Towards improving indoor air quality with pot -plants — A multifactorial investigation

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Towards Improving Indoor Air Quality With Potted -Plants
A Multifactorial Investigation

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Research Provider - Ambius

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The purpose of this Report is to present the background and findings of a project undertaken to advance the horticultural technology of indoor plant species, and so extend their uses to improve indoor air quality (IAQ) and overall indoor environmental quality (IEQ) for building occupants. The project has involved a series of laboratory investigations, with four test species, on several aspects of their air-cleansing functions, including: (a) the influence of pot size on the pot-plant microcosm's capacity to remove volatile organic compounds (VOCs), a major class of indoor pollutant; (b) characterising any changes in the potting-mix microbial community associated with VOC removal; and (c) the capacity of the plants reduce indoor CO_2 concentrations. The Report presents the aims, methodology and results of the research undertaken, and implications of the findings for nursery and interior plantscape horticulture. The findings can also contribute to the national environmental goal of 'greening the city' for sustainable urban communities in Australia.

Acknowledgements The research team thanks Ambius for the industry funding for this project, and for their consistent encouragement and interest. We also thank the National Interior Plantscape Association for support for this indoor plants program, and UTS Faculty of Science for facilities and guidance. Thanks also to HAL for providing matching funding and administrative assistance with the project.

30 September, 2009

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Media summary

International research (including that at UTS) has shown indoor plants can reduce all types of urban air pollution. The aims of this project have been threefold:

- to investigate the effect of pot size on the capacity of pot-plants to reduce concentrations of volatile organic compounds (VOCs), a major class of outdoor and indoor air pollution;
- to characterise the potting mix bacteria which are the primary VOC removal agents (plants nourish their root-zone bacteria – a mutualistic relationship at work); and
- to initiate testing of CO_2 reduction by indoor plants.

Key outcomes

- Our results, with three species, showed that for VOC reduction, three 125 mm pots are as effective as one 200 mm pot; and one 200 mm pot is as effective as a 300 mm pot.
    - *Applications*: The results show the very high capacity for pot-plants to remove VOCs. The findings allow for more flexibility in interiorscapes, eg with towers or clusters of small plants interspersed among larger pots.
- Our tests on potting mix of *Spathiphyllum* have provided the first-ever community physiological profile of the VOC-removing bacterial consortium, and tracked changes in that community as the result of exposure to a VOC.
    - *Applications*: The results confirm the mechanism by which VOCs are biodegraded, so the ability of indoor pot-plants to perform this role can be promoted with confidence.
- The preliminary studies on plant CO_2 removal in the 'office habitat' showed that they can adapt to the very low light levels for CO_2 reductions, but respiration of roots and potting mix must be taken into account in assessing effectiveness.
    - *Applications*: Indoor plants should be placed according to shade tolerance; they can acclimatise to prevailing lighting for CO_2 reduction.

Future R&D

Much more research is needed in this area. It should also be directed to comparative studies of VOC and CO_2 reductions of plants in hydroculture which is becoming more standard overseas and likely to become so in Australia. Indoor plants have the potential to reduce the energy consumption of air-conditioning and hence the C-imprint of the city, for sustainable urban living.

Technical summary

Nature of problem

Urban air pollution is a global health concern, and indoor air is almost always more polluted than outdoor, even in the CBD. Eighty percent of Australians live in urban areas, and spend 90% of our time indoors, so indoor air quality is critical to our health. International research (including that at UTS) has shown indoor plants can reduce all types of urban air pollution. The aims of this project have been threefold: to investigate effects of pot size on the capacity of pot-plants to reduce concentrations of volatile organic compounds (VOCs), a major class of outdoor and indoor air pollution; to characterise the potting mix bacteria which are the primary VOC removal agents (plants nourish their root-zone bacteria – a mutualistic relationship at work); and to initiate testing of CO_2 reduction by indoor plants, which have the potential to reduce the energy load of air conditioning systems and hence the C-imprint of the city.

VOC reduction

We have tested VOC removal in 12 species and found they are all approximately equally effective with high or low doses of VOCs, once acclimatised ('induced') by exposure to an initial dose. In this project, four pot sizes of each of three species were tested in bench-top chambers for VOC removal, using benzene as the model VOC.

Major findings: Results showed that, for VOC reduction, three 125 mm pots are as effective as one 200 mm pot; and one 200 mm pot is as effective as either a 250 mm or a 300 mm pot. *Recommendations*: The results conclusively demonstrate the very high capacity for pot-plants to remove VOCs. The findings allow for more flexibility in interiorscapes, eg with towers or clusters of small plants interspersed among larger pots.

VOC-removing bacteria of potting mix

We used Biolog Ecoplates to examine the pre- and post-benzene exposure community level physiological profile (CLPP) of the potting mix bacteria of *Spathiphyllum* as test species. This study has provided the first-ever such profiling of the VOC-removing bacterial consortium of indoor plant potting mix, and tracked changes in that community resulting from exposure to a VOC. *Recommendations*: The results confirm the mechanism by which VOCs are biodegraded in the indoor plant microcosm, so the ability of indoor pot-plants to perform this air-cleansing role can be promoted by the industry with complete confidence.

CO_2 reduction

These were preliminary investigations on plant CO_2 removal by plants in the 'indoor habitat of the built environment'. Two sets of tests were conducted, with each of two species. The first, with pot-plants in test chambers, using a portable CO_2 monitor, measured CO_2 flux over 1 hour at a 'high' indoor light level (120 µmol quanta m^{-2} sec^{-1}). It was found, although there was net CO_2 uptake by the shoots, there was almost no net change in the chamber air, because the respiration of root and potting mix microorganisms about balanced the photosynthetic uptake. The second investigation used a leaf-clip chamber (LI-COR system), from which light saturation curves were obtained. The results with *Spathiphyllum* showed a light saturation level of below 30 µmol quanta m^{-2} sec^{-1}, and at ambient light the levels in the laboratory, ie about 12 µmol quanta m^{-2} sec^{-1}, the plants had achieved 80% of their maximum CO_2 uptake. The results demonstrate that indoor plants can adapt to very low light levels for CO_2 reduction, but respiration of roots and potting mix must be taken into account in assessing effectiveness. *Recommendations*: Indoor plants should be placed according to shade tolerance they can acclimatise to prevailing lighting for CO_2 reduction.

Future R&D

Much more research is needed in this area. It should also be directed to comparative studies of VOC and CO_2 reductions of plants in hydroculture which is becoming more standard method overseas and likely to become so in Australia. Indoor plants have the potential to reduce the energy consumption of air-conditioning and hence the C-imprint of the city, for sustainable urban living.

1. Introduction

1.1 Project aims

The goal of this project has been to advance the horticultural technology of indoor plant species to extend their uses to improve indoor air quality (IAQ) and overall indoor environmental quality (IEQ) for building occupants. The project has involved a series of laboratory investigations, with three test species, on several aspects of their air-cleansing functions, including:

a) assessing the influence of pot size on the pot-plant microcosm's capacity to remove volatile organic compounds (VOCs), probably the major class of indoor pollutant;

b) characterising any changes in the potting-mix microbial community associated with VOC removal; and

c) preliminary studies aimed at examining the capacity of the plants to reduce indoor CO_2 concentrations.

This Report presents the background and need for the project, the results of the research undertaken, and the implications of the findings for the nursery and interior plantscape industry. The findings can also contribute to the national environmental goal of 'greening the city' for sustainable urban communities in Australia.

1.2 Health concerns of urban air pollution

The urban populations of the world are growing faster than global population as a whole. In Australia, as in North America and much of Europe, 80% of people live in urban areas, where we spend 90% of our time indoors (Cavallo *et al*., 1997; Environment Australia, 2003**)**. The quality of the indoor environment is therefore critical to our health. Urban air pollution (UAP) is a world-wide health concern, as is indoor air quality (Mølhave and Krzyzanowski, 2003; World Health Organisation, WHO, 2000, 2003, 2005).

About 90% of UAP comes from the combustion of fossil fuels – coal, petroleum and natural gas. Primary emission waste products include carbon dioxide (CO_2) and carbon monoxide (CO); nitrogen oxides (NO_x) and sulfur oxides (SO_x); fine particulates (PM_{10} & $PM_{2.5}$); and 'air toxics'. The last category includes a mix of volatile organic compounds (VOCs) from partial combustion, eg 'BTEX' - benzene, toluene, ethylbenzene, xylene - plus PAHs (polyaromatic hydrocarbons); together with 'metal air toxics' that come from fuels and vehicles, and include lead, chromium, nickel and others. Then there are secondary pollution products, produced by photochemical reactions between NO_x and VOCs – ozone and peroxyacetyl nitrate (PAN) (DECCW NSW, 2009).

In 1998, CSIRO estimated that the health costs of UAP in Australia were about $12 billion p.a., and in the Sydney region alone it is estimated to cause some 1,400 deaths, and about 2000 hospital admissions yearly (Dept. Health NSW, 2009). Acute health risks from UAP include asthma, strokes, heart attacks, and other cardio-vascular emergencies. Chronic effects include lung and other cancers, further cardiovascular problems and low birth weights (Höppe & Martinac,1998; Bobak, 2000; Ha *et al*., 2001; Arden Pope *et al*, 2002).

International research (including that of UTS) has shown that plants, including indoor plants, can absorb all these types of UAP (Coward *et al*., 1996; Lee & Sim, 1999; King &

Crosby, 2002, Yoneyama *et al*., 2002; Wood *et al*., 2006; Orwell *et al*., 2006; Tarran *et al*., 2007).

1.3 Health risks of indoor air pollution

Although it is often not realised, indoor air is almost always more polluted than outdoor air, even in the city centre (Brown, 1997; Environment Australia, 2003; Ohura *et al.*, 2006). This is because, as outdoor air enters, it mixes with pollutants derived from indoor sources, such as more VOCs, outgassing from synthetic (petroleum-derived) furnishings, finishes, solvents etc, and from unflued gas appliances. The US EPA (1989) has identified over 900 VOCs in indoor air. Efforts are now being made to use low-VOC building materials; however, in the modern world it is not possible to eliminate VOCs entirely. In any case, most buildings now standing have significant loads of total VOCs (TVOCs). Even at imperceptible levels (<200 µg m^{-3}), the mixture of VOCs can cause headache, dry eyes, nose, throat, loss of concentration, and nausea – symptoms of 'sick-building-syndrome' or 'building-related-illness' (Leikauf *et al*., 1995; Carrer *et al*., 1999). In addition, indoor environments commonly have raised CO_2 levels from human respiration, which can add substantially to headaches, stuffiness, drowsiness or loss of concentration. Longer term, the chronic health problems mentioned above may develop. In 2000, WHO predicted that by 2010 responsibility for healthy indoor air quality (IAQ) would begin to rest with building owners or managers. Indoor plants help cleanse indoor air.

1.4 Other benefits of indoor plants

Apart from reducing gaseous air pollutants, research has shown that indoor plants can improve other aspects of IAQ as well. Pot-plants reduce dust levels (Lohr & Pearson-Mims, 1996), stabilise humidity and temperature, and lower noise levels (Costa & James, 1999).

There is also a growing body of evidence showing directly-measurable benefits to the health and well-being of building occupants. It seems these benefits result both from the capacity of pot-plants to produce cleaner air (Carrer *et al*., 1999; Lim *et al*., 2006), and their ability to provide feelings of pleasure, calm and relief from 'attention fatigue' (Shibata & Suzuki, 2002). Reductions in sick-leave absences have been recorded, in both office workers and school children (Fjeld, 2002). Reductions in physical discomfort (Lohr & Pearson-Mims, 2000; Park *et al*., 2002), and increases in performance and productivity have also been reported (Bergs, 2002). Participant responses found in our office studies include comments such as: 'it is a pleasure having the plants'; 'they improve the office ambience'; 'they lift one's mood'; 'I think better with plants around'; and 'the office feels fresher when I come in'. An online survey in the USA, with about 450 respondents, showed job satisfaction ratings higher in those with plants on their desks, than those who had planted window views but no indoor plants. All these studies indicate that indoor plants improve wellbeing and performance/ productivity in building occupants (Park *et al*., 2002; Evans, 2003; Bringslimark *et al*., 2007). **Indoor plants therefore contribute to our national goal of sustainable city living** (House of Representatives Standing Committee, 2004).

2. Effects of pot size on VOC removal capacity

2.1. Introduction – summary of previous UTS studies

2.1.1 Laboratory studies

Prior to the current project, following on from the pioneering work of Wolverton and co-workers (1989, 1991, 1993), we tested VOC removal with seven common indoor plant species (for full list of UTS-tested species, see Appendix 1), using 216 L perspex bench-top test chambers, as described below. We used four test VOCs — three of the BTEX group - benzene, toluene and xylene (known or suspected carcinogens; present indoors as solvents in fittings etc.) - plus *n*-hexane (also used as a furnishing solvent). An initial high aerial dose of the VOC was injected into each chamber, and rates of removal measured with a gas chromatograph (GC). After removal of the initial dose, daily top-up doses were applied, and removal measured, over two to four weeks.

