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Formaldehyde removal by potted plant–soil systems

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ABSTRACT

Formaldehyde is a major indoor air pollutant. Formaldehyde removal from indoor air conduces to decrease the health risk for urban inhabitants. In this study, a dynamic chamber technique was employed to investigate formaldehyde removal by potted spider plant (*Chlorphytum comosum*), aloe (*Aloe vera*) and golden pothos (*Epipremnum aureum*) with potted soils. The results showed that the potted plant–soil systems could remove formaldehyde from air in a long time. The spider plant–soil system had the highest formaldehyde removal capacity compared with others. Higher metabolisms in plants and microorganisms in daytime may give a reasonable explanation for higher formaldehyde removal capacities for plant–soil systems in daytime. The order of formaldehyde removal capacity for the three plant species agreed well with the sequence of formaldehyde dehydrogenase activities from plant leaves. Formaldehyde removal by plant may be diffusion-limited rather than reaction-limited since the detached formaldehyde dehydrogenase activities from the leaves of the three plant species were higher than in vivo metabolic capacities. Formaldehyde in air can be largely absorbed and metabolized by the microorganisms in the potted soils indicating that further elevating formaldehyde removal capacity for plant–soil system will be realized by increasing exposed surface of potted soil.

1. Introduction

Currently, a tight space around inhabitants is provided owing to energy-efficient strategy, which results in an increase in the concentrations of indoor air pollutants. This creates a high health risk for urban inhabitants because they generally spend more than 80% of their time indoors [1,2]. Formaldehyde (HCHO), a major indoor air pollutant, attracts worldwide attention because the exposure to formaldehyde is known to cause irritation, allergic asthma and neurasthenia, and to induce genotoxicity and carcinogenesis [3]. Since synthetic resins including urea-formaldehyde, phenol-formaldehyde and melamine-formaldehyde are widely used in buildings and furnishings, newly built or remodeled residences are often found to release high levels of indoor formaldehyde [3,4]. The surveys in China during the period of 2002–2004 revealed that indoor formaldehyde levels in more than 69.4% of all new or newly remodeled houses exceeded the national standard of China (0.1 mg m^{-3})[3]. Therefore, the mitigation of formaldehyde is a significant practice. Till date, a lot of physical, chemical and biological techniques are well established for the purification of formaldehyde-polluted air [5–7].

Various plants can remove formaldehyde from indoor air by means of the uptake and metabolism [8–10]. One part of absorbed formaldehyde is oxidated into carbon dioxide in the Calvin cycle while the other is incorporated into the organism including organic acids, amino acids, free sugars, lipids and cell-wall components [9,11]. Much faster formaldehyde assimilation by plants appears in the light than in the dark [10,11]. There is a mass of literature demonstrating that plant roots can remove toxic pollutants by absorption and/or direct enzymatic degradation [12–14]. Besides, soil microorganisms are able to degrade pollutants and this degradation is found to be promoted by root exudates [13,15]. Some scientific findings revealed that formaldehyde was adsorbed by potted soil and was intensively degraded by microorganisms [10,16,17]. A chamber experiment indicated that ca. 92% formaldehyde was removed by the root zone rather than aerial plant parts at night, and the removal of ca. 90% formaldehyde was due to microorganisms and roots rather than soil adsorption [10].

Till date, the great majority in experiments investigating air purification by plants were conducted in static chambers [9,10,18]. An artifact that the ratios of humidity and CO_2 concentration vary with time may be caused in this method. In order to overcome this artifact, a dynamic chamber is preferable. Additionally, plants and soil microorganisms used to air purification may be acclimatized pollutants after a certain period. However, it is scarce that conclusions on air purification by plants and soil microorganisms were based on a long term of polluted air fumigation.

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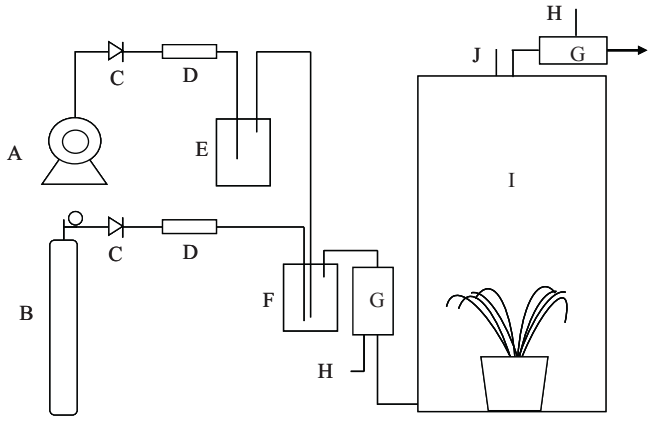

Fig. 1. Scheme of the experimental apparatus. (A) air pump, (B) N_2 gas cylinder, (C) needle vale, (D) flowmeter, (E) formaldehyde solution (37%) vessel, (F) mixing vessel, (G) buffer vessel, (H) gas sampling port, (I) dynamic chamber, (J) water injecting port.

