



Removal of indoor odors via phytoremediation: interaction between aromatic hydrocarbon odorants decreases toluene removal

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Abstract

The composition of volatile organic compounds (VOCs) in the air of homes and offices is often complex and can have a significant effect on the health of individuals exposed. Certain plant species and their associated microorganisms are known to remove VOCs from the air; however, the rate of removal of one VOC may be influenced by the presence of others. We investigated the effect of VOCs on toluene phytoremediation rate by comparing the interaction of toluene, xylene, and benzene, common indoor odorants. Golden pothos (*Epipremnum aureum* (L.) Engl.) and Cornstalk (*Dracaena fragrans* (L.) Ker Gawl.) were exposed to different concentrations of one or more gases in a sealed chamber. The removal of $0.9 \mu\text{L L}^{-1}$ toluene was little affected by the addition of $0.9 \mu\text{L L}^{-1}$ xylene until the concentration was $\geq 1.8 \mu\text{L L}^{-1}$. At 1.8 and $2.7 \mu\text{L L}^{-1}$ xylene, there was a progressive decline in toluene removal. Similarly, at $1 \mu\text{L L}^{-1}$ toluene, $1 \mu\text{L L}^{-1}$ of xylene did not have a significant effect on phytoremediation; however, with the addition of $1.0 \mu\text{L L}^{-1}$ benzene, removal of toluene declined an average of 50% in both plant species. The addition of xylene reduced toluene removal by 39% and with xylene + benzene 58% when the total VOC concentration remained constant, but total VOC removal by the plants was similar. Since homes and offices generally have a much more diverse VOC composition than described in this study, VOC interaction effects on phytoremediation are probably more complex in real-world situations.

Keywords Indoor air · Toluene · Xylene · Plants · Volatile organic compounds

Introduction

A large number of volatile organic compounds (VOCs) have been identified in homes and offices, some of which represent significant health hazards (Jones 1999). In a Finnish study, over 200 VOCs were identified in each of 26 homes (Kostiainen 1995). Collectively, VOCs are major contributors to reduced indoor air quality with many having unpleasant odors that significantly decrease the acceptability of the indoor environment. Perception of the composite odor depends upon

the VOC composition and concentration, olfactory acuity of individuals exposed, and a number of other factors.

The concentration at which the odor of different VOCs can be perceived by humans (i.e., odor threshold) varies widely, e.g., *n*-hexanoic acid— $0.0006 \mu\text{L L}$ (v/v), *m*-xylene— 0.041 , *p*-xylene— 0.058 , toluene— 0.33 , *o*-xylene— 0.38 , formaldehyde— 0.50 , *n*-decane— 0.62 , benzene— 2.7 , trichloroethylene— 3.9 , and propane 1500 (Nagata, 2003). Structures displaying “sick building syndrome” often have distinctly unpleasant odors; however, the odor threshold of an individual VOC is neither necessarily related to its toxicity nor level of sensory irritation to those exposed (Wolkoff et al. 2005).

Plants, bio filter system, and their associated microbes in the growing medium are known to remove certain VOCs (phytoremediation) and are thought to possibly be an effective means of removing VOCs from indoor air; however, only a very small number of VOCs to date have actually been shown to be removed (Fraser Torpy et al. 2018; Kays 2011; Kim et al. 2018; Naomi J. Paul et al. 2019; Pettit et al. 2019), i.e., acetone, benzene, benzaldehyde, *n*-butyraldehyde, *iso*-butyraldehyde, crotonaldehyde, diethyl ketone, formaldehyde, methacrolein,

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methyl ethyl ketone, methyl isobutyl ketone, methyl *n*-propyl ketone, methyl *iso*-propyl ketone, octane, pentane, α -pinene, propionaldehyde, toluene, trichloroethylene, and xylene (Aydongan and Montoya 2011; Chen et al. 2010; Cornejo et al. 1999; Kim et al. 2008; Kim et al. 2010; Kim et al. 2011; Liu et al. 2007; Orwell et al. 2004; Orwell et al. 2006; Oyabu et al. 2003; Son et al. 2000; Tani and Hewitt 2009; Tarran et al. 2007; Wolverton 1986; Wolverton et al. 1984; Wolverton and Wolverton 1993; Xu et al. 2011). The phytoremediation potential of plant–microbe systems varies with plant species, microbe population, time of day, VOC composition and concentrations, and other factors.