Our results clearly demonstrated that indoor potted-plants can eliminate high or low doses of airborne VOCs within about 24 hours, once they have been stimulated ('induced') by exposure to the substance (Wood *et al.,* 1997, 2006; Burchett *et al*., 2001, 2005; Tarran *et al*., 2002, 2007; Orwell *et al*, 2004, 2006). We found a common pattern in VOC removal response with all species tested. Removal rates started slowly, but over four to five days they rose to sometimes more than 10 times the initial rate; i.e. removal rates were stimulated ('induced') by exposure to the initial dose. Once induced, the potted-plant microcosm reliably eliminated daily top-up doses within about 24 hours, and if the dose was doubled, removal rates rose to meet it. Also, low, residual concentrations were removed, effectively to zero (i.e. below the detection limit of GC). The pattern was the same with all four test VOCs.

We also found that removal rates were maintained unchanged in light or dark (i.e. 24/7), and if the plant itself was finally removed, and the potting mix placed back in the chambers, removal rates were maintained for some days afterwards. The last two findings pointed to microorganisms of the potting mix being the primary VOC removal agents, a hypothesis that was confirmed by subsequent microbial testing. We presume that the role of the plant here is in nourishing the root-zone microbial community, since such symbiotic or mutualistic relationships are a universal feature of plant-and-soil interactions (eg Westover *et al*.,1997; Preston *et al*., 1998), and our results showed that potting mix alone cannot sustain removal rates for more than a few weeks. The consistency of results across all plant species tested suggested that almost *any* indoor species would have a similar capacity for VOC removal, although the rates of removal vary to some extent between species, for reasons to be investigated further - they point to complex plant-potting mix relationships that might be available for manipulation as part of the horticultural development of indoor plant varieties. Soil bacterial preparations are used in the bioremediation of oil spills (Raghavan and Vivekanandan 1999; Radwan *et al*., 2000), however research in this laboratory is the first demonstration of VOC removal from the gaseous phase (indoor air) with potting mixes.

2.1.2 Office field study

To examine potted-plant VOC performance under real-world conditions, we also conducted a field study using 60 UTS staff offices, in three buildings (two air-conditioned, one not), with 0, 3 or 6 plants (in either 300 mm or 200 mm pots), with *Dracaena* 'Janet Craig' or *Spathiphyllum* 'Petite'. In no-plant reference offices, total VOCs (TVOCs) ranged from

about 80–400 ppb, the same range as reported by Environment Australia (2003) in four Australian cities. (The Australian indoor maximum recommended TVOC load is 500 ppb; ASCC, 2006). However, in offices with *either* 3 or 6 plants, loads were maintained below 100 ppb, which is regarded as presenting a negligible respiratory health risk (US EPA, 2009). So, the minimum pot number needed to cleanse air of VOCs in offices of the size-range encountered (12-15 m^2) is one to two. All plant treatments worked equally well with or without air conditioning.

Figure 1. Although plants are sometimes a tight fit in small offices, they are much appreciated by UTS recipients.

2.2 To what extent does pot-size make a difference?

The Green Star Rating scheme of Australia's Green Building Council (GBC, 2009) awards:

- 1 point for one 'large' or two 'small' plants per 30 m^2 of net leasable area (NLA); and
- 2 points for one large or two small plants per 15 m^2 NLA;

where 'large' refers to a 300 mm diameter pot, and 'small' to a 200 mm diameter pot.

These specifications are presumably based on the fact that the mouth area of a 300 mm pot (708 cm^2) is a bit over twice that of a 200 mm pot (315 cm^2).

Indoor plants provide many benefits apart from VOC removal, and it is not known whether VOC removal was the only consideration involved in the GBC's drawing up of these specifications. However, since VOC uptake is primarily effected by the potting mix bacteria, it was necessary to investigate what influence pot size (obviously related also to plant size) has on capacity and rates of VOC removal. **The aim of the laboratory studies reported below was to investigate whether and to what extent pot-size affects pot-plant VOC removal rates. Two series of experiments were conducted to investigate this issue**.

2.2.1 Effects of pot size on VOC removal in three species

2.2.1.1 Aim

This experiment was aimed at testing the relative rates of VOC removal of different pot sizes when confronted with dosages at the upper limit of allowable human exposure to VOC pollution in Australia – ie under what might be called 'heavy industrial' exposures. For this purpose, using benzene as the test VOC, exposure started with three consecutive doses of 5 ppm, this concentration being equal to the Safe Work Australia 8-h time-weighted averaged occupational exposure maximum for this VOC (NOHSC, 1991). Three species were tested, *Zamioculcas zamiifolia* (Zanzibar, or ZZ plant), *Sansevieria trifasciata* (Mother-in-law's Tongue) and *Epipremnum aureum* (syn. *Scindap(s)us aureus*) (Pothos). The last two species had not previously been tested in this laboratory.

2.2.1.2 Methods

Plant materials Plant materials of the three species were supplied by Ambius. Four pot sizes were trialled: 125, 200, 250 and 300 mm diameter, with 6 replicate plants used in each trial.

Test VOC and dosages Benzene was chosen as the test VOC, since it is prevalent in urban air, and also emanates from indoor sources, being a common solvent in furnishings. Three successive topping-up doses of 5 ppm (16 mg m^{-3} at 1 atm, 23ºC) benzene were applied to ensure full induction of removal response. A 25 ppm dose was then applied, to test further the robustness of the potted-plant system.

Equipment The test apparatus was the same as used in our previous studies (eg Orwell *et al*., 2006). Eight replicate Perspex bench-top test chambers were used, 0.6 x 0.6 x 0.6 m (internal volume 0.216 m^3), with removable lids on stainless steel frames, sealed with adhesive foam-rubber tape and adjustable metal clips (Figure 2). Each chamber had silicone septa for VOC injections and air sampling, a coil of copper tubing (i.d. 4 mm) circulating water from a water bath at 23.0 ± 0.1^{o}C; a suspended min-max thermometer; a 2.4 W fan to accelerate dose evaporation and equilibration; an overhead light box (air gap 50 mm) with five 18 W fluorescent tubes designed for plant growth (Wotan L 18/11 Maxilux daylight, Ozram, Germany), with variable intensity to a maximum of ~120 µmol quanta m^{-2} s^{-1}). Plunger-in-needle syringes were used for VOC injections of 10 µL or less, and conventional syringes of similar precision for larger volumes (SGE Australia). Gas-lock syringes (SCG Australia) were used to obtain chamber air samples at regular 24 h intervals. Chamber VOC concentrations were determined using a Shimadzu GC-17A gas chromatograph (GC), equipped with a 15 m DB5 Megabore column (0.34 mm i.d; Alltech Australia), FID detector and Class-VP 4.2 integration software (Shimadzu, Sydney, Australia).

Procedures The set of replicates of the particular species and pot sizes were watered to saturation and allowed to drain for 1 h before being placed, one per chamber, with lids sealed and lights on at maximum intensity. After plants were sealed in the chambers, a 5 ppm (16 mg m^{-3} at 1 atm, 23ºC) dose of benzene (AR grade, Sigma) was injected into each chamber and left for 30 min for complete evaporation before an initial air sample was taken. Subsequent air samples were taken from each chamber over the next several days. Two top-up doses of 5 ppm were injected into all chambers after 95% of the previous dose had been removed; then a final, 25 ppm dose was applied.

Leak tests Before and after each trial, leak tests were conducted on plant-less chambers, using a 5 ppm benzene dose. A beaker containing 500 mL water was placed in each chamber to simulate pot-plant evapotranspiration.

Data analysis From the results of the leak tests corrections for each chamber were applied to the test data. VOC losses in blank chambers were 4–10% per day. VOC removal activity was assessed as daily removal rates per pot-plant. Results were also calculated on the basis of alternative plant and potting mix parameters. Statistical comparisons were performed using one-factor ANOVA (Excel 2001, Microsoft, Australia Corp.) and pair-wise Tukey's HSD tests. Differences between treatments are reported as statistically significant where $p \leq 0.05$.

Figure 2. F. Torpy injecting benzene dose into test chamber containing *Z. zamiifolia* specimen.

2.2.1.3 Results

The three species showed similar patterns of VOC removal, in all pot size classes (Figures 3a – 3c). All pot sizes showed increases in removal rates from the first to the third 5 ppm dose, ie at full induction for this dosage. At full induction with 5 ppm benzene:

a) There were no differences in removal rates among pot sizes 200 – 300 mm *within* any species;
b) However rates in the 125 mm pots were two to three times slower than those of the larger pots, in all three species;
c) There were no differences in removal rates *among* species, for the 200 – 300 mm pot sizes;
d) In all cases, in 200 to 300 mm sizes, the third 5 ppm benzene dose was largely removed within 20 - 24 hours.

With the final, 25 ppm dose:

a) All pot size classes in all species showed some increase in removal rates compared with that at the third 5 ppm dose;
b) However, species differences in removal rates emerged with this dose;

c) Rates in the 125 mm pot treatments for all species were much slower than in the larger pot sizes.

Table 1 presents a summary of the times taken to remove 75% of a dose (ie at the point where the graphs of removal rate start to taper off, because the VOC concentration has been substantially reduced). Results are for all species and pot sizes after (a) the first dose; (b) the third dose: full induction at 5 ppm dosage; and (c) the final 25 ppm dose.

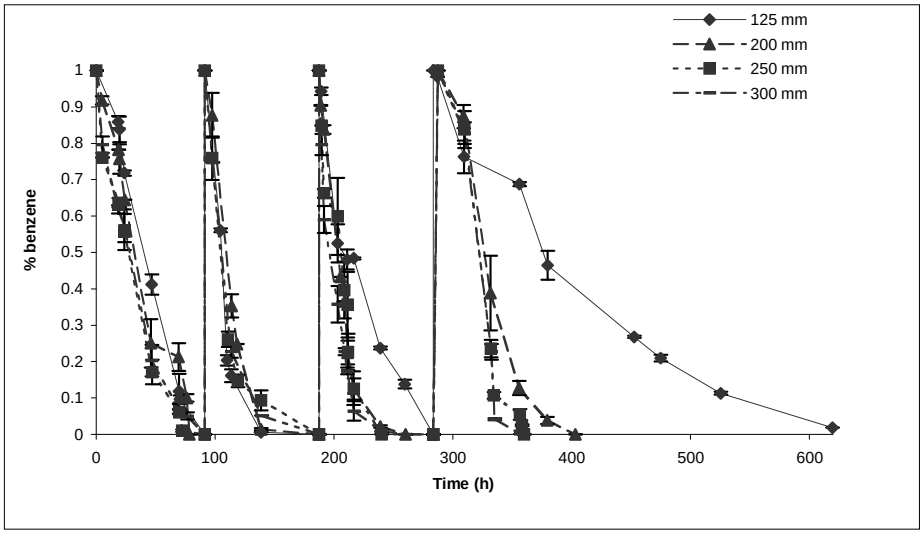
Table 1. Time taken to remove 75% of first and third 5 ppm benzene dose, and subsequent 25 ppm dose, in three species and four pot sizes; and increases in rate of removal.

Time (h)	**1st 5 ppm dose**	**3rd 5 ppm dose**	**Proportional increase in rate from initial**	**25 ppm dose**	**Proportional increase in rate from that with 3rd 5 ppm**
E.aureum					
125 mm	75	60	1.25	61	5
200 mm	44	24	1.8	17	7.4
250 mm	44	24	1.8	17	7.4
300 mm	44	24	1.8	17	7.4
S. trifasciata					
125 mm	78	61	1.3	67	4.5
200 mm	39	22	1.8	33	3.3
250 mm	39	22	1.8	22	5
300 mm	39	22	1.8	22	5
Z. zamiifolia					
125 mm	74	50	1.5	170	1.5
200 mm	74	20	3.7	67	1.5
250 mm	74	20	3.7	67	1.5
300 mm	74	20	3.7	67	1.5

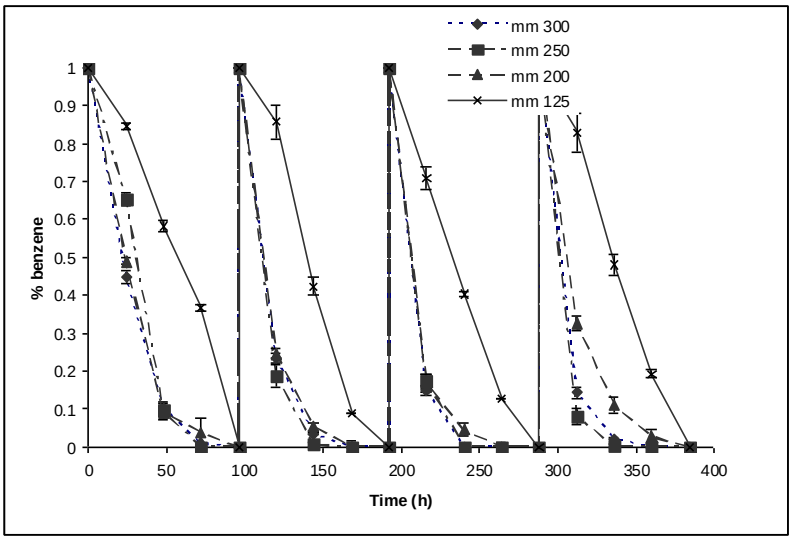
The values in Table 1 highlight the similarity of response at full induction with the 5 ppm dosage in the 200 to 300 mm pot sizes in each species, the VOC 75% removal times being 20, 22 and 24 hours respectively. Two of the three species also showed marked increases in removal rate with the fivefold increase in dose concentration to 25 ppm. In *E. aureum*, the 200 to 300 mm pots once more removed most of the dose in less than 24 hours, as did the 250 and 300 mm pots of *S. trifasciata* (with its 200 mm pots not far behind). In these two species, the 125 mm pots also showed about a fivefold increase in rate with the higher dose, although their final rates remained well below those of the larger pots.

