Which ornamental plant species effectively remove benzene from indoor air?

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Abstract

Phytoremediation—using plants to remove toxins—is an attractive and cost effective way to improve indoor air quality. This study screened ornamental plants for their ability to remove volatile organic compounds from air by fumigating 73 plant species with 150 ppb benzene, an important indoor air pollutant that poses a risk to human health. The 10 species found to be most effective at removing benzene from air were fumigated for two more days (8 h per day) to quantify their benzene removal capacity. *Crassula portulacea*, *Hydrangea macrophylla*, *Cymbidium Golden Elf*, *Ficus microcarpa* var. *fuyuensis*, *Dendranthema morifolium*, *Citrus medica* var. *sarcodactylis*, *Dieffenbachia amoena* cv. Tropic Snow; *Spathiphyllum Supreme*; *Nephrolepis exaltata* cv. Bostoniensis; *Dracaena deremensis* cv. Variegata emerged as the species with the greatest capacity to remove benzene from indoor air.

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1. Introduction

Indoor air pollutants infiltrate from the outside (Bérubé et al., 2004) and are released directly by material within buildings (e.g., carpeting, paint, solvents, fuels). Smoking and cooking can also affect indoor air quality (Isbella et al., 2005). Benzene is a ubiquitous trace pollutant in indoor air (Bono et al., 2005). Even at low dose exposure, benzene can cause leukemia, aplastic anemia, bone-marrow disorders and some cancers in humans

(Rinsky et al., 1987). Benzene can also increase the frequency of chromosomal aberrations, sister-chromatid exchanges and micronuclei in peripheral blood lymphocytes, even leading to genotoxic carcinogenicity (Crump, 1994; Karacic et al., 1995; Zhang et al., 2002). A safe level of benzene exposure is unknown. In 2000, the European Union recommended that benzene concentration in ambient air should not exceed $5 \mu\text{g m}^{-3}$, with a long-term target of less than $1 \mu\text{g m}^{-3}$ (Official Journal of the European Communities L 313 (OJL313), 2000). In China, the recommended benzene concentration in indoor air has been limited to 0.08 mg m^{-3} (General Administration of Quality Supervision and Inspection and Quarantine of People's Republic of China

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(GAQSIQPRC), 2002). In a recent study, however, 22.8% of indoor air samples in China exceeded the government standard (Liu et al., 2003).

Indoor air quality can be improved by three ways: controlling source, designing ventilation systems to exhaust contaminated air, and cleaning air (Guo et al., 2003). Recently, phytoremediation—using plants to remove toxins from air—has been proposed as an efficient and cost-effective way to ameliorate indoor air quality. Air pollutant amelioration by plants has been reported previously (e.g., Balsberg-Paehlsson, 1988), including the ability of some species to absorb benzene from air (Ugrekheidze et al., 1997; Collins et al., 2000). A variety of authors have reported that potted ornamentals can remove volatile organic compounds (VOCs) from indoor air at different rates (Wood et al., 2000, 2001, 2002; Tarran et al., 2002; Orwell et al., 2004). The aim of this study was to assess and quantify the ability of common ornamental houseplants to remove benzene from indoor air.

2. Materials and methods

2.1. Indoor plant material

Indoor ornamental plants representing 73 species and cultivars (35 families and 60 genera) were purchased from flower markets. Similar individuals of each species were chosen as replicates.

2.2. Methods

2.2.1. First fumigation experiment

A set of four interconnected, cylindrical Plexiglas chambers (40 cm in diameter, 60 cm tall, 75.36 dm³ in volume) were built for plant fumigation. The experiments were conducted in a controlled greenhouse: temperature of $25 \pm 10^\circ\text{C}$, relative humidity of $55 \pm 15\%$, with a 14 h light period ($260\text{--}350 \mu\text{mol m}^{-2} \text{s}^{-2}$). Pipes handling source gasses were made of stainless steel and silica gel (3 mm and 6 mm in diameter separately). After passing through a filter—stainless steel cylinder filled with activated carbon—compressed air entered a cylindrical, stainless steel mixing chamber at 2 L min^{-1} , regulated by a Float Flow Meter. Simultaneously, the standard benzene (49.8 ppm, from National Research Center for CRM's of China) entered the mixing chamber at 6.04 mL min^{-1} , regulated by a separate Mass Flow Meter. Float Flow Meter and Mass Flow Meter were calibrated by Bubble Flow Meter before use. Thus, air