Currently, little is known about the effect of the presence of other VOCs on the ability of plants to remove specific chemicals. In an initial study, Cornejo et al. (1999) found that the presence of trichloroethylene (TCE) in the atmosphere lowered the removal rate of benzene and pentane by the plant–microbe system. Furthermore, Yoo et al. (2006) found that VOC removal decreased when one or more gases (toluene and benzene) were present. The results indicated that the removal of a single gas was not necessarily indicative of the removal when other xenobiotic gases were in the air.

We investigated the effect of VOC composition on toluene phytoremediation rate by comparing the interaction of three closely related aromatic hydrocarbons that are common indoor odorants with relatively low odor thresholds.

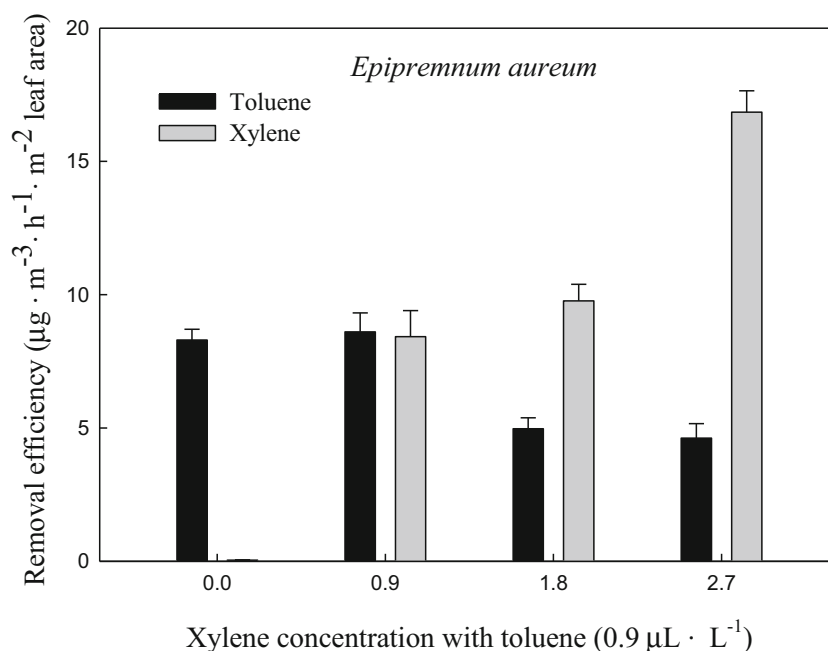
Materials and methods

Plant materials Foliage plants were obtained from a commercial market in Korea for the experiments. *Epipremnum*

aureum (Linden & André) G. S. Bunting (*Scindapsus aureus* is a synonym) was used in 2010 due to unavailability of *Dracaena fragrans* (L.) Ker Gawl. cv “Massangeana” and *E. aureum* and *D. fragrans* were used in 2011 and 2012. The plant heights of *E. aureum* and *D. fragrans* were ~23 and 42 cm, respectively. The plants were transplanted into pots containing a uniform growing medium (i.e., Mix #4 (Sun Gro Horticulture, Bellevue, WA), bark-humus (Biocom. Co., Seoul, Korea) and sand at 5:1:1, v/v/v). Mix #4 contained Canadian sphagnum peat moss (55 to 65% by volume), perlite, dolomitic lime, gypsum, and a wetting agent. All plants were grown in a greenhouse for 2 weeks after transplanting, and then acclimated for greater than 1 month within the indoor environment used for the experiments (23 ± 2 °C, 20 ± 2 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $40\% \pm 6\%$ RH) (Kim et al. 2008; Kim et al. 2010). The plants were watered every 3 days with the excess water allowed to drain. All plants were watered the day before the gas treatments. Three pots (19-cm dia with media volume of 2.2 L) were placed in a chamber at the Rural Development Center with a light intensity of 20 ± 2 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ using fluorescent lights and a 12-h photoperiod. Three replicates (chambers) of each species were tested. Chambers without plants were used to determine VOC losses not due to the plants (e.g., leakage, adsorption, chemical reactions). Plant height was measured and leaf area determined using a LI-3100 leaf area meter (LI-COR Inc., Lincoln, NE) at the end of each experiment.