In contrast, although *Z. zamiifolia* recorded the fastest rate of removal with the third 5 ppm dose, all pot sizes with this species showed only a 50% increase in rate with the 25 ppm dose It is possible that the performance of this species could pick up with repeated doses at this concentration, ie with further induction (a point which awaits further investigation). However, the result is probably of no importance from a plant use perspective, since this concentration is about fifty times higher as any that building occupants would be exposed to in the everyday environment. It was applied only to test the reserve capacity of the pot-plant microcosm to respond, and even *Z. zamiifolia* continued steadily to remove benzene at this final dosage — it just did not accelerate activity as much as the other two species.

a.



b.



c.

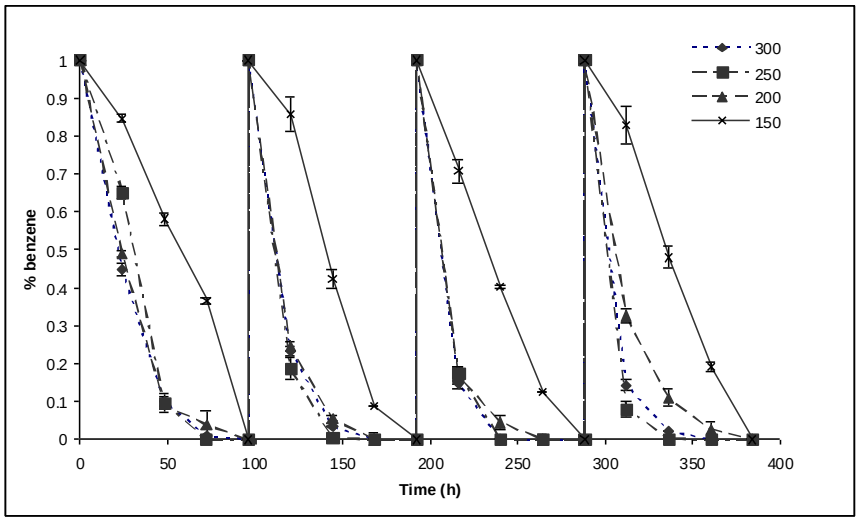


Figure 3. Removal of benzene (%) from test-chamber air of three doses of 5 ppm benzene, and one 25 ppm dose, with (a) *E. aureum*, (b) *S. fasciata* and (c) *Z. zamiifolia* (means ± SE; n=6).

Table 2 presents rates of benzene removal per hour calculated on the basis of rates per pot; rates per unit surface area of pots; and rates per litre of pot volume. The calculations show that, for each species, rates of removal per square metre of pot surface were about equal in the 125 mm and 200 mm pots. Since rates were equal *per pot* in the 200, 250 and 300 mm pots, inevitably rates calculated per unit area declined as sizes increased over this range. The results suggest that surface area for diffusion of the VOC could be a determinant of removal rates up to a point where an optimum or maximum rate is achieved for the exposure dosage present, beyond which the rate per unit area decreases, because the potting mix of larger pots is not as stimulated as those of smaller sizes. The relationship of similarity of removal rates for the two lower pot sizes did not hold when the rates were calculated on a per volume basis.

Table 2. Rates of removal of benzene (ppm h^{-1}) for the three tests species, per pot, per unit area at mouth of pot, and per litre of potting mix capacity per pot.

Species/ pot sizes	**Removal Rate (ppm pot^{-1} h^{-1})**	**Area of Pot (cm^2)**	**Removal Rate (ppm m^{-2} of pot h^{-1})**	**Volume of Pot (L)**	**Removal Rate (ppm L^{-1} h^{-1})**
E.aureum					
125 mm	0.066	123	5.36	1.24	0.053
200 mm	0.167	314	5.32	4.81	0.035
250 mm	0.167	491	3.40	9.95	0.017
300 mm	0.167	707	2.36	17.8	0.093
S. trifasciata					
125 mm	0.066	123	5.36	1.24	0.053
200 mm	0.18	314	5.73	4.81	0.037
250 mm	0.18	491	3.67	9.95	0.018
300 mm	0.18	707	2.5	17.8	0.010
Z. zamiifolia					
125 mm	0.08	123	6.5	1.24	0.064
200 mm	0.2	314	6.4	4.81	0.042
250 mm	0.2	491	4.07	9.95	0.020
300 mm	0.2	707	2.8	17.8	0.011

2.2.1.4 Discussion

The results clearly show that:

a) In all three species, VOC removal response at the 5 ppm benzene dosage was found to be consistent and robust. For all species, this VOC concentration was largely removed by the pot-plant microcosm within 24 hours;

b) Therefore, in these species at least, a 200 mm pot-plant is as effective as a 300 mm pot-plant for VOC removal up to concentrations equivalent to the 8-h averaged occupational exposure limit for the test VOC, which is ten times higher than the maximum TVOC loads in non-industrial buildings;

c) The results are completely consistent with those from our previous findings, which, taken together, indicate that other species would very likely perform similarly under these conditions.

The results also suggest that at lower, more realistic, dosages in normal indoor environments: (a) there might be a convergence of removal rates among all size classes, and (b) that

therefore a group of small pots might be as efficient as a single pot-plant in the 200-300 mm size range. **The next experiment was designed to investigate these two questions**.

2.2.2 Can several small pot-plants be effective in VOC removal?

2.2.2.1. Aim

To test the possible convergence of removal rates in pots of different sizes at lower VOC concentrations, in this experiment an initial dosage of 0.5 ppm benzene (ie 500 ppb) was used, this being the upper recommended limit for TVOC loads in normal indoor conditions, eg office, mall, school, dwelling etc. (Environment Australia, 2001). After three doses at 0.5 ppm, a follow-up dose of 5 ppm was then applied, again to test the robustness of the system to cope with raised pollution levels, and also to take these trials up to the starting concentration used in the previous study.

2.2.2.2 Methods

Plant materials One test species, *S. trifasciata*, was chosen for this study. This species was the median performer of the three tested above (Figure 3, Tables 1, 2). Tests were conducted using 1, 2, 3, or 4 pots per chamber, of 125 mm pots, plus a comparative treatment with one 200 mm pot per chamber. Four replicates were used for all treatments.

Test conditions Three successive topping-up doses of 0.5 ppm benzene were applied, to ensure full induction of removal response at that concentration, plus a final dose of 5 ppm. Equipment and procedures were as described for the previous study.

2.2.2.3 Results

Figures 4 and 5 show the results for this series of trials. Again, rates in all treatments increased with successive top-up doses of 0.5 ppm benzene. With every dose, removal rates were equal to each other in the 3- and 4-pot treatments; and they were faster than in the 1- and 2-pot treatments. Rates in the 2-pot treatment were also consistently faster than in the 1-pot treatment, and by the third 0.5 ppm dose, approached those of the 3- and 4-pot groups. And once more all treatments showed raised removal rates with the final, higher dose of 5 ppm. A comparison of times taken to remove 75% of the first and third 0.5 mm dose, and the final 5 ppm dose, are shown in Table 3.

The values show that, when fully induced (3^{rd} dose) the 2-, 3- and 4- x 125 mm pot treatments were able to remove 75% of the 0.5 ppm dose in less than 24 hours. In the 3- and 4-pot treatments, the time was just 16 hours. Furthermore, when the dose was raised to 5 ppm, in the 3- and 4-pot treatments it was again removed in just 16 hours, that is, there was a tenfold increase in their removal rates, in response to the tenfold increase in concentration (following first order kinetics of biochemical reaction response — the rate is directly proportional to concentration).

The 1- and 2-pot treatments also showed increases in rate with the higher dose (sevenfold), indicating that the response at the 0.5 ppm dosage was robust, with spare capacity, although in this case, for the 1- and 2-pot treatments, the removal rate at the 5 ppm dose was about half that of the other two treatments. From Table 2, it can be seen that three 125 mm pots have approximately the same surface area as one 200 mm pot, which adds weight to the notion that surface area may be a determinant of VOC removal rates between 125 mm and 200mm pot sizes.

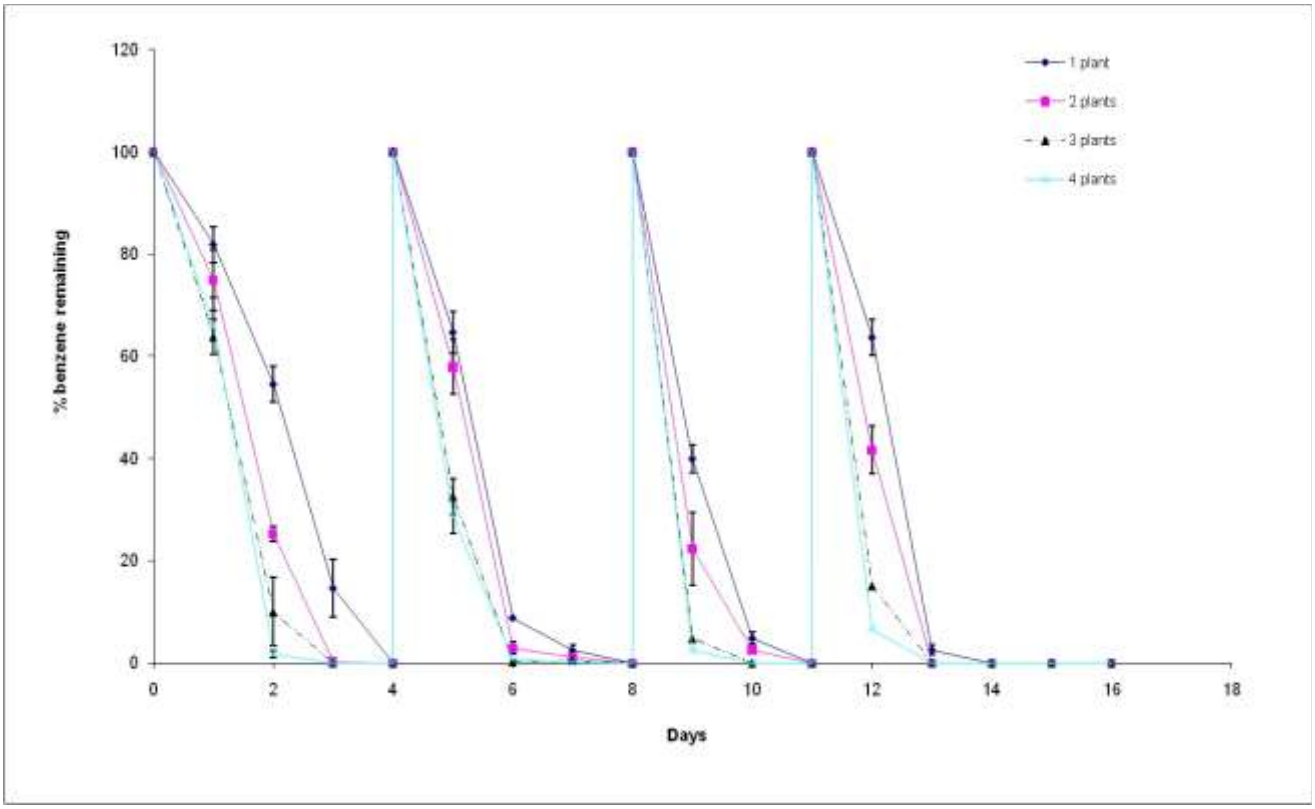


Figure 4 Removal from test-chamber air of three doses of 0.5 ppm benzene, and one 5 ppm dose, with 1,2,3, or 4 pots per chamber of *S. trifasciata* (means ± SE; n=6).

