

USE OF LIVING POT-PLANTS TO CLEANSE INDOOR AIR – RESEARCH REVIEW

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ABSTRACT

Urban indoor air quality (IAQ) is an international health issue, since city dwellers spend 90% of their time indoors. Research by a number of authors is reviewed here, demonstrating a range of capacities of indoor plants to improve IAQ and promote occupant wellbeing. Our laboratory studies, with nine 'indoor plant' species, and our 'field' studies in 60 offices, show that potted-plants can reliably reduce total volatile organic compound (TVOC) loads, a major class of indoor pollutants, by 75%, to below 100 ppb. They work equally well with or without air-conditioning, and in light or dark. An evaluation of these studies is presented, plus novel research showing that potted-plants can also remove indoor CO and, sometimes, CO₂. The evidence overall clearly shows that the potted-plant microcosm represents an innovative technology for solving indoor air pollution, which can otherwise cause a range of adverse health effects, including 'building-related illness'. This portable, flexible, attractive, low-cost technology can complement any engineering measures and can be used in any building. To ensure sustainability of the urban environment, satisfying the 'triple bottom line' of environmental, social and economic considerations, indoor plants can be expected to become standard technology for improving IAQ - a vital building installation element.

KEYWORDS

VOC, indoor air, IAQ, indoor plant, pollution reduction

INTRODUCTION

Urban air pollution, mainly emanating from fossil fuel combustion, is an international health problem. For example, in Australia (as in most developed countries) about 80% of people live in urban areas, where, for example in Sydney alone, air pollution causes an estimated 2,400 deaths p.a. (NSW EPA 2006). In addition, urban dwellers spend about 90% of our time indoors (at home, school or office) (Cavallo et al. 1997; US EPA 2000; Environment Australia (EA) 2003) where air pollution is typically even higher than outdoors (Brown 1997; Smith 1997; EA 2003). The outdoor-derived load of NO_x, SO_x, CO₂, CO, organics, particulates etc. diffuses indoors, where it is augmented by indoor-derived contaminants, mainly volatile organic compounds (VOCs), outgassing from other petroleum-based products, such as 'synthetics' in furnishings, detergents, paints, printers, 'air fresheners' and the like. The chemical mixtures, even at imperceptible levels, can cause 'building-related illness' and symptoms of headache, sore eyes, nose and throat, or nausea (Carrer et al. 1999; World Health Organisation

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(WHO) 2000; Mølhave and Krzyzanowski 2003). Dust, moulds and flueless gas appliance emissions can add to pollution loads.

As outlined below, indoor potted-plants have been shown to remove most types of air-borne pollutants arising from either outdoor or indoor sources. Studies have also shown that, where indoor plants have been installed, staff wellbeing is improved with sick-leave absences reduced by over 60% (Fjeld 2002; Bergs 2002). The aims of this paper are to provide a review of research on indoor plants to improve IAQ, to outline findings of our own studies, and to present new data that further demonstrate the ability of potted-plants to remove indoor air pollutants and enhance IAQ.

Potted-plants improve a number of aspects of IAQ

Yoneyama et al. (2002) reviewed absorption and metabolism of NO₂ and NH₃ in 220 species (sun- and shade-loving plants, the latter of which can be used indoors). In a UK study of homes with flueless gas appliances, Coward et al. (1996) found that houses with six or more potted-plants showed reductions of over one third in NO₂ levels. In 1999, Lee and Sim, in a study of Korean species, showed that indoor plants absorb and metabolise SO₂. In the USA, Lohr and Pearson-Mims (1996) showed that indoor plants significantly reduce dust (particulate) levels. In a study by Costa and James (1999), it was found that potted-plants also reduce indoor noise levels. The pioneering screening studies on indoor-air VOC removal by Wolverton and colleagues (1989; 1991; 1993) showed reductions in VOC levels with over 50 species. Wolverton suggested that both plants and potting-mix microorganisms could be involved in the process. Following the work of Wolverton et al., we conducted detailed bench-top test-chamber investigations on VOC removal by potted-plants, initially using seven 'international' species. We then conducted a 'real-world' study of potted-plants to enhance IAQ, using 60 offices and three planting regimes, and we recently completed laboratory trials with two previously untested species. The results of all these studies, summarised below, amply demonstrate the ability of indoor potted-plants to eliminate indoor VOC loads, and mechanisms involved.