Treatment system The experiments compared three benzenes (benzene, methylbenzene (toluene) and dimethylbenzene (xylene)) that differed significantly in water solubility ($1.8\text{ g}\cdot\text{L}^{-1}$, 0.52 , practically insoluble, respectively) and in molecular weight

Fig. 1 Effect of xylene concentration on the phytoremediation efficiency of toluene ($0.9\ \mu\text{L}\cdot\text{L}^{-3}$) and xylene at various xylene concentrations. The $0.0\ \mu\text{L}\cdot\text{L}^{-3}$ xylene concentration was exposed only to toluene. Potted plants (19-cm dia with media volume of 2.2 L) were exposed for 12 h in sealed chambers at a light intensity of $20 \pm 2\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Vertical bars denote the SE



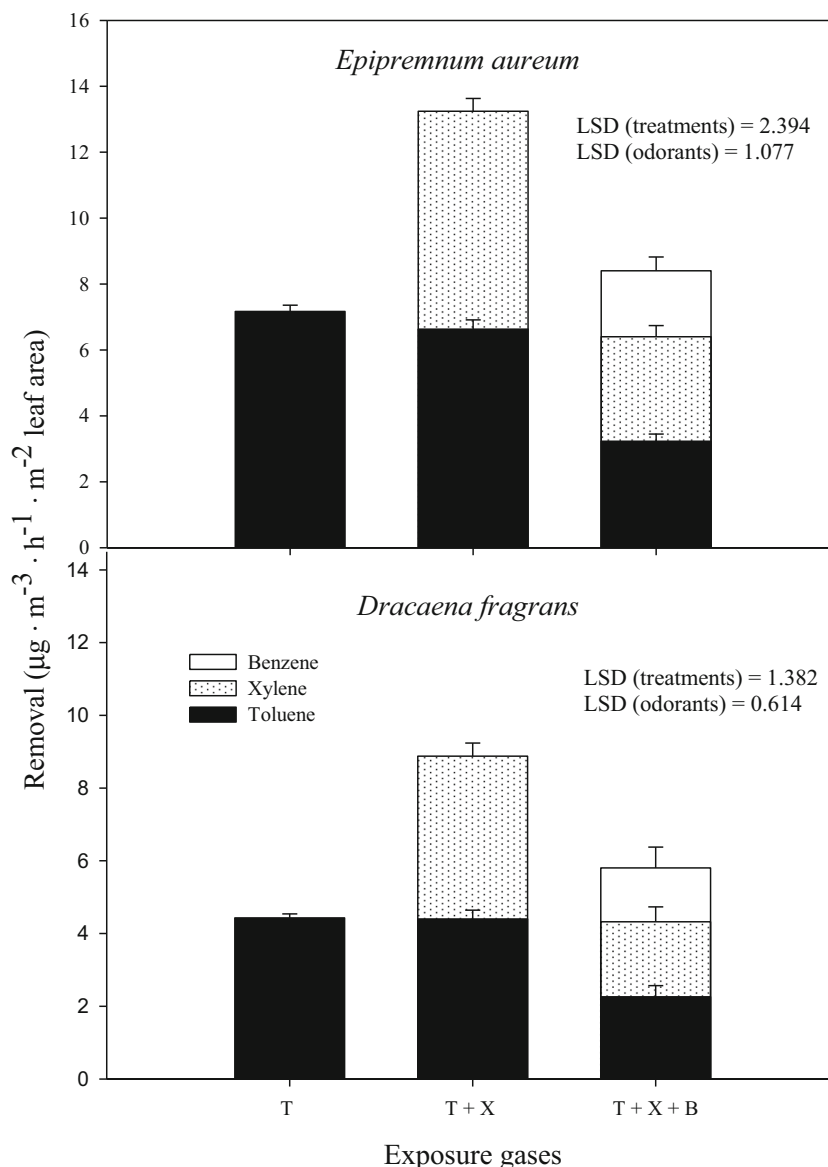
(78.11 $\text{g}\cdot\text{L}^{-1}$, 92.14 and 106.16, respectively). The treatment system consisted of controlled-environment rooms (i.e., temperature, light intensity, and relative humidity) containing the test chambers and a gas generator. The test chambers, described by Kim et al. [11], were 1.0 m^3 ($90 \times 90 \times 123\text{ cm}$) and impervious to VOCs. Interior air was circulated ($6\text{ L}\cdot\text{min}^{-1}$) and tested for benzene, toluene, and xylene concentration at three positions, 12, 70, and 98 cm above the base of the chamber.