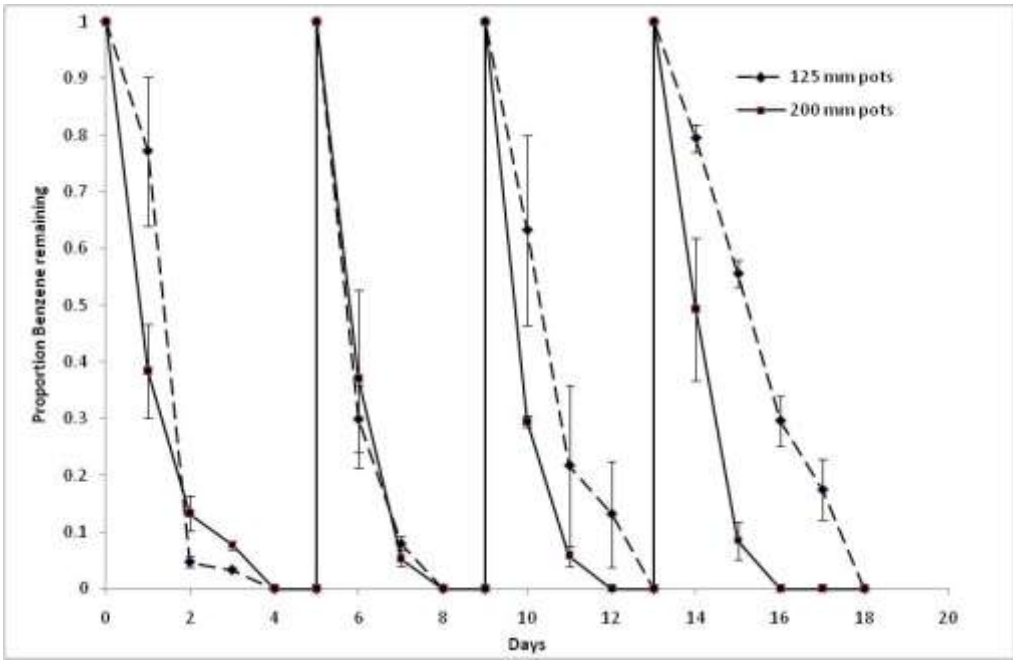


Figure 5. Removal from test-chamber air of three doses of 0.5 ppm benzene, and one 5 ppm dose, with one 125 mm pot, or one 200 mm pot per chamber of *S. trifasciata* (means ± SE; n=6).

Table 3. Time taken for *S. trifasciata* to remove 75% of first and third 0.5 ppm benzene dose and the subsequent 5 ppm dose, with 1 to 4 x125 mm pots per treatment, or 1 x 200 mm pots; and increases in removal rates.

Plant treatment time (h)	1st 0.5 ppm dose	3rd 0.5 ppm dose	Approx. increase in rate - initial to full induction	5 ppm dose	Approx. increase in rate- from 3rd 0.5 ppm
1 x 125 mm	66	27	2.5	40	7
2 x 125 mm	48	23	2	33	7
3 x 125 mm	42	16	2.5	16	10
4 x 125 mm	42	16	2.5	16	10
1 x 200 mm	35	22	1.6	35	6

The one 200 mm pot treatment also largely removed the 0.5 ppm dose within 24 hours at full induction, although the rate was slightly slower than that of the 3- and 4- x 125 mm pot treatments (22 hours compared with 16 hours). And, with the subsequent 5 ppm dose, the 200 mm pot treatment showed a very much slower removal rate than the 3- and 4-pot 125 mm pot treatments. However, a comparison between these results and those of the first experiment (Figure 3.b) shows that the 200 mm pot treatment, at full induction, is well able to remove a 5 ppm dose, and indeed a 25 ppm dose, within 22 hours (Table 1). It would appear, therefore, that the reason for its slower performance in this experiment is that the larger bacterial community in this pot size was not induced to respond as strongly at this relatively low concentration, as were the small pots. Paradoxically, this is further evidence of the robustness and reliability of the pot-plant microcosm in VOC removal.

2.2.2.4 Discussion

This second experiment demonstrates that, within the VOC concentration ranges that can be expected in most indoor environments (0.05 -0.5 ppm), groups of three or four 125 mm pots will be as effective as one 200 to 300 mm pot in VOC removal. The results of this series of trials, with the three species, are remarkable in showing the abundant capacity for VOC removal in pot-plants ranging in size from 125 to 300 mm pots. They also indicate circumstances under which increasing the number of pots can substantially increase removal rates.

From these results and those of our previous studies, we now have information on VOC removal in 12 commonly used indoor plant species (three of which will be presented fully in a later report to HAL; for list see Appendix 1), using four major urban outdoor/indoor VOC pollutants. The general pattern of VOC removal is very similar in all species tested, after about a week of acclimatisation/induction, and over more than the full range of VOC levels likely to be found in indoor environments.

The weight of this evidence leads us to the view that almost any commonly used indoor foliage species is likely to be equally as effective as those investigated in this laboratory (although we aim to test further species). Our conclusions modify and extend those of Wolverton and colleagues (1989, 1991, 1993) who, in their pioneering test-chamber screening studies with over 50 indoor plant species and a number of VOCs, found highly variable removal percentages. However, their experiments were essentially short-term, and

they were therefore unaware of the necessity for, and consequences of, an induction period – ie the influence of continued exposure to the contaminant. Accordingly, Wolverton's results can be taken as over-conservative estimates of the capacity of indoor plants for VOC reduction (which is on the whole desirable in a new field of investigation).

The reason for the consistency of VOC removal response among the species we have tested appears to be that, because the potting mix bacterial community primarily responsible for the VOC removal is among the microbial decomposers of organic matter in any indoor pot-plant formulation, it can be relied on to respond in a similar way to exposure to air-borne VOCs. The next step, therefore, was to test this hypothesis by examining the components and functioning of the potting mix microbial community. The results of these investigations are presented below in Section 3.

2.3 Significance to industry

The results of these two pot-size studies have practical implications for the indoor plant industry. It is clear that:

- For VOC removal, a 200 mm pot is as effective as a 300 mm pot, under any allowable Australian indoor conditions;
- A group of three 125 mm pots is as effective as one 200 mm pot, under general non-industrial indoor conditions (offices, homes, etc.);
- The findings have the potential to enable more flexibility in plant usage - eg clusters or towers of small plants interspersed in interiorscape arrangements with larger specimens;
- The results of the first study show that appropriate indoor plantings could be installed to alleviate occupational VOC exposures in situations where high VOC concentrations are a fact of life, eg in motor service garages, dry cleaning shops, etc.

3. Potting mix microorganisms in VOC removal

3.1 Introduction

3.1.1 Previous UTS studies

Our earlier test-chamber studies showed that the VOC removal rates of pot-plants remained unchanged in light or dark conditions, and that the potting mix continued to remove VOC concentrations for some days after the plant was removed and pots with potting mix replaced in the chambers. Both facts pointed to the participation of the potting mix microorganisms in the VOC removal process (Burchett *et al*. 2001). We therefore conducted an examination, using *Spathiphyllum* 'Petite', of changes to the potting mix microbial community associated with VOC induction. This showed that after benzene exposure, the total culturable bacterial numbers in the potting mix were reduced by about half. A diverse range of bacterial types were detected in the active extract, with four aerobic types showing positive growth as a result of benzene exposure. This suggested that these four bacteria (at least) were associated with VOC biodegradation (Wood *et al*., 2002). The total culturable numbers of anaerobic bacteria were unaffected, and thus are somewhat less likely to play a role in VOC removal.

In a follow-up investigation, this time using *Dracaena* 'Janet Craig', 49 culturable species of bacteria were isolated from potting mix after benzene removal, (Tarran *et al*. 2002) a majority of which were aerobic. However, when each culture was tested individually for VOC removal ability, none was effective in removing significant amounts of benzene. This indicated that removal is effected by a consortium of species, each of which contributes in some stepwise manner to the biodegradation process. This was not surprising, since it is common for more than one species to be integrally involved in a biodegradation process. For example there are seven species in the bacterialx consortium shown to degrade diesel fuel (which includes benzene and many other aromatic hydrocarbons) (Richard & Vogel 1999). Many other such bacterial biodegradative consortia have been identified in soils and waters (Okpokwasili & Olisa 1991; Ghazali *et al*. 2004; Pesce & Wunderlin 2004, Östberg *et al*. 2006). Such results also demonstrate that at least some of the species concerned are culturable.

3.1.2 Bacterial responses to new carbon sources

It is said that there are bacterial species that can degrade any organic (carbon) compound found on earth. It is also well known that, in general, with respect to many bacterial species that each can use any one of a small range of carbon sources as its 'food'. The normal nutrition of bacterial species in soils or potting mixes is by decomposition (biodegradation) of the organic matter therein. Mixtures thereof are used to clean up oil spills (Raghavan and Vivekanandan, 1999; Jørgensen *et al*., 2000).

What is remarkable in the indoor plant microcosm is that the potting mix bacteria can be stimulated to 'switch on' their responses with such minute, gaseous concentrations of VOCs. We have not experimentally controlled any potting mix formulations in our trials, because the indoor plant industry grows different species in different mixes, as appropriate. And, as discussed in Section 2, whatever the species/potting-mix combination in any of the 12 species we have tested, the VOC removal response always follows the same pattern, with approximately equal efficiency. However, the influence of different potting mix formulations on removal has not been investigated *per se*, and requires research.

Bacteria appear to be the dominant degraders of hydrocarbons in soil habitats generally (Kanaly and Harayama, 2000; Viñas *et al.*, 2005), and engineering biofilters are now used routinely in processing plants to remove air-borne VOCs (Barbosa *et al.*, 2007). The most common chemical process involved in bacterial degradation of aromatic hydrocarbons, including benzene, is oxidation carried out by aerobic bacteria, eg *Pseudomonas* species; the process has been well described (see eg, Brock and Madigan, 1991).

The time taken for a microbial community to become adapted to the degradation of hydrocarbons — the *induction* period — has been observed in other systems (described as *adaptation* by Spain and van Veld, 1983). The process of induction involves three inter-related mechanisms:

a) the initiation of production of enzymes to digest the material, and the repression of enzymes not currently needed;

b) the selective enrichment, ie growth in numbers and relative dominance, of specific microbial species (taxa) able to degrade the substance (possibly with a diminution in numbers of other types that cannot utilise the carbon source); and

c) possible genetic changes in the bacterial DNA which could result in new metabolic characteristics, including favourable new enzyme capacities (Spain and van Veld 1983).

d) Selective enrichment in particular has frequently been observed experimentally (see Leahy and Colwell 1990), and is the subject of the study reported here.

3.1.3 Bacterial community profiling

Since from our earlier results it appeared that VOC biodegradation in the potting mix was the result of a communal bacterial response, **the purpose of this study was to identify changes in the microbial community resulting from the VOC induction process**.

One approach to studying the nature of microbial communities is based on an investigation of their physiological capabilities. One of the most common methods is through the use of Biolog MicroPlates. Although originally created to identify and analyse changes in pure bacterial cultures (Bochner 1989), Garland and Mills (1991) demonstrated how they could be used to analyse successfully functional abilities of microbial communities. The original plate type, the Biolog GN MicroPlate, comprises 96 wells, 95 of which contain a different carbon source, with the remaining well being a control. Inorganic nutrients and tetrazolium violet dye are also present in each well. The dye is reduced as a result of bacterial respiration in the well, leading to colour formation which can be measured using spectrophotometry (Garland & Mills 1991). The results provide a community level physiological profile (CLPP) by indicating the array of carbon sources used in supporting growth, which gives information on the functional abilities of the microbial community as a whole. In simple terms, the CLPP of a microbial community is a ‘summary’ of the physiological capabilities of the collection of culturable organisms present. That is, it shows what that community can do, in terms of degrading (digesting) particular carbon compounds, rather than addressing which individual bacterial species/types make up that community.

In this study the Biolog EcoPlate was used, which was designed for ecological applications. The 96 wells in this case comprise triplicates of 31 different carbon sources, plus three control wells (Preston-Mafham *et al.* 2002). This system has been used to compare soil microbial communities of different plant species (Fang *et al.* 2001; Grayston and Prescott 2005), and of different habitats (Garland and Mills 1991). Other studies have examined

changes in the CLPP accompanying environmental changes in the soil associated with metal pollution (Niklińska *et al.* 2006); flooding by wastewaters (Gelsomino *et al.* 2006); and the application of organic amendments (Gomez *et al.* 2006). A general criticism raised concerning the Biolog MicroPlate method is that only culturable microorganisms can be detected, whereas it is considered that less than 1% of soil organisms are culturable (Degens and Harris 1997). However, the fact that the potting mix cultures we previously obtained were found to degrade benzene efficiently (Wood *et al.,* 2002), indicates that at least some active part of the bacterial complement involved in the process is culturable.

3.2 Study aims

Compared with the body of research published on bacterial interactions in soil and water, the phenomenon of soil (or potting mix) bacteria degrading air-borne pollutants has received minimal study. **The experimental aim of this study was to investigate any selective enrichment of bacterial response occurring when exposed to an introduced air-borne carbon source –benzene.** Specific objectives were to: (a) establish a baseline community level physiological profile (CLPP) for the potting mix bacteria of an internationally used plant species, *Spathiphyllum* 'Petite', to provide information on the functional abilities of the potting mix root-zone microbial community; and (b) investigate whether and how the CLPP might change as a result of induction of benzene biodegradation.