LABORATORY STUDIES OF POTTED-PLANT VOC REMOVAL

The seven species we originally tested were the commonly used, 'international species' *Spathiphyllum* 'Petite' (Peace Lily), *S. 'Sensation'*, *Dracaena 'Janet Craig'*, *D. marginata*, *Howea forsteriana* (Kentia palm), *Epipremnum aureum* (Pothos, Devil's Ivy) and *Schefflera 'Amate'* (Dwarf Queensland Umbrella Tree) (Tarran et al. 2002; Wood et al. 2002; Orwell et al. 2004). Four VOCs were tested: benzene, toluene and xylene (three of the 'BTEX' 'dirty four' outdoor-derived organics, known or suspected carcinogens, but also used indoors as solvents) plus *n*-hexane. An initial dose of up to 100 or 150 ppm of the VOC was injected into the test chambers (vol. 216 L; described below) followed by daily top-up (or doubled) doses, over two to four weeks. These dosages are from 2 to 10 times higher than the Australian maximum allowable 8-h averaged occupational exposure concentrations (ASCC 2006). The potted-plants proved highly effective in eliminating the VOCs, as follows: (a) after the initial dose, removal rates gradually rose, over four or five days, to more than 10 times initial rates; (b) once stimulated ('induced'), the potted-plant microcosm (PPM) eliminated daily top-up doses within about 24 hours; (c) when the dose was doubled, removal rates rose to meet it; (d) low, residual concentrations were also removed, effectively to zero (i.e. below detection limits of gas chromatography (GC)); (e) rates remained unchanged in light or dark (day/night, 24/7); and (f) finally, removal rates remained

unchanged (in the short term) when plants were removed and potting-mix in pots replaced in the chambers. Findings (e) and (f) pointed to soil microorganisms being the primary agents of VOC removal, and this was confirmed by microbiological testing. The normal role of these microorganisms is breaking down soil organic matter. The role of the plants here is nourishing their species-specific root-zone microbial communities. This symbiotic microcosm relationship is a universal feature of plant-and-soil interactions. Soil microorganisms are known to break down liquid petroleum, so are used in bioremediation of spills. However, this was the first demonstration of removal of gaseous-phase VOCs by *in situ* soil microorganisms. These studies showed that the PPM represents a self-regulating biofilter and phytoremediation unit of indoor air.

POTTED-PLANT VOC REDUCTION IN THE 'REAL-WORLD' - OFFICE STUDY

How many plants would make a difference to IAQ in the real-world? To start to answer this, we sampled the effects of indoor plants on total VOC (TVOC) loads in 60 single-occupant offices (12 per treatment), over two 5- to 9-week periods, in three buildings (two air-conditioned, one naturally ventilated) (Burchett et al. 2005; Wood et al. 2006). Three planting regimes were used, plus reference offices, as follows: (a) 3; or (b) 6, floor specimens of *Dracaena* 'Janet Craig' (300 mm diam. pots); or (c) 6 mixed 'table-sized' specimens comprising 5 *Spathiphyllum* 'Sweet Chico' plus 1 *Dracaena* 'Janet Craig' (200 mm pots). We found that: (i) ambient indoor TVOC loads ranged from ~80-400 ppb; (ii) whenever levels rose above ~100 ppb, any of the three plantings reduced loads by up to 75%, to ~60 ppb (always below 100 ppb again); and (iii) the plantings were equally effective with or without air-conditioning. The results demonstrate that the PPM works very effectively in the real world, being induced to respond by TVOC loads above ~100 ppb, reducing them down to below 100 ppb once more (very clean air). Since the three plantings worked equally well, it means that the smallest was still more than enough for this air-cleansing purpose. Subsequent laboratory trials (Orwell et al. 2006) confirmed the graded induction of VOC removal from a low threshold in the range encountered in the office air and, from there, to meet tested concentrations of up to 500 times as high (to 100 ppm). One of our current research directions is to determine the minimum amount of potted-plant material needed for this VOC removal.

INDUCTION OF VOC REMOVAL IN TWO UNTESTED PLANT SPECIES

The main aim of this more recent test-chamber study was to compare VOC removal capacities in two untested species - *Aglaonema modestum* and *Zamioculcas zamiifolia*. A second aim was to examine whether removal rates with either species could be correlated with any plant or potting-mix attribute.

Materials and methods

Plants in 200 mm pots were used (Tropical Plant Rentals, Sydney). Plant and potting-mix variables were analysed to provide alternative bases of comparison of removal rates: leaf area, and fresh and dry weights of shoots, roots and potting-mix. Benzene was used as the test VOC. Six replicate perspex test chambers were used (0.6 x 0.6 x 0.6 m) as described in previous studies (e.g. Orwell et al. 2006). Pots were first watered to saturation, drained for 1 h and placed in chambers, and an initial dose of 25 ppm benzene was injected. Benzene vapour concentrations in the chamber air were sampled (using a 1.0 mL syringe) at hourly or daily intervals, as required, using a GC. Leak tests were carried out before and after experiments to ensure that benzene removal was solely related to the

PPM. Three sets of data were collected for each species: (a) *induction removal rate*: time taken for the PPM to be stimulated to heightened activity and removal of initial dose - typically several days to one week; (b) *secondary removal rate*: time taken to remove a second, top-up dose; generally some days shorter than induction period; and (c) *maximum removal rate*: our previous results had shown that maximum removal rates are normally achieved after the removal of the second dose, so, in these trials, removal of the 3rd dose was taken to represent maximum removal rate.