Gas exposure and measurement The plants were pretreated with benzene, toluene, and xylene in that pretreatment is known to enhance their phytoremediation potential for each gas (Kim et al. 2011; Kim et al. 2012). Gaseous benzene, toluene, and xylene were introduced into test chambers containing plants as previously described (Kim et al. 2011) and allowed to equilibrate for 15 min. The internal concentration

was determined and corrected to $2.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$ for the stimulation treatment. The plants remained in the stimulation treatment for 12 h and then were moved to fresh air for 12 h. After the stimulation treatment, the subsequent benzene, toluene, and xylene removal by the plants was determined according to the VOC treatment.

The first experiment was conducted in 2010 (Fig. 1). The plants were exposed to different concentrations (0, 0.9, 1.8, and $2.7\text{ }\mu\text{L}\cdot\text{L}^{-1}$) of xylene with $0.9\text{ }\mu\text{L}\cdot\text{L}^{-3}$ toluene. In the second experiment (2011), the concentrations of toluene, xylene, and benzene were $1.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$, respectively. Benzene, xylene, and toluene were assessed in 2012. Therefore, total concentrations of each treatment were different: toluene ($1.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$), toluene + xylene ($2.0 + 1.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$), and toluene + xylene + benzene ($3.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$) (Fig. 2). A third experiment in 2012 was the same as the second; however, the total VOC treatment

Fig. 2 Effect of xylene (X) and benzene (B) on the phytoremediation efficiency of toluene (T), xylene, and benzene by two species of indoor plants. Initial concentration of each gas $1.0\text{ }\mu\text{L}\cdot\text{L}^{-1}$. Potted plants (19-cm dia with media volume of 2.2 L) were exposed for 12 h in sealed chambers at a light intensity of $20 \pm 2\text{ }\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Vertical bars denote the SE. LSD represents values according to Fisher's least significant difference (LSD) test at $p < 0.05$ determined between treatments, and all odorants within treatments



concentrations were fixed with $1.5 \mu\text{L}\cdot\text{L}^{-1}$, toluene ($1.5 \mu\text{L}\cdot\text{L}^{-1}$), toluene + xylene ($0.75 + 0.75 = 1.5 \mu\text{L}\cdot\text{L}^{-1}$), and toluene + xylene + benzene ($0.5 + 0.5 + 0.5 = 1.5 \mu\text{L}\cdot\text{L}^{-1}$) (Figs. 3, 4, and 5).

The rate of VOC removal was measured within the chambers after 0, 6, and 12 h (Kim et al. 2011). Changes in VOC concentration within the chambers were expressed as cumulative removal on a leaf area (LA) basis ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{m}^{-2}$ leaf area) and as the rate of removal ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ leaf area). Chambers devoid of plants were treated similarly to determine gas losses resulting from chamber effects.

VOC quantification Air samples were collected at the appropriate time intervals using a quartz cold trap (120 mm long, 2.9 mm o.d., 1.0 mm i.d. (inlet), 2.0 mm i.d. (outlet); Markes International Ltd., Llantrisant, UK) connected to each

chamber with the air collected for 5 min at 5 mL min^{-1} . An automated thermal desorption system with Air Server autosampler (UNITY; Markes International Ltd.) was connected to the injection port of the gas chromatograph–mass spectroscopy (TRACE DSQ; Thermo Electron Co., Waltham, MA). The desorbed sample was cryofocused at 5°C for 5 min on the first few centimeters of the column, desorbed at 280°C , and separated using a ZB-624 capillary column (30 m length, 0.25 mm i.d., 1.40-mm film thickness of 6% cyanopropylphenyl, 94% dimethylpolysiloxane; Phenomenex, Torrance, CA). The injection port temperature was 180°C with a split ratio of 29:1. Helium was used as the carrier gas at a flow rate of 1.0 mL min^{-1} . The column temperature was held at 45°C for 1 min and increased at a rate of $15^\circ\text{C min}^{-1}$ to 100°C and held for 1 min and then increased at a rate of 5°C min^{-1} to 135°C .