3.3 Methods

Plant materials Twelve-month old specimens of *Spathiphyllum* 'Petite', in 140 mm pots, were provided by Ambius (from Dalwood Wholesale Nursery, NSW). The plants were in a standard potting mix of 5% coco peat: 80% composted pine bark: 15% basalt crusher dust; and small amounts of aglime, dolomite and superphosphate (Dalwood Nursery, pers. comm.). Plants had received foliar feed (nitrogen-based soluble fertiliser), Mancozeb fungicide and Crown insecticide, and had been top-dressed with controlled release fertiliser (Osmocote; Scotts Australia Pty Ltd, Sydney) at 8–9 months after planting. Several weeks prior to use in the current experiments, plants were fertilised with Osmocote Plus controlled release fertiliser, at approximately 10 g/plant. That is, both plants and their root-zone microbial communities were well nourished for healthy growth. Eleven replicates were used in this study, and the equipment and procedures involving the use of the bench-top test chambers were similar to those described above.

Test design Plants were watered to field capacity and allowed to drain for 1 h before use. Just prior to placement in the chambers, a pre-benzene-dose sample of potting mix was removed from each pot for EcoPlate inoculation. To obtain maximum induction of the VOC removal response, a 25 ppm dose of benzene was injected into each chamber and left for 30 min to allow complete evaporation before commencing sampling of chamber air concentrations. Two successive top-up doses of 25 ppm were injected into all chambers after 95% of the previous dose had been removed, and reduction rates over a full three-dose induction period recorded. Post-benzene potting mix samples were also made, taken immediately as pot-plants were removed from the chambers after the 3rd dose of benzene had been reduced by at least 95%. Samples were taken with a spoon, from between 5 and 15 mm depth. Pieces of organic material >3 mm in any dimension, and any residual Osmocote granules, were removed from samples prior to weighing.

Procedural control was also performed, to determine whether, or by how much, the observed changes in the CLPP of the potting mix bacteria were related to benzene exposure

or to some other effect related to enclosure in the chambers. Four replicate plants were used in this trial, placed in the chambers for 14 days without any dose of benzene. EcoPlates were made up before and after confinement in the chambers.

Preparation of Biolog EcoPlates The method used was modified from that of Grove *et al.*, 2004). Each potting mix sample was added to 10 mL of phosphate buffer (composed of: 1.236 g Na_2HPO_4 [BDH]; 0.18g NaH_2PO_4 [Sigma]; 8.5g NaCl [Caledon]; per L deionised water; sterilised by autoclave at 121ºC for 15 min). The buffer was used in preference to water to reduce bacterial cytolysis (cell destruction). Samples were shaken for 1 h at 300 rpm, and the resulting suspensions were filtered through paper tissue to obtain 2.5 mL of suspension. This was then diluted 10-fold and used to inoculate the EcoPlates, using 150 µL of suspension per well. EcoPlate inoculations were conducted under laminar flow, in a tissue culture clean room.

Plate Readings The intensity of colour development in a well is proportional to the strength of the physiological behaviour of the bacterial community. The resultant optical densities (ODs) of the wells were read at a wavelength of 590 nm, the peak absorbance of tetrazolium dye (Zak *et al.* 1994), using a Bio-Tek PowerWave HT microplate spectrophotometer with KC4 Ver. 3.2 software, immediately after inoculation, and at 24 h intervals for the following 7 days. Between readings, EcoPlates were incubated in the dark at 23±1 ºC. This temperature was chosen because it is a standard office temperature in Australia, and hence the 'normal habitat' for indoor plants. Means of the triplicate ODs for each the 31 carbon-source wells were corrected for any colour development in the blank water wells.

Data analysis Changes in carbon source utilisation in samples taken before and after benzene induction, were determined using multivariate analysis of variance (MANOVA with the Wilk's λ test), and Tukey's *post hoc* tests. EcoPlate readings were made at 4 d after inoculation, when the greatest variation in OD amongst EcoPlate wells occurred (Glimm *et al.* 1997). The relationship between the multivariate CLPP data before and after benzene exposure was examined using Principal Components Analysis (Minitab Ver. 14, Minitab Inc. 2003).

3.4 Results

Induction of benzene removal The benzene removal rates are presented in Figure 6. The graph demonstrates that these pot-plants displayed the now familiar pattern of induction of response to benzene exposure. Though removal rates were slow, in face of the high dosage exposure, the results follow a generally similar pattern to those of all previous trials.

Results of the principal components analysis (PCA) of the potting mix bacterial community level physiological profile (CLPP) pre- and post-benzene exposure, are shown in Figure 7. The pre-benzene exposure data points are clearly separated from the cluster of post-benzene exposure data points along the PC1 axis. This finding indicates that overall carbon source usage by the bacterial community changed as a result of benzene exposure: a clear effect of the VOC on the potting mix bacterial community. The points represent simultaneous variations in all 31 carbon sources, so it is a general change in physiology which is displayed.

CLPP of procedural controls The PCA comparison of CLPP data from pre- and post- no-benzene chamber controls (Figure 8) also showed significant differences in distribution between the two lots of readings, on both PC1 and PC2. The pre-chamber data points were more closely placed along both axes, while the post-chamber points were widely dispersed

from one another. The test confirmed that 14 days in the test chambers in itself leads to changes in the potting mix microbial community, even in the absence of benzene.

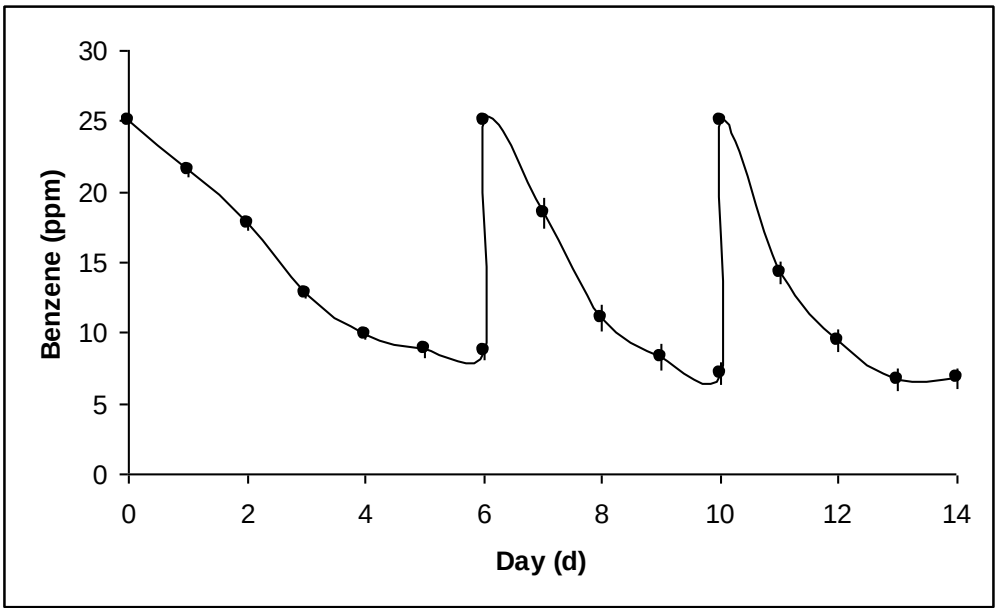


Figure 6: Rate of benzene removal with three doses of 25 ppm benzene, in *Spathiphyllum* 'Petite' (n=11; Means ± SE).

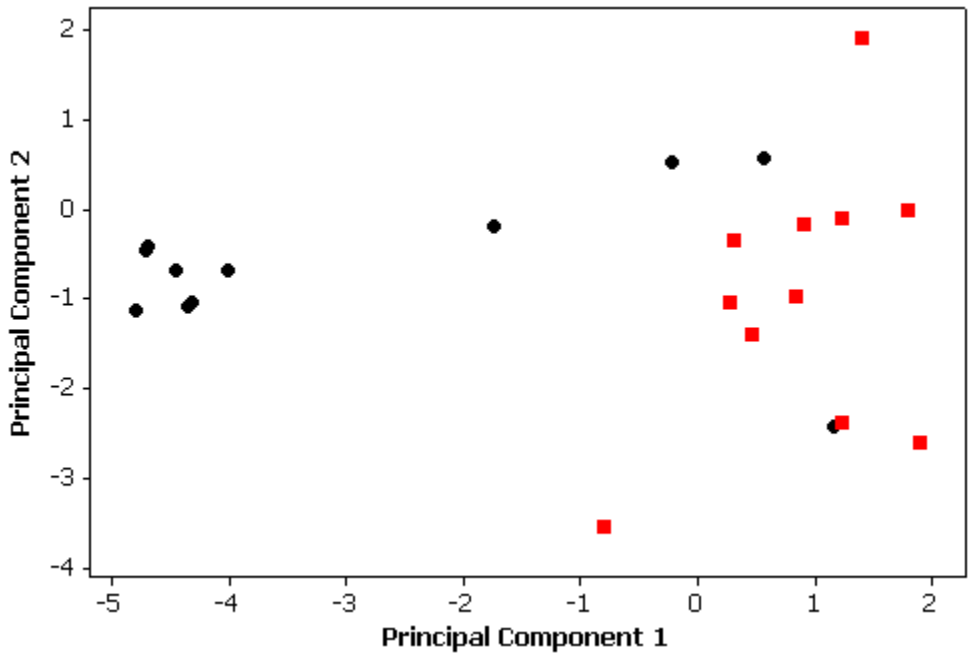


Figure 7: Ordination from PCA of first and second principal componenets of pre- and post-benzene exposure CLPP, for potting mix of *Spathiphyllum* 'Petite'. ■ = pre-benzene exposure; ● = post-benzene exposure.

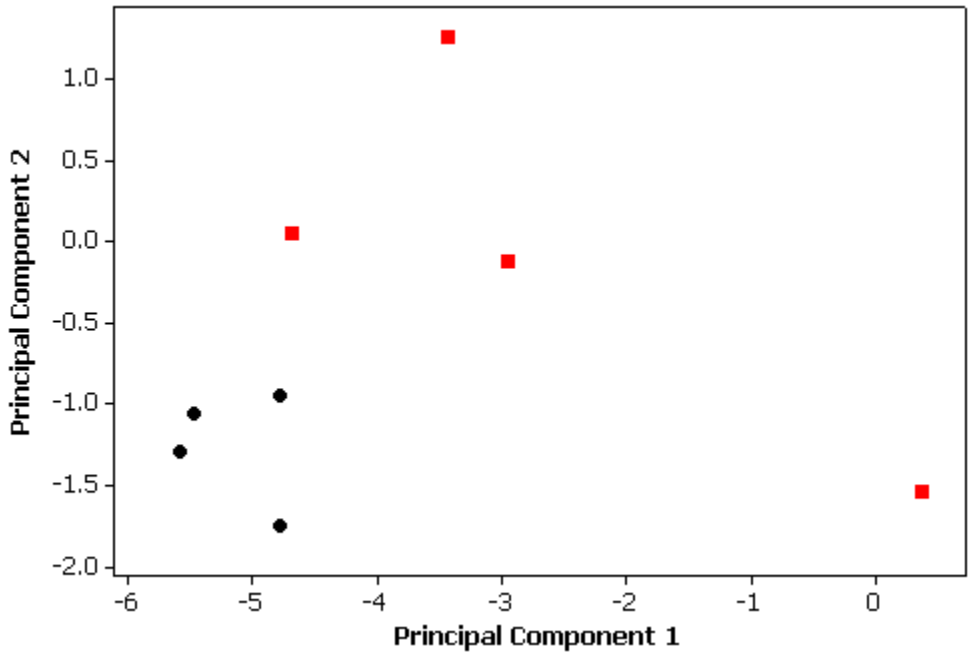


Figure 8: Ordination from PCA of first and second principal components of procedural control test – CLPP before and after confinement in empty chamber, for potting mix of *Spathiphyllum* 'Petite'. ■ = pre-benzene exposure; ● = post-benzene exposure.

Two weeks is the longest period that plants are ever kept in chambers in our experimentation, and although each is placed in a saucer of water, that dries out over the period. Also, although the chambers have 100% humidity, plant and potting mix will be suffering from water stress at the end of the run. However, a comparison of Figures 7 and 8 shows that the responses of the bacteria are quite different in the two sets of conditions. This means that the changes indicated in Figure 7 can be taken to reflect the effects of benzene on the physiological profile of the community, rather than simply the effects of the chambers.

3.5 Discussion

Benzene removal The pot-plants showed an induction to benzene removal exactly similar to those in our previous studies (Figure 6), although the removal rates were not nearly as fast as in the trials presented in Section 2. The time taken to remove 75% of the first dose was 143 hours, and for the third dose, 62 hours (more than double the initial rate). There are probably at least two reasons for the slower removal rates here than in earlier studies. First, the pots were small (140 mm), not much bigger than the smallest pots used in the pot-size experiments above. Secondly, these pot-plants were exposed to three doses of 25 ppm benzene – a ten times higher concentration than the maximum used in any of the three-dose sequences above. The high concentration was chosen to accentuate any changes the benzene may have on the bacterial community, and emphasise the role of benzene-degrading species. However, with the final dose in Experiment 1 (Table 1), and in earlier investigations with 200 mm pots, we have observed removal of 25 ppm benzene within 24 hours, once the system was fully induced (Wood *et al.*, 2002; Orwell *et al.*, 2004).