In this work, a dynamic chamber technique was employed to investigate formaldehyde removal by potted spider plant (*Chlorphytum comosum*), aloe (*Aloe vera*) and golden pothos (*Epipremnum aureum*) with potted soils in a long term of fumigation. Formaldehyde dehydrogenase (FDH) activities in plant leaves and the effects of formaldehyde concentration and light on formaldehyde removal capacities were also investigated.

2. Experimental

2.1. Apparatus

The apparatus, schematically given in Fig. 1, consisted of two major components: a dynamic chamber and a gaseous formaldehyde generation system. The dynamic chamber was made of cylindrical plexiglass chamber with an inner diameter of 40 cm and a height of 60 cm. The gas stream with high-concentration formaldehyde was obtained by bubbling a low flowrate of N_2 stream through a formaldehyde solution vessel. Then the gas containing formaldehyde vapor was adequately mixed with a high flowrate of air stream. The high flowrate of air stream was humified to 50–60% before mixing. The inlet polluted air stream with the desired concentration of formaldehyde was obtained by regulating both the low flowrate of and the high flowrate of streams with two needle valves. Since it is difficult to control accurately formaldehyde concentration to an integer, a variation of 0.2 mg m^{-3} from the objective inlet concentration is permissible. The actual inlet and outlet formaldehyde concentration were determined by a formaldehyde analyzer (4160, Interscan Co., USA). The apparatus ran at 23 ± 1 °C during the whole study.

2.2. Plant material preparation

All experimental plants including spider plant, aloe and golden pothos were planted to the porcelain pots with an inner diameter of 15 cm and a height of 10 cm. Each pot contained 2 kg of dry fluvo-aquic soil. The soil has a pH of 8.3, an organic matter content of 15.8 g kg^{-1}, a clay (<0.005 mm) fraction of 36%, a total N content of 1.12 g kg^{-1}, and total P content (as P_2O_5) of 1.07 g kg^{-1}. Prior to the transplant, urea, superphosphate and potassium chloride were applied into the soil as (per kilogram soil) 0.18 g N, 0.12 g P_2O_5 and 0.12 g K_2O. During the whole study, enough deionized water was added into spider plant and golden pothos pots every day and into aloe pots every 2 days to hold 15% volumetric soil moisture. All plants have been cultivated in a light intensity of 240 μmol m^{-2} s^{-1} (12 h in light) for more than 5 months before formaldehyde fumigation experiments.

The three potted plant species were put into the dynamic chamber. The chamber was fed with an initial formaldehyde concentration of 4.0 mg m^{-3} and formaldehyde concentration was increased by 0.5 mg m^{-3} every 5 days depending on a visible foliar injury. The phytotoxic formaldehyde concentrations for spider plant, aloe and pothos were quantified as 11.5, 8.5 and 6.5 mg m^{-3}, respectively. The exposure formaldehyde concentration for each plant species in the experiments described below was less than the respective phytotoxic concentration.

2.3. Formaldehyde removal measurement

Each potted plant species placed into each dynamic chamber was subjected in turn to the light intensities of 80, 160, 240 μmol m^{-2} s^{-1} (12 h in light). For each light intensity treatment, the chamber was fed with an initial formaldehyde concentration of 1.0 mg m^{-3} and formaldehyde concentration was increased by 1.0 mg m^{-3} every 3 days until the concentration approached the phytotoxicity for each species. At the end of each period of 3 days, formaldehyde removal by potted plant–soil systems was measured by determining formaldehyde concentrations of the inlet and the outlet of the dynamic chamber with a formaldehyde analyzer (4160, Interscan Co., USA).