Fig. 3 Time course (12 h) of toluene (T) removal in the presence and absence of xylene (X) and benzene (B) by two indoor plant species. Initial total gas concentration was $1.5 \mu\text{L}\cdot\text{L}^{-1}$ (T ($1.5 \mu\text{L}\cdot\text{L}^{-1}$), T + X ($0.75 + 0.75 \mu\text{L}\cdot\text{L}^{-1}$), T + X + B ($0.5 + 0.5 + 0.5 \mu\text{L}\cdot\text{L}^{-1}$)). Potted plants (19-cm dia with media volume of 2.2 L) were exposed for 12 h in sealed chambers at a light intensity of $20 \pm 2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Vertical bars denote the SE. LSD represents values according to Fisher's least significant difference (LSD) test at $p < 0.05$ determined between treatments at 12 h after gas exposure

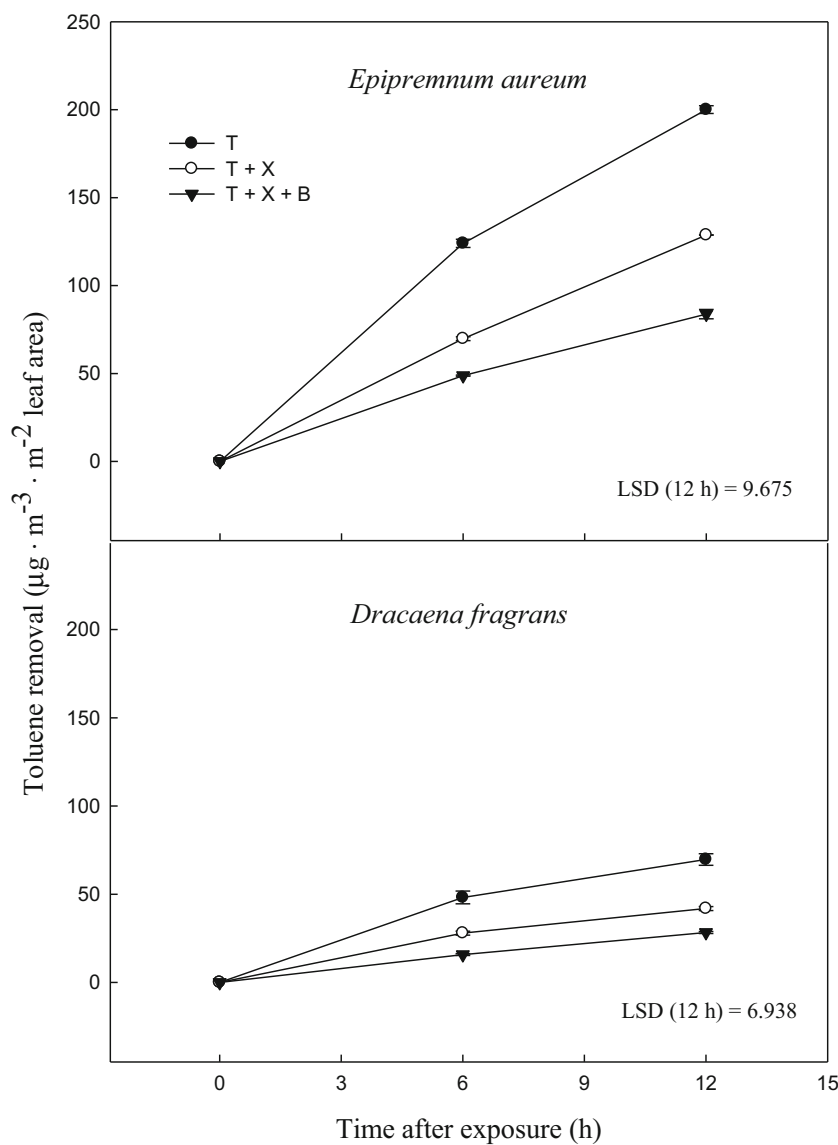