containing 150 ± 6.7 ppb benzene flowed continuously through the chambers in which plants were placed. Teflon pipes were used to carry the air–benzene mixture to the fumigation chambers in order to minimize the loss of benzene. The benzene concentrations at the inlet and outlet of the four empty chambers were measured and flows adjusted to achieve 150 ± 6.7 ppb outlet air benzene concentration. The manufacturer's stated accuracy of the benzene standard was 5%; precision was measured to be 7% or better. Of the four chambers, one was used as a control, holding only pots and soil similar to those used in the experimental chambers; the other three chambers housed three different plant species per trial. After two hours of exposure, gas was sampled using a 25 mL airtight injector and stored in dark for analysis. The benzene removal rate was calculated as follows:

$$\text{GFS} \times (\text{BC}_{\text{control}} - \text{BC}_{\text{sample}}).$$

Where GFS represents gas flow speed (mL min^{-1}) and BC represents benzene concentration ($\mu\text{g mL}^{-1}$).

After sample collection, chambers were evacuated and prepared to test the next three species. Fumigation steps were repeated 25 times to evaluate a total of 73 plant species.

2.2.2. Second fumigation experiment

From those indoor plant species that removed more than 20% of the benzene to which they were exposed, 10 species were chosen for a second fumigation experiment. In the second trial, we sought to quantitatively estimate the rate and efficiency of phytoremediation in the test species. Four chambers (three replicates and one control) were connected as in Section 2.2.1. In this treatment, plants were fumigated for two days (8 h per day, 8:30 am to 4:30 pm) in a flow-through fumigation chamber, where they were exposed to air containing 150 ± 6.7 ppb benzene. An additional chamber served as a negative control, in which another individual of the same species was exposed to only carbon-filtered compressed air. Gas released from the outlet was collected every 2 h as described above. After fumigation, all leaves of each plant were removed and imaged using Beijing Electronic Map 2003.

2.2.3. Gas analysis

To measure benzene concentrations in post-treatment air, a 1 mL air sample taken from fumigation chambers at room temperature were introduced into a Photovac 10A10 (Portable Photoionization Gas Chromatograph). Benzene was separated by a Teflon

column (3 mm × 2 m) filled with 5% SE30 on Chromosorb P NAN (60–80 mesh). Carbon-purified compressed air was used as carrier gas at a flow rate of 32 ml min⁻¹. The equipment was calibrated with the standard benzene after each measurement.

2.2.4. Data analysis

Data were analyzed by one way analysis of variance (ANOVA) using Statistical Program for Social Sciences (SPSS) 11.2 for windows at $\alpha = 0.05$.

3. Results and discussion

3.1. Screening species for benzene removal

Some plants produce and emit VOCs (Georgieva et al., 2005). In this study, comparison of the control with treatment plants demonstrated that none of the investigated species emitted detectable quantities of benzene.

Data from the 2-h fumigation treatment documented the relative ability of species to remove benzene from ambient air. Of the 73 species studied, 23 did not alter benzene concentration in air, 13 species removed between 0.1–9.99% of benzene in contaminated air, 17 species removed 10–20%, and 17 species removed 20–40%. Three species removed 60–80% of benzene in the experimental air. This differential accumulation of VOCs by plants is well documented (Keymeulen et al., 1993).

For species that removed more than 20% of benzene from contaminated air, benzene removal rate was calculated and standardized to leaf area. These results, combined with the aesthetic qualities of the plants, were used to select 10 species for the second fumigation trial. These species included: *Crassula portulacea* (Crassulaceae), *Hydrangea macrophylla* (Hydrangeaceae), *Cymbidium* Golden Elf (Orchidaceae), *Ficus microcarpa* var. *fuyuensis* (Moraceae), *Dendranthema morifolium* (Asteraceae), *Citrus medica* var. *sarcodactylis* (Rutaceae), *Dieffenbachia amoena* cv. Tropic Snow (Araceae), *Spathiphyllum* Supreme (Araceae), *Nephrolepis exaltata* cv. Bostoniensis (Davalliaceae), and *Dracaena deremensis* cv. Variegata (Dracaenaceae).