In order to investigate the contributions of soil and aboveground part of plant to formaldehyde removal, each potted plant species placed into each dynamic chamber was subjected to the light intensity of 240 μmol m^{-2} s^{-1} (12 h in light). The chamber was also fed with an initial formaldehyde concentration of 1.0 mg m^{-3} and formaldehyde concentration was increased by 1.0 mg m^{-3} every 3 days until the concentration approached the phytotoxicity for each species. At the end of each period of 3 days, formaldehyde removal by potted plant–soil systems was measured by determining formaldehyde concentrations of the inlet and the outlet of the dynamic chamber with a formaldehyde analyzer (4160, Interscan Co., USA). Hereafter, aboveground part of plant was surgically removed and the soil (including roots) was put back into the dynamic chamber. The formaldehyde removal capacity of soil was measured at 240 μmol m^{-2} s^{-1} light intensity (12 h in light) with an initial formaldehyde concentration of 1.0 mg m^{-3}. The fumigating formaldehyde concentration was also increased by 1.0 mg m^{-3} every 3 days until the concentration approached the phytotoxicity for each species. At the end of each period of 3 days, formaldehyde removal by potted soils was measured by determining formaldehyde concentrations of the inlet and the outlet of the dynamic chamber with a formaldehyde analyzer (4160, Interscan Co., USA). The formaldehyde removal capacity of shoot was calculated by subtracting the removal capacity of the soil from the removal capacity of the corresponding potted system. It is noted that new plantlets for plants were removed during the fumigation. In this study, only one experimental result was selected for formaldehyde removal measurement since the differences in the weights of same pant species, especially aloe, were obvious for replicates.

Formaldehyde adsorptions by a dynamic chamber and soil were investigated in a range of 1.0–12.0 mg m^{-3} inlet formaldehyde concentrations. The observation indicated that the outlet formaldehyde concentration in the chamber without potted soil was not consistent with the inlet concentration until ca. 18 h of fumigation. The outlet formaldehyde concentration in the chamber with the sterilized potted soil of 2.0 kg was not equal to the inlet concentration until ca. 25 h of fumigation.

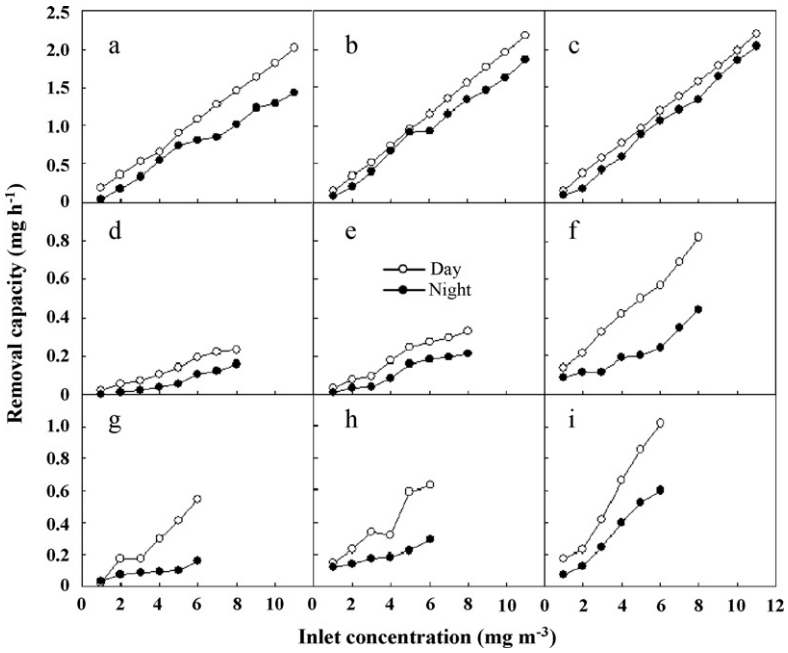

Fig. 2. Formaldehyde removal by potted spider plant–soil (top: a–c), aloe–soil (middle: d–f) and golden pothos–soil (bottom: g–i) systems as affected by inlet formaldehyde concentrations and light intensities during daytime and nighttime. The light intensities are 80 (left: a, d and g), 160 (middle: b, e and h), 240 (right: c, f and i) $\mu mol\,m^{-2}\,s^{-1}$.