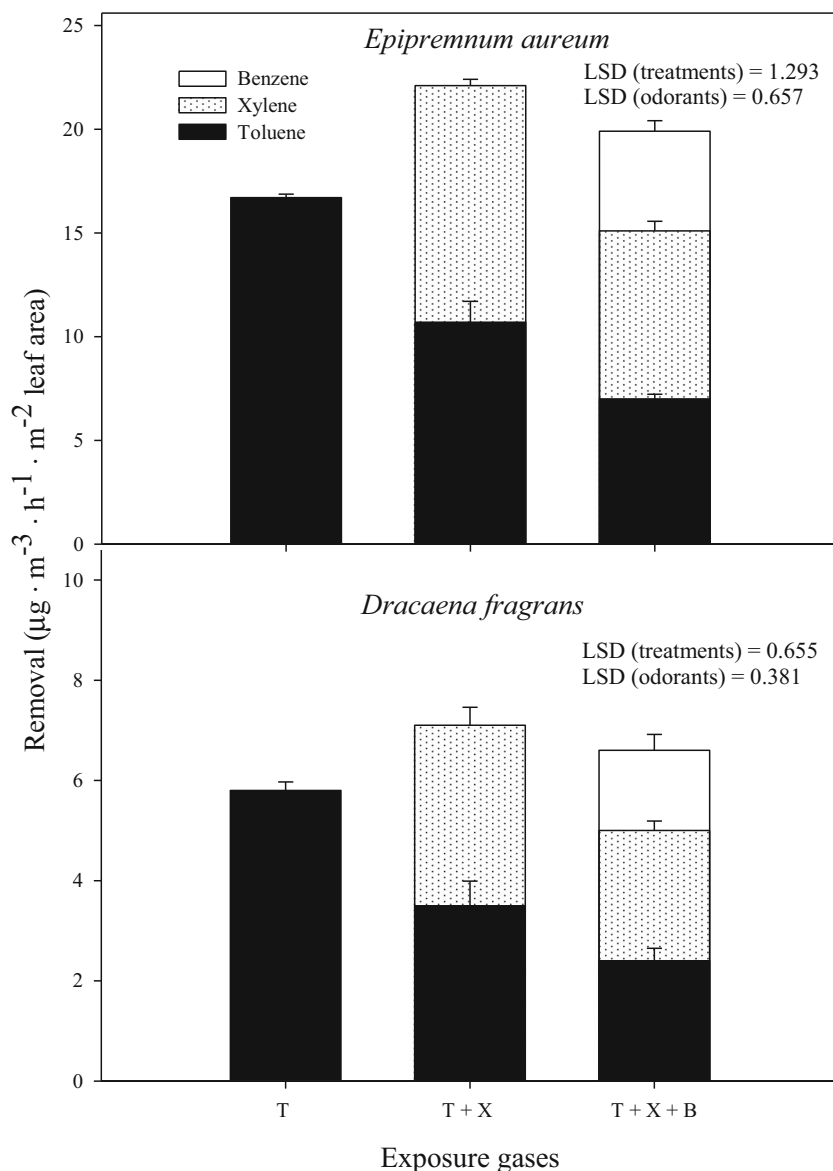


Fig. 4 Effect of xylene (X) and benzene (B) on the phytoremediation efficiency of toluene (T), xylene, and benzene by two species of indoor plants when the total concentration of gas was initially $1.5 \mu\text{L}\cdot\text{L}^{-1}$ (T ($1.5 \mu\text{L}\cdot\text{L}^{-1}$), T + X ($0.75 + 0.75 \mu\text{L}\cdot\text{L}^{-1}$), T + X + B ($0.5 + 0.5 + 0.5 \mu\text{L}\cdot\text{L}^{-1}$)). Potted plants (19-cm dia with media volume of 2.2 L) were exposed for 12 h in sealed chambers at a light intensity of $20 \pm 2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Vertical bars denote the SE. LSD represents values according to Fisher's least significant difference (LSD) test at $p < 0.05$ determined between treatments, and all odorants within treatments