3.2. Evaluation of species with strong benzene removal capacity

Since the synthesis and use of many plant compounds varies throughout the day (Lopes

et al., 2002), the ability of plants to remove air pollutants might also vary diurnally. We indeed observed such variation in this study. For example, *F. microcarpa* var. *fuyuensis* and *Dieffenbachia amoena* cv. Tropic Snow removed little benzene during the first 2 h of fumigation (8–10 am), then increased pollution removal significantly. In contrast, *N. exaltata* cv. Bostoniensis showed high benzene removal only during the first 2 h of the fumigation test. Some species, such as *Crassula portulacea*, *H. macrophylla*, *Cymbidium* Golden Elf, *Dendranthema morifolium*, *Citrus medica* var. *sarcodactylis*, *Spathiphyllum* Supreme maintained constant rates of pollution removal throughout the two-day fumigation.

Among the 10 species tested in the two-day fumigation, benzene removal rate varied between 22.1 and 561.3 $\mu\text{g m}^{-2} \text{min}^{-1}$ (Table 1). *Crassula portulacea* was notable for its consistently high benzene removal during the two-day fumigation. When normalized for leaf area, *Crassula portulacea*'s benzene removal rate was 12 times higher than that of *deremensis* cv. Variegata, the least effective of the 10 species studied in the two-day fumigation trial. Throughout most of the two-day trial, *H. macrophylla* and *Cymbidium* Golden Elf also show greater benzene removal rates than those of most other species that we tested (Table 1). Unfortunately, no data have been previously published on these species for comparison with our results although benzene removal in static test chambers has been investigated for several other species such as *Dracaena deremensis* var. Janet Craig, *Epipremnum aureum*, *Dracaena marginata*, *Schefflera actinophylla* var. Amate, *Spathiphyllum floribundum* var. Petite, etc. (Wood et al., 2002; Tarran et al., 2002; Orwell et al., 2004).

These results can be extrapolated to examine indoor air-quality phytoremediation. If the average indoor benzene concentration is about 150 ppb, a standard room (10 m² floor area and 2.55 m high) contains 13.26 mg benzene. Assuming that plants maintain the same benzene removal rate as gas concentration drops, *Crassula portulacea* with a leaf area of 1 m² could completely remove benzene contamination in about 0.44 h. With similar leaf areas, *H. macrophylla* would require 1.08 h and *Cymbidium* Golden Elf could complete the job in 1.19 h. The least effective species in our two-day trial, *Dracaena deremensis* cv. Variegata, would require 5.39 h to remove this quantity of benzene from room air.

Table 1
Benzene absorption rate normalized for leaf area ($\mu\text{g m}^{-2} \text{ min}^{-1}$) of 10 species tested in the two-day fumigation trial