2.4. Formaldehyde dehydrogenase isolation and characterization

The determination of FDH activity was employed by a modified method described by Giese et al. [9] and Schmitz et al. [11]. After 4.5 $mg\,m^{-3}$ formaldehyde fumigation for 10 days, plant leaves (100 g fresh weight) was powdered under liquid nitrogen in a mortar with pestle. The powder was transferred into 200 ml of enzyme-extraction medium composed of 50 mM Na_2HPO_4/KH_2PO_4 buffer (pH 7.4), 10% (w/v) insoluble polyvinylpolypyrolidone (PVPP), 0.05% Triton × 100 (v/v), 5 mM dithioerythritol (w/v) and 5 mM ascorbic acid (w/v). After stirring for 30 min in a stirrer, the mixture was filtrated through a 100 μm-mesh nylon net. The crude extract was centrifuged for 15 min at 40,000 g at 4 °C. Powdered solid $(NH_4)_2SO_4$ was added into the supernatant to 75% saturation. The mixture was stirred for 30 min at 4 °C and centrifuged for 30 min at 40,000 g at 4 °C. The precipitate was collected and dissolved in 2.5 ml of 50 mM Na_2HPO_4/KH_2PO_4 buffer (pH 7.4) and 5 mM DTE. The mixture was desalted by dialyzing at 4 °C until no SO_4^{2-} was detected in the dialysate. The remainder was used for determining protein content and FDH activity. The protein was determined by the Bio-Rad Protein Assay with albumin fraction V from bovine blood as standard. The reaction mixture for FDH consisted of 120 mM $Na_4P_2O_7$ buffer (pH 8), 20 mM GSH, 30 mM NAD^+ and 50 μl of enzyme extract. Absorbency at 340 nm was recorded every 30 s for 5 min. After addition of 50 μl of 30 mM formaldehyde, the increase in absorbency at 340 nm was recorded every 30 s for 5 min. FDH activities were calculated in terms of $nmol\,min^{-1}\,mg^{-1}$ protein by using a molar absorption value (340 nm) of 6300 ($l\,mol^{-1}\,cm^{-1}$) for NADH [9]. Herein, three replicates were set for the measurements of protein contents and FDH activities.

2.5. Statistical analysis

Data analysis was performed with SYSTAT for Windows (SPSS, Inc.). An analysis of variance test (ANOVA) was applied to test the effects of light and plant species on formaldehyde removal and to test the difference among FDH activities in the three plant species.

3. Results

3.1. Effects of formaldehyde concentration and light intensity on removal capacity

Fig. 2 shows the changes in formaldehyde removal by plant–soil systems with inlet formaldehyde concentration at the light intensities of 80, 160 and 240 $\mu mol\,m^{-2}\,s^{-1}$. The removal capacity for each plant–soil system increased with inlet formaldehyde concentration within the corresponding phytotoxic formaldehyde concentration. All plant–soil systems significantly ($P < 0.01$) removed more formaldehyde in daytime than in nighttime. Formaldehyde removal efficiencies for spider plant–soil system were ca. 90%, 92% and 95% at the light intensities of 80, 160 and 240 $\mu mol\,m^{-2}\,s^{-1}$ in daytime, respectively. Correspondingly, formaldehyde removal efficiencies appeared 14%, 20% and 53% for aloe–soil system, and 34%, 56% and 84% for golden pothos–soil system, respectively. These results showed that increasing light intensity slightly (not significantly) stimulated formaldehyde removal by spider plant–soil system while increasing light intensity significantly ($P < 0.01$) stimulated formaldehyde removal by aloe–soil and golden pothos–soil systems. At the same inlet formaldehyde concentration and light intensity, the order of formaldehyde removal capacity for the three plant–soil systems was: spider plant–soil > golden pothos–soil > aloe–soil (significant difference, $P < 0.01$).

3.2. Contribution of plants to formaldehyde removal

Formaldehyde removal by shoots of potted spider plant, aloe and golden pothos is presented in Fig. 3. The removal capacity for each plant shoot increased with inlet formaldehyde concentration within the corresponding phytotoxic formaldehyde concentration. All plant shoots significantly ($P < 0.01$) removed more formaldehyde in daytime than in nighttime. The difference