Data analysis Gas concentrations were expressed as $\mu\text{g m}^{-3}$ with the data normalized to $24 \pm 1 \text{ }^\circ\text{C}$ and 100 kPa (Hines et al. 1993). Data were expressed as the average of three replicates. The accumulated removal of toluene or xylene per unit leaf area (Eq. 1) and the removal efficiency per unit leaf area and time (Eq. 2) were calculated (Kim et al., 2008; Kim et al. 2011) as

$$\text{VOC removal } (\mu\text{g m}^{-3} \text{ m}^{-2} \text{ leaf area}) = [(P_i - (C_i - C)) - P] \times (F \times CV) / L \quad (1)$$

$$\text{Rate of removal } (\mu\text{g m}^{-3} \text{ h}^{-1} \text{ m}^{-2} \text{ leaf area}) = [(P_i - (C_i - C)) - P] \times (F \times CV) / (T \times L) \quad (2)$$

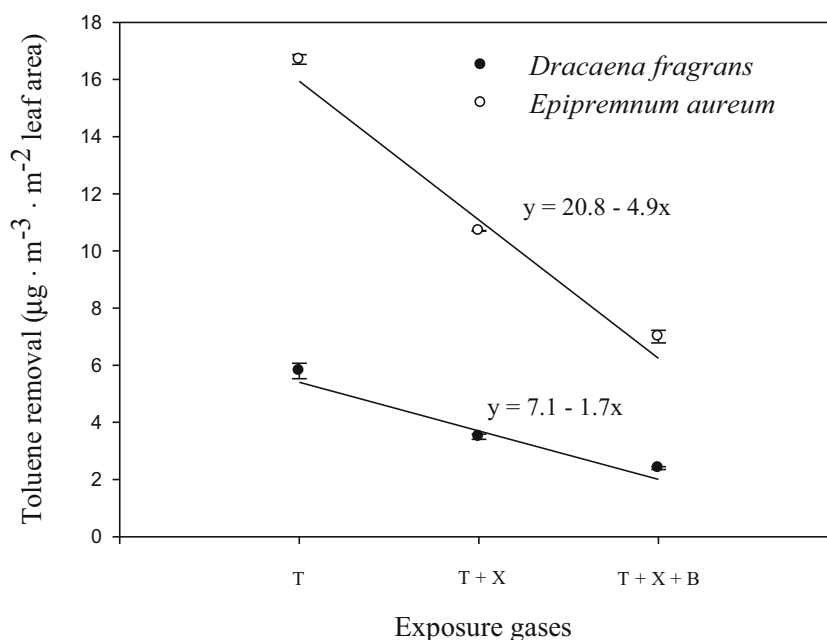
where P is the gas concentration measured in a chamber with plants ($\mu\text{L}\cdot\text{L}^{-1}$), P_i is the initial gas concentration

measured in a chamber with plants ($\mu\text{L}\cdot\text{L}^{-1}$), C is the gas concentration measured in a chamber without plants ($\mu\text{L}\cdot\text{L}^{-1}$), C_i is the initial gas concentration measured in a chamber without plants ($\mu\text{L}\cdot\text{L}^{-1}$), F is the toluene or xylene conversion factor for volume ($\mu\text{L}\cdot\text{L}^{-1}$) to mass ($\mu\text{L}\cdot\text{L}^{-1}$), CV is the volume of the chamber (m^3), L is the total leaf area per chamber (m^2), and T is the gas exposure time (h). The loss of toluene or xylene ($C_i - C$) not resulting from the plant and media was determined using empty chambers.

Results and discussion

While VOC removal in this study is termed phytoremediation, removal is via plant and microbe metabolism. Losses due to adsorption and absorption and other reactions (e.g., among