Results

Benzene removal rates with the two species are shown in Figure 1. The *Zamioculcas* and *Aglaonema* showed similar patterns of induction of a stimulated VOC removal with the first dose, and, by the third dose, each removed the high benzene dose effectively to zero in less than 48 h. These results show a similar pattern to those of the seven species previously tested.

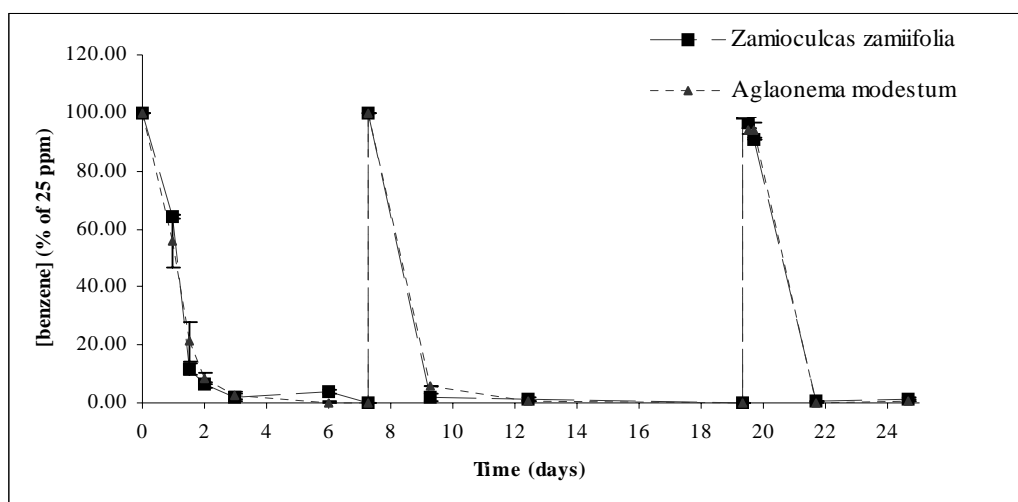


Figure 1. Removal of benzene from test-chamber air by potted *Zamioculcas zamiifolia* and *Aglaonema modestum*, challenged with three consecutive doses of 25 ppm benzene (means \pm SE; n=6).

Plant and potting-mix parameters of the two species are shown in Table 1. The *Zamioculcas* had 70% more leaf area and larger root and shoot weights than *Aglaonema*. The potting-mix of *Aglaonema* had a greater water-holding capacity than that of *Zamioculcas*.

Table 1. Plant and potting-mix variables in two test species (means \pm SE; n=6).

PLANT OR POTTING-MIX PROPERTY		AGLAONEMA	ZAMIOCULCAS
SHOOTS	Leaf area (cm ²)	2256 \pm 588	3861 \pm 81
	Wet weight (g)	229 \pm 43	1149 \pm 63
	Dry weight (g)	22.8 \pm 4.6	66.0 \pm 1.6
	Water content (%)	90	94
ROOTS	Wet weight (g)	155 \pm 11	781 \pm 60
	Dry weight (dwt) (g)	13.8 \pm 2.1	80.4 \pm 4.6
	Shoot/root (dwt ratio)	1.7	0.8
POTTING-MIX	Wet weight (g)	2313 \pm 289	2649 \pm 115
	Dry weight (g)	876 \pm 14	2191 \pm 93

Pot volume (incl. root mass) (cm ³)	4360	4206
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Table 2 presents the results of the maximum benzene removal rates on the basis of alternative parameters. There were no correlations found between removal rates per pot and any plant attribute *per se*. However, hourly removal rates per kg wet weight of potting-mix were equal, which is consistent with the potting-mix microorganisms being the main VOC removal agents. Rates per kg dry weight of potting-mix were different, however, suggesting that it is the water-holding matrix that is important for the microorganisms functioning in VOC removal. The findings contribute to the body of evidence showing that the PPM of any species can be expected to have a capacity for VOC removal.

Table 2. Averaged hourly, fully induced benzene removal rates (ppm/h) in two test species, expressed on basis of alternative pot-plant parameters.