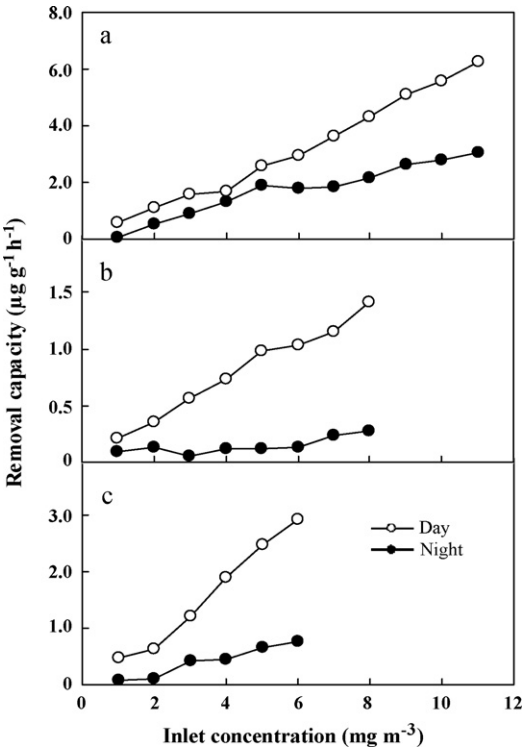

Fig. 3. Formaldehyde removal by potted spider plant shoot (a), aloe shoot (b) and golden pothos shoot (c) with increasing inlet formaldehyde concentration at the light intensity of 240 μmol m^{-2} s^{-1} during daytime and nighttime.

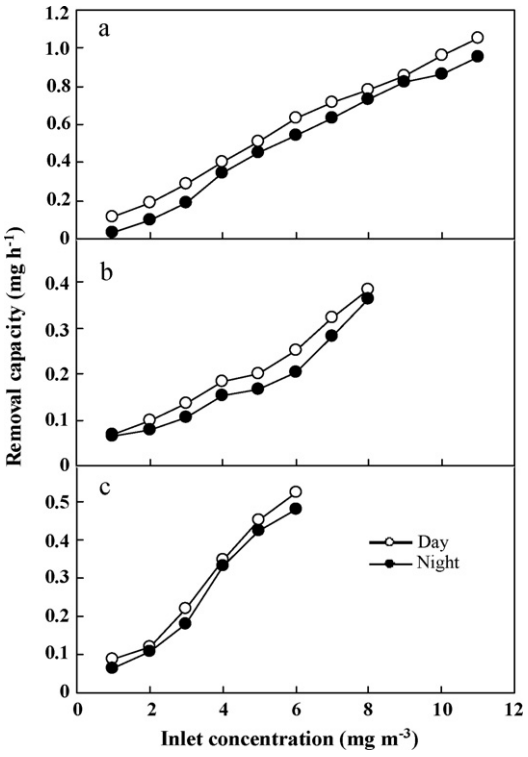

Fig. 4. Formaldehyde removal by potted soils for spider plant (a), aloe (b) and golden pothos (c) with increasing inlet formaldehyde concentration at the light intensity of 240 μmol m^{-2} s^{-1} during daytime and nighttime.

of formaldehyde removal between daytime and nighttime for spider plant shoot appeared less than those for the others. At the same inlet formaldehyde concentration (>2 mg m^{-3}), the order of formaldehyde removal capacity for the three plant shoots was: spider plant > golden pothos > aloe (significant difference, $P < 0.01$).

3.3. Contribution of soils to formaldehyde removal

Although a small surface (0.018 m^2) of soil in the pot was exposed to formaldehyde, the potted soils planted the three plant species all played an important role in formaldehyde removal (Fig. 4). The contributions of the soils planted spider plant, aloe and golden pothos to formaldehyde removal accounted for 55%, 52% and 45% of the total formaldehyde removed by the plant–soil systems, respectively. Formaldehyde removal capacities for all soils in daytime were still greater (not significant) than those in nighttime within observed formaldehyde concentrations. However, the differences of the removal capacities for the soils between daytime and nighttime obviously reduced compared with the corresponding plants. At the same inlet formaldehyde concentration, the soil planted spider plant attained the greatest removal capacity, and then the soil planted golden pothos (significant difference, $P < 0.01$).

3.4. Formaldehyde dehydrogenase activity

Formaldehyde dehydrogenase activities in the leaves of spider plant, aloe and golden pothos were 7.8, 2.8 and 4.4 nmol min^{-1} mg^{-1} protein, respectively (Table 1). This indicated that a significant ($P < 0.01$) difference among FDH activities in the leaves of spider plant, aloe and golden pothos. Considering that protein contents in the leaves of spider plant, aloe and golden pothos were 0.67, 0.49 and 0.66 mg g^{-1} f.w., respectively, the fresh leaves of the three plant species theoretically hold formaldehyde removal capacities of 9.4, 2.5 and 5.2 μg g^{-1} h^{-1}, respectively. Compared with data presented in Fig. 3, this indicated that detached FDH activities from the leaves of the three species were higher than in vivo metabolic capacities.

