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 (~2000 $\mu g\ m^{-3}$) 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.

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).

1352-2310/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2011.02.062

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