RATES OF REMOVAL(ppm/h) / PROPERTY		AGLAONEMA	ZAMIOCULCAS
PER POT (AS INDICATED IN FIG. 1, AFTER DAY 20)		0.5	0.5
SHOOTS	Leaf area (/m ²)	2.2	1.3
	Wet weight (/kg)	2.1	0.4
	Dry weight (/kg)	22	7.5
ROOTS	Wet weight (/kg)	156	0.64
	Dry weight (g)	36	6.3
POTTING-MIX	Wet weight (/kg)	0.2	0.2
	Dry weight (/kg)	0.6	0.2

EFFECTS OF POTTED-PLANTS ON CO₂ AND CO LEVELS IN OFFICES

With adequate lighting, green plants photosynthesise and, in the process, refresh air in two ways - absorbing CO₂, and releasing equimolecular concentrations of O₂ as a by-product. There has been no research on the ability of indoor plants to refresh air via this gas exchange. However, it is recognised that the main purpose of ventilation is not so much to replenish O₂ as to remove CO₂ (Höppe and Martinac 1998). Studies have shown that student performance declines with increasing CO₂ (Shaughnessy et al. 2006), as does workplace productivity (Seppänen et al. 2006). Carbon monoxide is a very much more toxic fuel combustion product. However, plants and some soil bacteria consume CO. In plants, CO can stimulate root growth and seed germination and alleviate salt stress (Dekker and Hargrove 2002; Huang et al. 2006; Xu et al. 2006; Liu et al. 2007). Bacteria can use it as a nutrient (King and Crosby 2002; King 2007) and in normal metabolic redox processes (Tolli and King 2005; Chan and Steudler 2006). There has also been no previous research on effects of indoor plants on CO levels. Therefore, along with our studies on potted-plants to reduce office TVOC levels (discussed above), we also sampled CO₂ and CO levels in two sets of 12 offices. The results of this preliminary study are presented below.

Methods

The study was conducted May–October (winter/spring; outdoor max. temp. range 17-21°C). The offices had areas of 10-12 m² (vol. 30-50 m³). One building was air-conditioned, offices being supplied with 6-8 air changes h⁻¹, with 10-15% external air input. The other building was not air-conditioned; windows were frequently closed and flueless gas heaters were intermittently used. Weekly 5-min

samplings of CO₂ and CO were made in all offices, over two 9-week periods, each comprising ten 30-sec readings taken from all parts of the office, using a Portable IAQ-Calc Indoor Air Quality Meter (TSI Inc., MN, USA). In each building, 6 offices were unplanted (reference), and 6 supplied with three floor-specimens of *Dracaena* 'Janet Craig' (300 mm pots).

Results

Combined results for levels of CO₂ and CO in offices, with and without plants, are shown in Table 3. We found that potted-plant presence was associated with significant reductions in both CO₂ and CO concentrations ($P < 0.004$) in offices without air-conditioning. In the presence of plants, CO₂ levels were reduced by about 10% in offices in the air-conditioned building, and by about 25% in the naturally ventilated building. We are investigating factors of lighting, plant placement and species differences that may render the PPM more effective in CO₂ reduction. The CO concentrations were greatly reduced with plant presence, with or without air-conditioning, down to about 8-14% of those in unplanted offices (Table 3). We are further researching this impressive phenomenon, including the relative roles of plant and potting-mix microorganisms in the removal.

Table 3. Effects of three potted-plants (floor specimens of *Dracaena* 'Janet Craig') on levels of CO₂ and CO (ppm) in office air, in an air-conditioned and a naturally ventilated building ($n \geq 50$ offices / treatment).

Air conditioning	No. of plants	Mean [CO ₂] ± SE (ppm)	Mean [CO] ± SE (ppm)
Yes	0	409 ± 6.2	0.225 ± 0.035
Yes	3	366 ± 7.3	0.017 ± 0.008
No	0	386 ± 17	0.071 ± 0.024
No	3	290 ± 15	0.010 ± 0.005

CONCLUSIONS

Air conditioning	No. of plants	Mean [CO ₂] ± SE (ppm)	Removal %	Mean [CO] ± SE (ppm)	Removal %
Yes	0	409 ± 6.2		0.225 ± 0.035	
Yes	3	366 ± 7.3	10	0.017 ± 0.008	92
No	0	386 ± 17		0.071 ± 0.024	
No	3	290 ± 15	25	0.010 ± 0.005	86

Together, the numerous studies reported here, from both our own research and a number of different sources around the world, show conclusively that the potted-plant microcosm (PPM) can greatly improve IAQ by removing many major pollutants. Thus the PPM represents an adaptive, self-regulating, portable, flexible, low-cost, sustainable and beautiful biofiltration and bioremediation system for IAQ. This innovative technology can complement any engineering measures and can be used in any building. To ensure sustainability of the urban environment, satisfying the 'triple bottom line' of environmental, social and economic considerations, it is expected that indoor plants will become standard technology - a vital building installation element, for improving IAQ.

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