Fig. 5 Regression equations for the effect of xylene (X) and xylene + benzene (B) on the phytoremediation of toluene (T). The initial concentration of all gases was $1.5 \mu\text{L}\cdot\text{L}^{-1}$ (T ($1.5 \mu\text{L}\cdot\text{L}^{-1}$), T + X ($0.75 + 0.75 \mu\text{L}\cdot\text{L}^{-1}$), T + X + B ($0.5 + 0.5 + 0.5 \mu\text{L}\cdot\text{L}^{-1}$)). Potted plants (19-cm dia with media volume of 2.2 L) were exposed for 12 h in sealed chambers at a light intensity of $20 \pm 2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Vertical bars denote the SE



chemicals, photodegradation) were compensated for via controls and therefore were not monitored. The removal of $0.9 \mu\text{L}\cdot\text{L}^{-1}$ toluene was little affected by the addition of xylene ($0.9 \mu\text{L}\cdot\text{L}^{-1}$) until the concentration of xylene was $\geq 1.8 \mu\text{L}\cdot\text{L}^{-1}$ (Fig. 1). At 1.8 and $2.7 \mu\text{L}\cdot\text{L}^{-1}$ xylene, there was a progressive decline in toluene removal although the total VOC removal increased with increasing xylene. The results suggest the absence of direct competitive inhibition between toluene and xylene for uptake and/or metabolism.

Similarly, at $1 \mu\text{L}\cdot\text{L}^{-1}$ toluene, $1 \mu\text{L}\cdot\text{L}^{-1}$ of xylene did not have a significant effect on phytoremediation (Fig. 2); however, with the addition of $1.0 \mu\text{L}\cdot\text{L}^{-1}$ benzene (i.e., to $1.0 \mu\text{L}\cdot\text{L}^{-1}$ toluene + $1.0 \mu\text{L}\cdot\text{L}^{-1}$ xylene) there was an appreciable decline in the removal of each VOC (e.g., 50% toluene, 47% xylene on average for both species). With the addition of benzene, the ratio of toluene to xylene removed remained approximately the same as without benzene, though the combined rate (toluene + xylene) was reduced. The phytoremediation rates were substantially lower in *D. fragrans* than *E. aureum*; however, the general relationship between the 3 odorants did not essentially differ.

In both species of indoor plants, there was a fairly linear removal rate over the 12 h exposure period (Fig. 3) suggesting that the inhibition response is rapid, and most likely not due to progressive damage to the system controlling metabolism of the hydrocarbons during the 12 h test period. In this case, the total VOC concentration in each treatment was $1.5 \mu\text{L}\cdot\text{L}^{-1}$. The toluene removal rate decreased in the presence of xylene and more so when all 3 odorants were present (toluene + xylene + benzene) although the total VOC removal increased.

Xylene reduced toluene phytoremediation rate though the combined removal rate increased (Fig. 4). When all three

odorants were present, the removal rate of toluene and xylene declined slightly over when benzene was absent, although the total removal rate increased over that of toluene alone. The same general relationship among the VOCs was present in both species of plants. Phytoremediation by *D. fragrans* was substantially lower than *E. aureum*.

Plant species had a major impact on the rate of VOC removal (Fig. 5). Even though the total VOC concentration remained constant, the addition of xylene and benzene resulted in a pronounced decline in toluene removal rate, i.e., the addition of xylene reduced toluene removal by 39% and with xylene + benzene 58%.

The presence of toluene + xylene resulted in a greater total VOC removal rate than toluene alone. Likewise, the presence of xylene + benzene also increased the total VOC removal rate, which was just slightly less than toluene + xylene. The increase in total removal of VOCs with increasing complexity of the VOC composition would suggest that a competitive inhibition between toluene and xylene is not operative.

In conclusion, indoor plants have the potential to remove three common odorants (toluene, xylene, benzene) from the air; however, there were significant interactions among the chemicals. Toluene removal was repressed by xylene and benzene, which bracket toluene in molecular weight and water solubility. The uptake and/or metabolism of toluene, xylene, and benzene are not totally independent. As the mixture of VOCs became more complex (i.e., toluene \rightarrow toluene + xylene \rightarrow toluene + xylene + benzene), the rate of toluene removal declined even when the total initial VOC concentration remained constant. Since homes and offices generally have a much more diverse VOC composition than toluene, xylene, and benzene (e.g., Kostiaineh (1995) reported over 200 VOCs

in 26 homes), the VOC interaction effects on phytoremediation are most likely much more complex in real-world situations. While the results indicate that *E. aureum* and *D. fragrans* are capable of removing these odorants, the critical question is whether the rate of phytoremediation is sufficient that a reasonable number of plants within an office/home would be adequate to significantly improve indoor air quality. The effect on phytoremediation of even more complex VOC compositions and variations in concentration of individual components remains to be determined.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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