Effects of benzene exposure on CLPP There was a distinct difference in the CLPPs pre- and post-benzene exposure (Figure 7). Such differences could result from changes in the relative

abundances of different bacterial types, or in stimulation of specific enzyme production of the bacteria involved, or a combination of both. As mentioned above, our preliminary study of benzene exposure with *S.* 'Petite' (Burchett *et al.*, 2001), found a reduction to about half of the culturable bacterial density, but with a simultaneous increase in abundance of a small number of aerobic species. So it appears that the changes in bacterial composition of the potting mix observed here primarily result from changes in relative abundance among the potting mix bacterial complement, in response to benzene exposure (Siciliano *et al.*, 2003).

3.6 Significance to industry

This is the first systematic investigation conducted on the physiological profile and behaviour of VOC degrading bacteria in the potting mix of ornamental plants, and in particular indoor plants. The results of the study:

- Confirm the primary role of the potting mix bacteria in VOC removal by indoor plants;
- Establish the normal CLPP of potting mix bacteria associated with the root zone of what is probably the most commonly used indoor plant species in the world;
- Has also, for the first time, thrown light on the responses of the CLPP of the bacterial community to exposure to one of the commonest urban air pollutants worldwide, benzene. (This compound can often be found at higher concentrations in indoor air than outdoors, since it is used as a solvent in many furnishing/finishing materials.)

Further investigation of the bacterial agents of removal is needed, both of the variations in bacterial communities that could be specific to different plant species, and also in the changes in CLPPs that may occur in response to other VOCs. However, the results provide a baseline for directing future horticultural improvement of indoor plants, including means of increasing further their VOC biodegradation capacity.

4. Potential for indoor plants to reduce CO_2 and hence building energy consumption

4.1 Introduction

4.1.1. Air-conditioning ventilation requirements

Air-conditioning in city buildings has two main purposes – temperature control and air refreshment. For the second purpose, refreshment rates with outside air are commonly in the range of 11-15% p. h. (which tends to result in higher air pollution levels indoors than outside). The compelling purpose for air refreshment is not so much to replenish O_2 (21% of the atmosphere) but to remove CO_2 (Höppe and Martinac, 1998). This is because raised CO_2 levels lead to loss of concentration and drowsiness more rapidly than O_2 depletion. Studies have shown that student performance declines with increasing CO_2 (Shaughnessy *et al*., 2006) as does workplace productivity (Seppänen *et al*., 2006). Global CO_2 concentrations are currently estimated at about 380 ppm. Australia follows the standards of the WHO and the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 2001) for indoor CO_2 levels, which recommend 1,000 ppm as the maximum acceptable indoor air concentration. Some organisations (eg UTS) select 800 ppm CO_2 as the trigger cut-in maximum for extra ventilation. (We have observed that three people talking in an office can increase CO_2 concentrations to this limit within about 10 minutes.) Global warming forecasts predict ambient outdoor CO_2 levels to rise, possibly to greater than 500 ppm, over the next 25-30 years (IPCC, 2009), which will further narrow the gap between outdoor air and when indoor air needs accelerated refreshment ventilation.

In our first office study, we found that three pots of *Dracaena* 'Janet Craig' reduced office CO_2 levels in an air-conditioned building by 10%, and in a non-air-conditioned building by 25% (to below external ambient levels) (Tarran *et al*., 2007). Indoor plants could potentially play a significant role in keeping CO_2 levels below the extra-ventilation cut-in point for air-conditioning systems of city buildings, hence reducing the power consumption of the system, and the C-footprint of the city.

Pot-plants are only just beginning to be considered for this purpose. The Australian Council of Built Environment Professionals Ltd (BEDP) recently published a *National Policy Framework on Sustainable Settlements* (BEDP, 2009), and an associated design guide - *Living Walls: A Way to Green the Built Environment*, which relates to both external and internal plant arrangements, installed on a framework with built-in irrigation. Internal plant walls of this type are in use in Australia, eg the plant wall at Sydney airport; installed by Ambius), and overseas, eg with the pioneering work of Darlington *et al.* (2001) in Canada, and others (Hoyano, 1988; Alexandri and Jones, 2006). If predicted climate change consequences become a reality, such installations are likely to become more common on or in new city buildings, which would have a number of benefits for urban sustainability. However, plant-walls of this type are expensive to construct and maintain compared with indoor greening strategies based on pot-plant arrangements, which are portable and flexible in positioning. This has advantages with respect to changing uses or staff arrangements in an indoor space, and allows retro-installation in already standing buildings technically easy to accomplish. It is also currently unknown just how many plants are required to influence indoor CO_2 levels. We report here the results of preliminary laboratory studies on the light requirements for effective CO_2 reduction in two indoor species, to help lay the foundation for further horticultural development of indoor plants for their air-freshening function.

4.1.2 Photosynthesis in shade-tolerant plants

4.1.2.1 Variables affecting photosynthesis

With adequate light plants not only absorb CO_2 via photosynthesis, but release an equimolecular concentration of O_2, refreshing air in two complementary ways, but achieving enough light indoors for effective CO_2 reduction is often difficult. In addition, with the pot-plant system, it is necessary to take account that non-green plant parts and potting mix microorganisms (bacteria and fungi) continually respire, emitting CO_2; in the dark, so do green shoots. For a pot-plant to have a favourable energy balance (positive net photosynthesis) to maintain itself (let alone grow), photosynthetic sugar yield from CO_2 assimilation must be significantly higher than the amount needed to fuel its own respiration. To make a significant difference to indoor air quality, net photosynthesis of the pot-plant must also be greater than the combined forces of respiratory CO_2 production of the microcosm unit as a whole.

Rates of photosynthesis (measured most commonly as CO_2 uptake) depend on interactions of a number of biological variables, including: species-specific differences eg light/shade tolerance; foliage area; age; and capacity for acclimatisation to the prevailing indoor light regime. A number of environmental factors are also involved: light intensity at the pot-position – and the daily/weekly light period in the space; nutritional status of the potting mix, moisture levels, surrounding humidity, temperature, and CO_2 concentration (commonly higher indoors than outside).

4.1.2.2 Light requirements

Although shade-tolerant plants (including most indoor species)have lower photosynthesis rates overall than 'high light' plants, they generally show higher net photosynthesis rates at low light intensities than do high light species (Boardmann, 1997). The light *'compensation point'* is the light intensity at which the photosynthetic uptake of CO_2 by the plant exactly equals the CO_2 output produced by its own respiration. If kept at this light level there is obviously no net carbohydrate yield – the plant is starving. As light intensity is increased, CO_2 uptake rate will increase also, up to a light *'saturation point'*, where the shoot's photosynthetic apparatus is fully engaged. Any further light increases are redundant, and will even start to inhibit photosynthesis, by damaging chlorophylls and other parts of the photosystems (photoinhibition). The intensity of full sunlight is about 2000 µmol quanta m^{-2} sec^{-1}, and the light saturation points for shade-tolerant species are generally below about 400 µmol m^{-2} sec^{-1}. In a recent office study we found light intensities varied greatly with time of day and weather in offices with windows, but in internal offices light intensities were sometimes lower than 10 µmol m^{-2} sec^{-1} - very low for the achievement of any positive net CO_2 uptake.

The very limited information available on light requirements of indoor plants comes mainly from studies associated with the practical problems of transferring micropropagated plantlets from *in vitro* to *ex vitro* conditions, and mainly on *Spathiphyllum*. Van Huylenbroeck *et al.* (1995) found *Spathiphyllum* 'Petite' plantlets grown under 300 µmol m^{-2} sec^{-1} were photoinhibited compared with those at 100 µmol m^{-2} sec^{-1}. A more recent study (Akoumianiki *et al*., 2004) found that *Spathiphyllum* (unnamed sp.) grown at 40 and 420 µmol m^{-2} sec^{-1}, showed differences in leaf morphology and photosystem biochemistry in the two regimes. The lower-light plants developed higher concentrations of light-capturing pigments in their leaves. Dewirl *et al.* (2005) reported that, among various treatments, best

growth in *Spathiphyllum* was observed at 70 – 100 µmol m^{-2} sec^{-1}, in a perlite- hydroculture substrate. A micropropagation study of four varieties of *Aglaonema* (Yeh *et al.,* 2007) found that: "After transferring [from tissue culture laboratory] to a shaded greenhouse, plants under 130 µmol m^{-2} sec^{-1} during *ex vitro* acclimatization had higher dry weight than those under 80 or 200 µmol m^{-2} sec^{-1}". And *Epipremnum aureum* was found to have a light saturation point of about 300 µmol m^{-2} sec^{-1} (Kittel *et al.,* 2001).

It is known that shade-tolerant plants have the capacity to acclimatise to lower light intensities by down-regulating their photosynthetic processes - both light compensation points and saturation points can be reduced (Vidal *et al*., 1990; Thompson *et al*., 1992). However, the abilities of indoor plants in these processes have previously received little research.

4.1.2.3 Carbon dioxide requirements

Increased CO_2 uptake has been observed in *in vitro* plantlets of *Spathiphyllum floribundum* and *Pelargonium zonale* with CO_2 enrichment of from 400 to 1000 ppm, at a light intensity of 80 µmol quanta m^{-2} sec^{-1} (Reuther,1987). Marcelis *et al*. (2005), in a greenhouse study with four species - *Kalanchoe*, Poinsettia, *Ficus* and *Dracaena* - found that the relative effects of light on growth, in increments of 1%, was greater at lower light levels, higher CO_2 concentrations, and warmer temperatures. They concluded that: "Light should not be considered a separate growth factor in greenhouse horticulture, as it forms an integral part of total [plant] management". The same must be true when considering CO_2 uptake capacity of indoor plants, and minimum and optimum lighting requirements have yet to be established.

The objectives of this study were to conduct controlled laboratory investigations of the capacities for CO_2 reduction in two indoor plant species *S.* 'Petite' and *E. aureum*.

4.2 Test-chamber CO_2 flux with pot-plants of two species

4.2.1 Aim

The aim of this investigation was to examine the CO_2 flux of the plant-and-pot microcosm as a whole in a closed environment, for two species. A light intensity of 45 µmol quanta m^{-2} sec^{-1} was used, which is the maximum light intensity supplied to the chambers, and is in the range reported above for *Spathiphyllum* (although only for tissue-cultured plantlets), and about only one quarter of that reported for *E aureum*, a less shade-tolerant species.

4.2.2. Methods

Plant materials Plants of the two species in 200 mm pots were tested, with four replicates of each. The pots had been kept in the laboratory (light intensity of 10-15 µmol m^{-2} sec^{1}) to acclimatise to building conditions for at least five weeks prior to testing. Plants were well watered and allowed to drain for 1 hour prior to placement in the chambers.

CO_2 monitoring Measurements of chamber CO_2 concentrations were made using a portable CO_2 monitor, (TSI IAQ-CALC; TSI Inc., MN, USA)**.** Readings were made continuously at 1 min intervals, and logged directly into a computer.

Test conditions One of the bench-top perspex chambers described in Section 2 was used for the purpose. When the pot-plant was placed in the chamber, the CO_2 monitor was positioned in the corner before sealing the unit.

Procedure Changes in chamber CO_2 concentration were measured over 1 hour, after which the pot was removed, the shoot cut off at the surface of the potting mix, and the pot containing roots and potting mix placed back in the chamber for another 1 hour of measurement. Fresh weights and leaf areas were measured for the decapitated shoots.

4.2.3 Results

Spathiphyllum Initial CO_2 concentrations in laboratory and chamber were approximately 500 ppm. The changes in chamber CO_2 concentrations for this species are presented in Figure 9. It can be seen that the pot-plant unit as a whole did not detectably alter the CO_2 concentration in the chamber over the 1 hour of testing. That is, any net photosynthesis achieved by the plant shoots was balanced by the respiration of the roots plus potting mix micoorganisms. When the shoots were cut off and the pots replaced in the chambers, however, the CO_2 concentration in the chamber rose over the subsequent hour, because of the combined respiration of roots and potting mix microorganisms. The third line, calculated by difference between the first two lines, shows the net photosynthetic uptake of CO_2 by the green shoots over a I-hour period. In this species the rate of uptake was 4.8 mg CO_2 m^{-3} m^{-2} h^{-1}, however that uptake was equalled by the CO_2 emission from the roots and microoganisms.

E. aureum Initial laboratory and chamber CO_2 concentrations during this trial were approximately 300 ppm. Results are shown in Figure 10. In this species a small average net reduction in CO_2, of approximately 0.04%, was recorded for the whole pot-plant over the 1 hour of testing. The rate uptake for these plants was calculated as 2.8 mg CO_2 m^{-3} m^{-2} h^{-1}.

4.2.4 Discussion

The results show that:

- Both species photosynthesise at a light intensity of 45 µmol quanta m^{-2} sec^{-1}; though the *rate* in *E.aureum,* as expected was about one third less than that in the *Spathiphyllum*.
- However, in this chamber experiment:
    - With *Spathiphyllum* 'Petite' there was no net CO_2 reduction from the plant-and-pot microcosm; and
    - With *E. aureum* there was a very small net reduction in CO_2 concentration over the 1 h period from the pot-plant unit.

It is clear that, when considering the contribution of pot-plants to indoor CO_2 reduction, the entire microcosm must be considered when estimating the potential of the indoor plant species, as well as other issues such as light levels.