Species No.	Day1_2h	Day1_4h	Day1_6h	Day1_8h	Day2_2h	Day2_4h	Day2_6h	Day2_8h	BA/A/M	BA/A/D
1	513.5 ± 68.1 ^a	526.9 ± 71.6 ^a	534.3 ± 70.4 ^a	491.2 ± 52.1 ^a	391.2 ± 43.9 ^a	487.4 ± 69.9 ^a	521.4 ± 87.1 ^a	561.3 ± 68.1 ^a	503.4	724.9
2	215.4 ± 35.0 ^b	187.3 ± 34.5 ^{bc}	214.9 ± 32.8 ^b	217.8 ± 28.3 ^{bc}	181.4 ± 38.3 ^b	189.2 ± 34.9 ^{bc}	210.4 ± 36.2 ^b	215.1 ± 35.3 ^{bc}	203.9	293.7
3	148.1 ± 32.1 ^{bc}	169.8 ± 32.3 ^{bcd}	181.2 ± 34.3 ^b	201.3 ± 41.3 ^{bcd}	176.2 ± 38.5 ^{bc}	194.1 ± 41.4 ^{bc}	205.3 ± 33.4 ^b	209.5 ± 35.5 ^{bc}	185.7	267.4
4	120.4 ± 9.2 ^{cde}	202.6 ± 12.9 ^b	170.6 ± 4.7 ^{bc}	237.5 ± 27.2 ^b	90.2 ± 22.8 ^{cde}	209.8 ± 6.9 ^b	162.3 ± 31.0 ^{bc}	226.0 ± 13.0 ^b	177.4	255.5
5	107.4 ± 44.6 ^{cde}	211.6 ± 58.3 ^b	136.1 ± 43.5 ^{bcd}	119.2 ± 51.1 ^{de}	131.0 ± 51.0 ^{bcd}	147.2 ± 34.5 ^{bcd}	153.8 ± 35.0 ^{bc}	131.9 ± 40.2 ^{cd}	142.3	204.9
6	93.5 ± 9.7 ^{cdef}	96.7 ± 17.7 ^{cde}	126.0 ± 12.6 ^{bcde}	138.0 ± 15.1 ^{cde}	95.0 ± 10.7 ^{bcde}	110.7 ± 9.8 ^{cde}	119.0 ± 20.8 ^{bcd}	147.2 ± 19.7 ^{bcde}	115.8	166.7
7	14.4 ± 7.3 ^f	69.9 ± 18.2 ^{de}	80.4 ± 8.4 ^{cde}	51.9 ± 9.8 ^{ef}	61.1 ± 26.7 ^{de}	93.3 ± 21.4 ^{de}	143.4 ± 20.6 ^{bcd}	125.5 ± 14.0 ^{cde}	80.0	115.2
8	54.2 ± 18.8 ^{def}	65.3 ± 5.3 ^e	74.5 ± 11.8 ^{de}	60.2 ± 14.0 ^{ef}	75.4 ± 11.6 ^{de}	81.9 ± 13.2 ^{de}	95.0 ± 18.8 ^{cd}	87.5 ± 17.6 ^{de}	74.2	106.9
9	128.3 ± 6.0 ^{bcd}	72.6 ± 9.0 ^{de}	39.1 ± 4.2 ^e	23.7 ± 11.6 ^f	29.1 ± 2.0 ^e	23.0 ± 6.6 ^e	56.3 ± 6.0 ^{cd}	36.0 ± 7.2 ^e	51.0	73.5
10	32.0 ± 3.5 ^{ef}	39.9 ± 10.5 ^e	45.2 ± 5.4 ^e	51.3 ± 4.6 ^{ef}	35.6 ± 6.0 ^e	22.1 ± 1.6 ^e	44.5 ± 2.3 ^d	57.1 ± 1.8 ^{de}	41.0	59.0

1. *Crassula portulaca*; 2. *Hydrangea macrophylla*; 3. *Cymbidium Golden Elf*; 4. *Ficus microcarpa* var. *fiyuensis*; 5. *Dendranthema morifolium*; 6. *Citrus medica* var. *sarcodactylis*; 7. *Dieffenbachia amoena* cv. *Tropic Snow*; 8. *Spathiphyllum Supreme*; 9. *Nephrolepis exaltata* cv. *Bostoniensis*; 10. *Dracaena deremensis* cv. *Variegata*.

Data are list as average ± standard error for three replicates. BA/A/M: Benzene absorption of different plant species based on per minute and per m² leaf area ($\mu\text{g m}^{-2} \text{ min}^{-1}$). BA/A/D: Benzene absorption of different plant species based on per day and per m² leaf area ($\mu\text{g m}^{-2} \text{ day}^{-1}$). Superscript letters indicate groups with statistically insignificant differences in benzene removal at the same sampling time.

4. Future work

The focus of this study was to identify popular houseplant species that might also function well in phytoremediation of VOCs. However, a variety of questions remain unanswered. Firstly, our work did not explore the mechanism of benzene removal or address the fate of the compound within the plant. Secondly, differences in age, water status of the plant and stomatal conductance might influence benzene removal rate of individual species. Thirdly, we did not specifically investigate diurnal variation in benzene removal ability. And lastly, studies in which the concentration of benzene varies are needed to thoroughly describe benzene removal capabilities of target species. These questions will be explored in future research.

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References

- Balsberg-Paehlsson, A.M., 1988. Effects of heavy-metal and SO₂ pollution on the concentrations of carbohydrates and nitrogen in tree leaves. *Canadian Journal of Botany* 67, 2106–2113.
- BéruBé, K.A., Sexton, K.J., Jones, T.P., Moreno, T., Anderson, S., Richards, R.J., 2004. The spatial and temporal variations in PM10 mass from six UK homes. *Science of The Total Environment* 324, 41–53.
- Bono, R., Traversi, D., Maestri, L., Schilirò, T., Ghittori, S., Baiocchi, C., Gilli, G., 2005. Urban air and tobacco smoke in benzene exposure in a cohort of traffic policemen. *Chemico-Biological Interactions* 153–154, 239–242.
- Collins, C.D., Bell, J.N.B., Crews, C., 2000. Benzene accumulation in horticultural crops. *Chemosphere* 40, 109–114.
- Crump, K.S., 1994. Risk of benzene-induced leukaemia: a sensitivity analysis of the pliofilm cohort with additional follow-up and new exposure estimates. *Journal of Toxicology and Environmental Health* 42, 219–242.
- General Administration of Quality Supervision, Inspection and Quarantine of People's Republic of China (GAQSIQPRC), 2002. Ministry of Health, State Environment Protection Administration of PR China. Indoor Air Quality Standard GB/T 18883-2002. Standards Press of China.
- Georgieva, E., Handjieva, N., Popov, S., Evstatieva, L., 2005. Comparative analysis of the volatiles from flowers and leaves of three *Gentiana* species. *Biochemical Systematics and Ecology* 33, 938–947.