4. Discussion

The results showed that the three plant–soil systems could efficiently remove formaldehyde from air in a long time of formaldehyde fumigation. Formaldehyde removal might be attributed to the adsorption by the surfaces of plant and soil, the uptake by the stomas of plant and the degradation by microorganism [8,10,16,17]. Since the saturation points of formaldehyde adsorption on the surfaces of plant and soil easily reach in a short time, formaldehyde removal in this study was due to plant metabolism and microbial degradation rather than the adsorption by plant and soil. As seen in Figs. 2–4, the spider plant–soil system attained the greatest formaldehyde removal capacity among the three plant–soil systems as both spider plant and the soil planted it removed more formaldehyde than the others. High formaldehyde removal capacity for spider plant–soil system was previously reported in literature [9,16,19].

Much more formaldehyde removal by plant shoots during daytime in this study was consistent with the result reported by

Table 1
Protein contents and formaldehyde dehydrogenase (FDH) activities in the leaves of spider plant, aloe and golden pothos after 4.5 mg m^{-3} formaldehyde fumigation for 10 days.

Plant species	Protein content (mg g^{-1} f.w.)	FDH activity (nmol min^{-1} mg^{-1} protein)
Spider plant	0.67 ± 0.04	7.8 ± 1.2
Aloe	0.49 ± 0.07	2.8 ± 0.4
Golden pothos	0.66 ± 0.06	4.4 ± 0.7

Values represent means ± standard deviation.

Kim et al. [10]. Formaldehyde removal is highly related to plant metabolism because formaldehyde is believed to be a central intermediate of photosynthetic carbon dioxide fixation. During formaldehyde metabolism, it is coupled with glutathione to form S-hydroxymethylglutathione, which is subsequently converted to S-formylglutathione [20,21]. Thus, higher photosynthesis and metabolism in plant in daytime lead to more formaldehyde removal compared with nighttime. A little more formaldehyde removed by the soils during daytime in this study might be also explained as higher absorption and metabolism of formaldehyde by the rhizosphere [10].

Great formaldehyde removal capacity in potted soils in this study was also previously documented in literature [16,19]. This result may be attributed to high microbial activity in soil. Root exudates and root autolysis products acting as nutrients available for soil microorganisms would stimulate microbial activity [7]. In this study, formaldehyde removal by the soil surface of 0.018 m^2 accounted for ca. a half of that of plant–soil system, indicating that further elevating formaldehyde removal capacity will be realized by increasing exposed surface of potted soil.

Formaldehyde removal by plant is heavily dependent on FDH activity because both formaldehyde incorporation into plant tissue and formaldehyde conversion into CO_2 are involved in FDH [21]. In this study, formaldehyde removal capacity for the three plant species agreed well with FDH activities in them (As shown in Fig. 3 and Table 1). The finding from Giese et al. [9] indicated that cultured maize cells, wheat cells and spider plant leaves had specific activities of 10, 13and 15 nmol min^{-1} mg^{-1} protein, respectively, and that formaldehyde removal capacity of the spider plant enzyme is more than 100-fold higher than in vivo metabolic rate of the spider plant leaves. Our results showed that FDH activities of leaves from the three plant species were weaker than those reported in Giese et al. [9]. Nevertheless, formaldehyde removal capacities of plant FDH were still higher than in vivo metabolic rate of plant leaves. Considering that formaldehyde removal is composed of stomatal uptake (diffusion) and enzymatic metabolism (reaction), formaldehyde removal by plant may be diffusion-limited rather than reaction-limited.

5. Conclusions

The potted plant–soil systems investigated in this study were capable of formaldehyde removal from air in a long time. Of the systems, spider plant–soil system had the highest formaldehyde removal capacity. Formaldehyde removal capacities for the plant–soil systems were much higher in daytime than in nighttime. The result that detached FDH activities from the leaves of the three species were higher than in vivo metabolic capacities demonstrated that formaldehyde removal by plant may be diffusion-limited rather than reaction-limited. Formaldehyde removal by the microorganisms in the potted soils accounted for ca. 50% of all formaldehyde removed by plant–soil systems, which implies that further elevating formaldehyde removal capacity for plant–soil system will be realized by increasing exposed surface of potted soil.

Acknowledgements

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