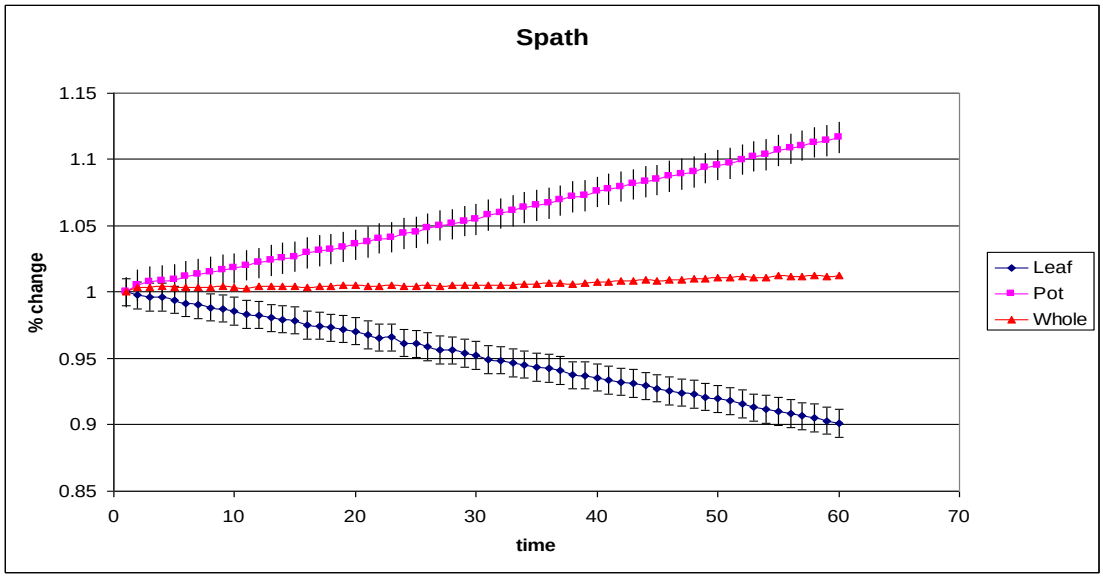


Figure 9. CO_2 fluxes in 1-hour chamber trials with 200 mm pots of *Spathiphyllum*; with whole plant, roots and potting mix only, and (by difference) shoots only (n = 4; Mean ± SE).

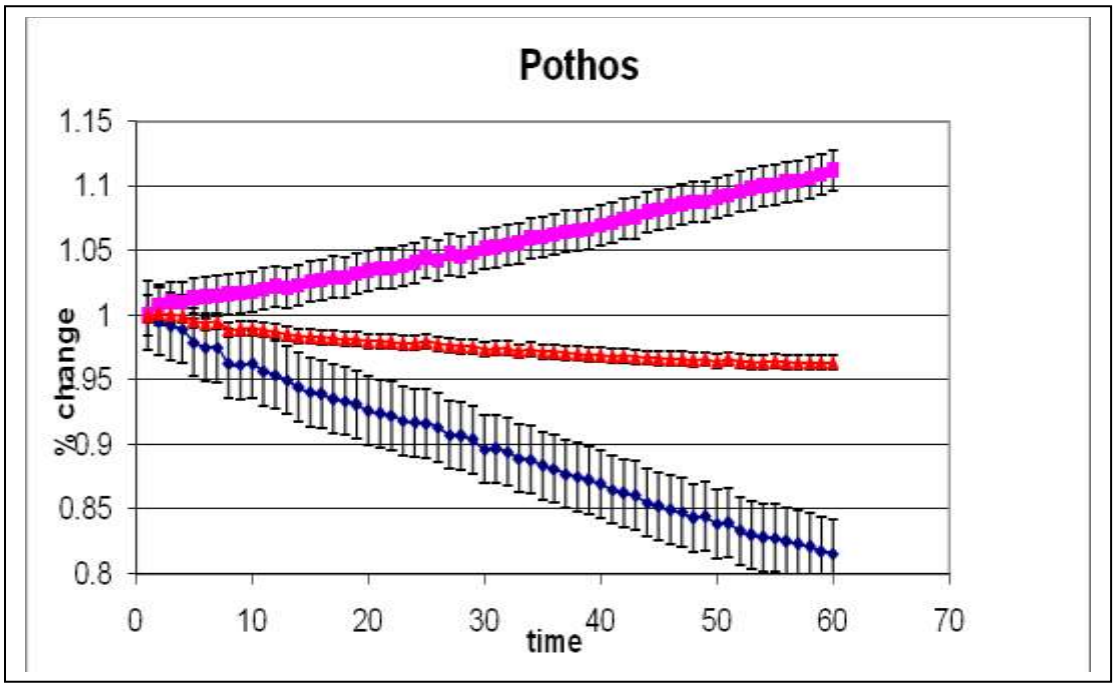


Figure 10. CO_2 fluxes in 1-hour chamber trials with 200 mm pots of *E. aureum*; with whole plant, roots and potting mix only, and (by difference) shoots only (n = 4; Mean ± SE).

4.3 Leaf light / CO_2 uptake responses in two species

4.3.1. Aim

This study took a complementary approach to that of the previous experiment. In this study leaf photosynthetic rates for each species were measured using a leaf-clip chamber, in which both light and CO_2 concentrations can be controlled. **The aim of this study was to discover the photosynthetic light compensation and saturation points for the two species, under the indoor conditions to which they had been acclimatised.**

4.3.2 Methods

Plant materials The pot-plants were new plants from the same batches used in the first chamber CO_2 study, ie they were acclimatised to indoor light levels. In this case, however, the pot-plants remained intact on the open bench, and the test chamber was applied to individual sample leaves in turn. Three replicate plants were used of each species, and 4 healthy mature leaves were sampled on each plant.

CO_2 monitoring Measurements were made using a LI-COR LI-6400 Portable Photosynthesis System (Lincoln, NA), with which both leaf chamber light intensity and CO_2 concentration can be controlled. This measures changes in CO_2 concentration by infrared absorbance. The leaf chamber was gently clamped onto the sample leaf, and an air stream with an entering test CO_2 concentration of 400 ppm (a usual minimum office air concentration) was passed through the chamber. With no light in the chamber, air exiting will have a higher CO_2 concentration than that of the entering stream, because of 'dark respiration' in the leaf. As light intensity is increased, exiting air will have progressively lower CO_2 concentrations than that of the entering air.

4.3.3. Results

Spathiphyllum The photosynthetic light response curve for this species is presented in Figure 11. The results show that:

- The light intensity at *compensation point* (where photosynthetic CO_2 uptake equals output from respiration, and the curve intersects with the x axis) was approximately 4 µmol quanta m^{-2} sec^{-1}.
- The light intensity at *saturation poin*t for CO_2 uptake (ie rate of photosynthesis reaches a maximum and the curve becomes horizontal) was at 28 µmol quanta m^{-2} sec^{-1}, and the net CO_2 uptake rate was 0.8 µmol CO_2 per m^2 leaf area, sec^{-1}.
- At a light intensity equal to the *average light level* in the laboratory (12-13 µmol quanta m^{-2} sec^{-1}), the rate of CO_2 uptake had reached about 80% of the maximum achieved (0.63 µmol CO_2 m^{-2} sec^{-1}).
- This light intensity saturation point value is four or five times lower than those reported above as optimum for *growth*, and indicates the capacity for acclimatisation to very low light levels in this species.

The results overall indicate that at prevailing light intensities in internal offices (no windows), active net CO_2 uptake is occurring in the green shoots, which would assist in the maintenance metabolism of the plants, though probably no real growth.

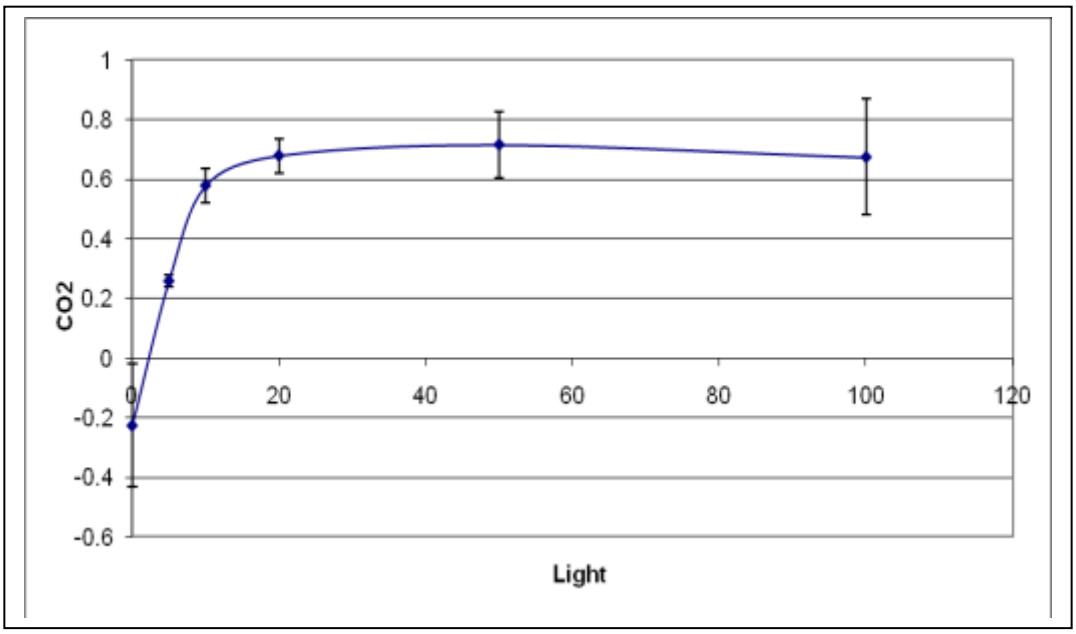


Figure 11. Light saturation curve of CO_2 uptake in *Spathiphyllum*. Values are expressed as a µmol CO2 m^{-2} sec-^{1}, and light intensity as µmol quanta m^{-2} sec^{-1}. (Means ± SE).

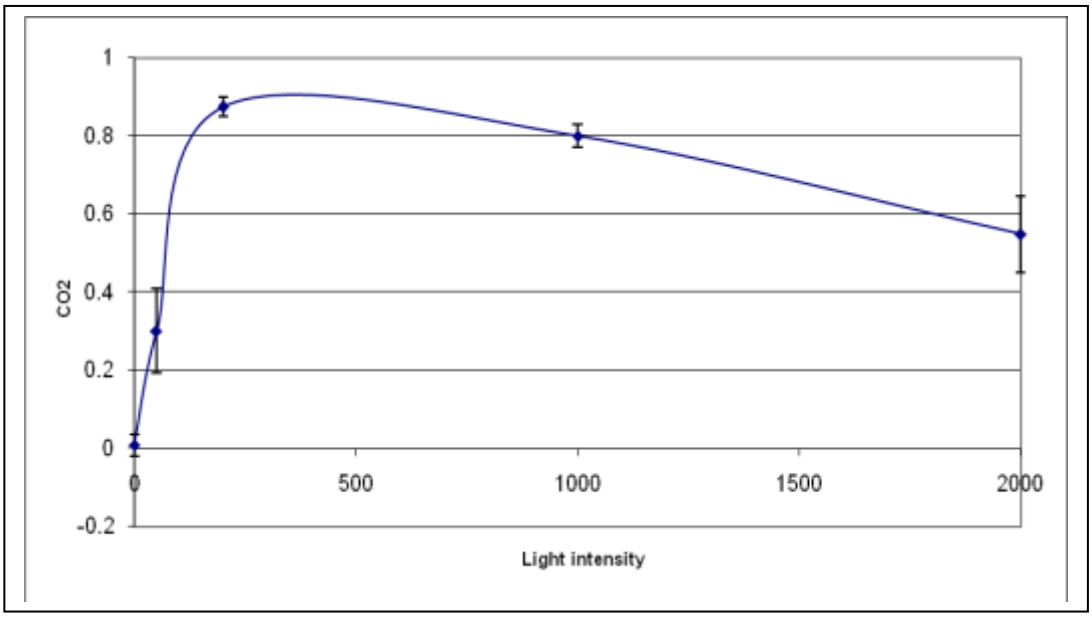


Figure 12. Light saturation curve of CO2 uptake in *E. aureum*. Values are expressed as a µmol CO2 m^{-2} sec-^{1}, and light intensity as µmol quanta m^{-2} sec^{-1}. (Means ± SE).

E.aureum The photosynthetic light response curve for this species is presented in Figure 12. In this species:

- The light intensity at *compensation point* was approximately 10 µmol quanta $m^{-2}sec^{-1}$, ie at the prevailing indoor light levels (10-15 µmol quanta m^{-2} sec^{-1}) there would be very little net uptake of CO_2 in these plants (as shown also in the chamber experiment);

- The light intensity at *saturation poin*t for CO_2 uptake was at about 200 µmol quanta m^{-2} sec^{-1}, where the net CO_2 uptake rate was 0.8 µmol CO_2 per m^2 leaf area, sec^{-1}.

