanSteele for their technical assistance. Thank you also to Mark Mistur and Anna Dyson for insight into the future application of this work. This work was partially supported by New York State Foundation for Science, Technology and Innovation (NYSTAR) and a Humanities, Art and Social Sciences (HASS) Fellowship from Rensselaer Polytechnic Institute.

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