- Guo, H., Murray, F., Lee, S.C., 2003. The development of low volatile organic compound emission house—a case study. *Building and Environment* 38, 1413–1422.
- Isbella, M.A., Stolzberg, R.J., Duffy, L.K., 2005. Indoor climate in interior Alaska: simultaneous measurement of ventilation, benzene and toluene in residential indoor air of two homes. *Science of the Total Environment* 345, 31–40.
- Karacic, V., Skeder, L., Bosner-Cucancic, B., Bogadi-Sare, A., 1995. Possible genotoxicity in low level benzene exposure. *American Journal of Industrial Medicine* 27, 379–388.
- Keymeulen, R., Schamp, N., Van Langenhove, H., 1993. Factors affecting airborne monocyclic aromatic hydrocarbon uptake by plants. *Atmospheric Environment* 27, 175–180.
- Liu, W., Zhai, D., Yu, Y., Yang, H., 2003. Analysis of current situation of indoor air pollution and its control. *Urban Environment and Urban Ecology* 16, 53–55.
- Lopes, P.F., Oliveira, M.C., Colepicolo, P., 2002. Nitrate reductase in *Gracilaria tenuistipitata* (Rhodophyta) characterization and daily variation of nitrate reductase in *Gracilaria tenuistipitata* (Rhodophyta). *Biochemical and Biophysical Research Communications* 295, 50–54.
- Official Journal of the European Communities L 313 (OJL313), 2000. Directive 2000/69/EC Relating to Limit Values for Benzene and Carbon Monoxide in Ambient Air. 13/12/2000.
- Orwell, R.L., Wood, R.L., Tarran, J., Torpy, F., Burchett, M.D., 2004. Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water, Air, and Soil Pollution* 157, 193–207.
- Rinsky, R.A., Smith, A.B., Hornung, R., Fillioon, T.G., Young, R.J., Okun, A., 1987. Benzene and leukemia: an epidemiological risk assessment. *The New England Journal of Medicine* 316, 1044–1050.
- Tarran, J., Orwell, R., Burchett, M.D., Wood, R., Torpy, F., 2002. Quantification of the capacity of indoor plants to remove volatile organic compounds under flow-through conditions. Final Report to Horticulture Australia, Sydney, Australia.
- Ugrekhelidze, D., Korte, F., Kvesitadze, G., 1997. Uptake and transformation of benzene and toluene by plant leaves. *Ecotoxicology and Environmental Safety* 37, 24–29.
- Wood, R.A., Orwell, R.L., Burchett, M.D., Tarran, J., Brown, S.K., 2000. Absorption of organic compounds in indoor air by commonly used indoor plants. In: O. Seppanen, J. Sateri (Eds.), *Proceedings of Healthy Buildings 2000. Sixth International Healthy Buildings Conference*, vol. 2, August 2000, Espoo, Finland, pp. 125–130.
- Wood R., Orwell R., Tarran J., Burchett, M., 2001. Pot-plant really do clean indoor air. *The Nursery Papers*, No. 2001/2, 1–4. NIAA (Nursery Ind. Assocn. Aust.) Sydney, Australia.
- Wood, R.A., Orwell, R.L., Tarran, J., Torpy, F., Burchett, M.D., 2002. Potted plant-growth media: interactions and capacities in removal of volatiles from indoor air. *Journal of Environmental Horticulture and Biotechnology* 77, 120–129.
- Zhang, L., Eastmond, D.A., Smith, M.T., 2002. The nature of chromosomal aberrations detected in humans exposed to benzene. *Critical Reviews in Toxicology* 32, 1–42.