The light intensity saturation point value for this species was thus about ten times higher than that for the *Spathiphyllum*. The data are in accord with what is known in the industry of the relative shade tolerances of these two species. These are preliminary findings; it is possible that plants of either obtained from other provenances would give somewhat different results. Further R&D could no doubt produce new varieties of *E. aureum* with lower light requirements. Meanwhile, the results indicate the importance of appropriate placing of indoor plants according to their known relative light/shade tolerances, to help ensure effective CO_2 uptake in the built environment.

4.3.4 Discussion

The results reported here provide preliminary baseline information on the CO_2 reducing capacity of indoor pot-plants, and the light intensity ranges likely to be needed to ensure that they can make a significant difference to a building's air-conditioning loads. Even at very low light intensities, such as those typically found in offices, indoor plants can play a potentially effective role in reducing CO_2 accumulations. Future research needs are discussed below.

5. Discussion - Significance of findings

5.1 Summary overview

The findings of this project provide much needed information on the value of indoor plants to cleanse indoor air, and the flexibility with which they can be deployed. Air conditioning is very rarely designed to reduce gaseous pollutants, arising either from outdoors or inside, apart from refreshment to reduce CO_2 concentrations if they rise to the maximum level for health. The results of the studies reported here, together with previous findings from our own research and international studies, show conclusively that the pot-plant microcosm (PPM) can greatly improve indoor air quality by removing many major pollutants. Thus the PPM represents an adaptive, self-regulating, portable, flexible, low-cost, sustainable, beautiful biofiltration and bioremediation system for indoor air quality. This (truly) 'green technology' can complement any engineering measures in any type of building.

5.2 Recommendations for Industry

The results of this project confirm the efficiency of VOC uptake by the PPM. The results of have practical implications for the indoor plant industry, in terms of interiorscape design and use of plant materials.

5.2.1 On VOC removal

- A group of three 125 mm pots is at least as effective as one 200 mm pot, under general non-industrial indoor conditions (offices, homes, etc.); and
- A 200 mm pot is as effective as a 300 mm pot, under any allowable Australian indoor conditions;
- A 200 mm pot is as effective as a 300 mm pot, under any allowable Australian indoor conditions;
- The number of individual plants has a greater effect on VOC removal ability than the size of the pot (and hence plants), thus larger number of smaller plants is might well be the ideal system for maximising VOC removal;
- Clusters or towers of small plants could be used in place of larger pots, or interspersed with larger specimens;
- Indoor plantings could also be recommended to alleviate occupational VOC exposures in situations where high VOC concentrations are a fact of life, eg in motor service garages, dry cleaning shops, etc.

5.2.2 On potting mix bacterial activity

This is the first systematic investigation to have been conducted on the physiological profile and responses of VOC-degrading bacteria of indoor plants. The results:

- Confirm the primary role of the potting mix bacteria in VOC removal by indoor plants;
- Establish the normal profile of the bacteria associated with the VOC removal activity in the internationally used species, *Spathiphyllum* 'Petite';

- Indicate the responses of the bacterial community to VOC exposure, using one of the most common urban outdoor and indoor air pollutants worldwide, benzene;
- Demonstrate that, taken together with the results we have obtained from 11 other indoor species, it can be inferred that similar or equivalent profiles of potting mix bacteria will be found in the other species also;
- Highlight the abundant capacity of the pot-plant microcosm to remove indoor air-borne VOCs; it is thus now a well established indoor plant function, and can be promoted with confidence to clients.

5.2.3 On CO_2 reduction

The results of the preliminary laboratory studies reported here are the first such studies ever carried out on indoor plant CO_2 uptake capabilities in their 'indoor habitat'. They show that at normal (ie low) light intensities in offices, a small amount of active net CO_2 uptake by plant shoots does occur. But the test-chamber trials showed that the whole pot-plant microcosm has to be taken into account, because the respiration of the roots and potting mix microorganisms together may result in CO_2 emissions equal to the uptake by the leaves – in which case no net CO_2 reduction is achieved.

As mentioned in Section 4, we found in an office 'field' study that indoor plants reduced CO_2 levels by 10% in an air-conditioned building, and by 25% in a naturally ventilated building. However, we found in a later office study, with newer buildings, that any CO_2 reductions were lower than 10%, because the air-conditioning systems in the newer buildings sampled were more efficient, with forced ventilation at CO_2 levels of 800 ppm. Pot-plants have the potential to reduce the load on such air-conditioning systems, and hence reduce the C-imprint of the city. Much more research is needed before this goal can be reached, however, as discussed in Section 5.3 below.

Meanwhile indoor plants can be arranged to optimise their contribution to CO_2 reduction, by applying general principles of use - by placing them in accordance with their known light/shade tolerances; maximising the foliage area; and utilising their capacity for acclimatisation by down-regulating, to some extent, their light requirements to the prevailing indoor light regime.

5.3 Recommendations for future R&D

To help ensure the national goal of producing sustainable urban communities (House of Representatives, 2004), satisfying the 'triple bottom line' of environmental, social and economic considerations, the evidence is that interior plants should become standard installation elements of 'urban facility ecology'. To achieve this aim, however, further targeted research is needed in a number of directions.

5.3.1 On VOC reduction

As discussed above, the 12 indoor plant species we have tested all show approximately equal (high) capacity to reduce or eliminate air-borne VOC loads, and we consider it likely that most indoor plants, via their potting mix bacteria, would show similar propensities. However, we understand from discussions with industry members that it would of benefit for more plant species to be investigated for this air-cleansing capacity, for example including other families, such as Bromeliads, Crassulaceae, and Cacti – succulents which have various different root/shoot ratios from those of the Araceaea, Liliaceae or some Agavaceae/

Dracaenaceae (see Appendix), and which therefore might have quite different root-zone bacterial communities.

5.3.2 On VOC-removing bacterial consortia

To extend an understanding of indoor plant environmental horticulture, studies are also needed on characterising the root zone bacterial communities in other plant species, and their responses in VOC removal activities. Also, we have direct information only on the consortia concerned with benzene biodegradation. In an earlier study (Orwell et al., 2006) we found a synergistic interaction when a mixture of two VOCs was tested. The presence of toluene accelerated the removal of *m*-xylene (though not *vice versa*). More information is clearly needed in this area, from which it is possible that particular plant species could be chosen for situations with chronic problems of specific VOCs (eg manufacturing involving specific substances, such as formaldehyde, or toluene, etc), or defined mixtures of VOCs (eg petrol and other fuels).

5.3.3 On CO_2 reduction

From the results presented above, it can be predicted that if indoor plants are correctly matched to prevailing light levels in specific locations, considerable reductions in HVAC power consumption can be achieved. However, before the prediction can be realised, further baseline research on the photosynthetic capabilities of indoor species is clearly required. Research first needs to focus on:

(a) establishing the minimum and maximum light requirements for optimum net photosynthesis for each species/variety. This is a complex question, since gross and net photosynthesis rates depend not only on light levels, but also on interactions among a number of environmental factors, as outlined above;

(b) profiling responses of the same species to different ambient CO_2 concentrations. CO_2 enrichment response profiles (ie, testing with increasing CO_2 concentrations) would further identify species most suited for use in reducing the ventilation load on air-conditioning systems.

The scientific information obtained from such research can then be used to recommend the most suitable species/varieties for various lighting conditions in a building. At the same time the information would provide a basis for collaboration with lighting and design experts on how to achieve maximum benefit from interior plantscapes of the future that really can take the load off the air-conditioning system, and contribute to the goal of sustainable city living.

5.3.4 Other R&D needs

In addition, there is an emerging need for studies to be undertaken on the effectiveness of plants to reduce VOCs and CO_2 by plants grown in hydroculture - their plant and microbiological physiology and responses. European countries are moving away from cultivation of indoor plants in potting mix in favour of hydroculture of plants on inert inorganic media, supplemented by pelletised or liquid growth media.

Claimed advantages for hydroculture of indoor plants include the fact that they do not rely on organic potting mix components that may be in short supply, or that should be protected from such use. In addition, it is stated that: a substrate of clay pellets or similar inert material is ‘everlasting’ (although to presumably must be ‘reconditioned’ for each new plant); the

system provides good root aeration; causes fewer allergies (eg, asthma, sometimes attributed to moulds of potting mix, although without clear evidence of this as a significant mould source, to date); is cleaner to clear up in case of spills; is odour-free and pest-free; plus, over or under watering problems are eliminated; plants (with sub-irrigation) need watering only at 3-4 week intervals; and fertilising is needed only two or three times per year. There is no systematic scientific literature available on these claims, and they urgently require thorough investigation. . We are especially interested in hydroculture for CO_2 removal as it is possible that this medium will release far lower CO_2 from microbial respiration than potting mix, thus leading to the potential for greater net CO_2 removal rates.

5.4 In conclusion

Horticultural research on other ornamentals, eg. carnations or roses, has a history of several thousand years, and is continuing. The horticultural development of indoor plants for improved indoor environmental quality is in its infancy. There is a growing body of evidence that indoor plants are needed for sustainable urban communities, that they are not just 'pretty faces' (although that is also important). In addition to their air-filtration functions, they are a spirit-lifting oasis and aid to job satisfaction, work performance and productivity, which, it has been estimated (Burchett *et al*., 2008), will repay the cost of their presence in the built environment.

Acknowledgements

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Bibliography

Alexandri E and Jones P, 2006, Temperature decreases in an urban canyon due to green walls and green roofs, *Building and Environment*, 43 (4), 480- 493.

Aitken JR and Palmer RD, 1989, The use of plants to promote warmth and caring in a business environment, *Proceedings of 11th Annual Meeting of American Culture Assocn*., St Luis, MO.

Akoumianaki-Ioannidou A, Georgakopoulos JH, Fasseas C and Argyroudi-Akoyunoglou JH, 2004, Photoacclimation in *Spathiphyllum, Journal of Photochemistry and Photobiology B: Biology*, 73 (3), 149-158.

Arden Pope III C, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K and Thurston GD, 2002, Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *JAMA* 287, 1132-1141.

ASHRAE, 2001, ANSI/ASHRAE *Standard 62-2001, Ventilation for Acceptable Indoor Air Quality*. ASHRAE Inc., Atlanta, GA, USA.

ASCC (Aust. Safety & Compensation Council), 2006, *Adopted National Exposure Standards for Atmospheric Contaminants in the Occupational Environment*, [NOHSC: 1033,1995].

Barbosa BL, Tandlich R and Burgess JE, 2007, Bioremediation of trace organic compounds found in precious metals refineries' wastewaters: A review of potential options, *Chemosphere*, 68 (7), 1195-1203.

BEDP, 2009, *Living Walls – A Way to Green the Built Environment*, http://www.bedp.asn.au/settlement/ (viewed 02/09/09).

Bergs J, 2002, Effect of healthy workplaces on well-being and productivity of office workers, *Proceedings of International Plants for People Symposium*, Floriade, Amsterdam, NL.

Boardman NK, 1977, Comparative photosynthesis of sun and shade plants, *Annual Review of Plant Physiology*, 28, 355-377.

Bobak M, 2000, Outdoor air pollution, low birth weight and prematurity, *Environmental Health Perspectives*, 108 (2), 167-176.

Bochner BR, 1989, Sleuthing out bacterial identities, *Nature* , 339, 157–158.

Brock TD and Madigan MT, 1991, *Biology of Microorganisms* Ed 6. Prentice-Hall International, London.

Brown SK, 1997, Volatile organic compounds in indoor air: sources and control, *Chemistry in Australia*, 64 (Jan/Feb), 10-13.

Bringslimark T, Hartig T and Patil GG, 2007, Psychological benefits of plants in workplaces: Putting experimental results into context, *HortScience*, 42 (3), 581-587.

Burchett MD, Orwell R, Tarran J, Wood R and Torpy F, 2001, *Towards Improving Capacity of Indoor Plants and Potting Mix Components for Indoor Air Pollution Reduction*. Project No. NY98025, Final Report to Horticulture Australia Ltd., Sydney.

Burchett MD, 2005, *Improving Indoor Environmental Quality Through the Use of Indoor Potted Plants*, Final Report to Horticulture Australia Ltd, Sydney.

Burchett MD, Torpy F and Tarran J, 2008, Interior plants for sustainable facility ecology and workplace productivity, *Proceedings of Ideaction'08 – Enabling Sustainable Communities;* 7-9 May 2008, Qld.

Carrer P, Alcini D, Cavallo D, *et al*., 1999, Home and workplace complaints and symptoms in office workers and correlation with indoor air pollution, *Proceedings the 8th International Conference on Indoor Air Quality and Climate*, Edinburgh, Scotland, Vol. 1, 129-134.

Cavallo D, Alcini D, Carrer, *et al*., 1997, Exposure to air pollution in home of subjects living in Milan, *Proceedings of Healthy Buildings/IAQ '97*, Washington DC, Vol. 3, 141-145.

Costa PR and James RW, 1999, Air conditioning and noise control using vegetation, *Proceedings of the 8th International Conference on Indoor Air Quality and Climate*, Edinburgh Scotland, Vol. 3, 234-239.

Coward M, Ross D, Coward S, *et al*., 1996, *Pilot Study to Assess the Impact of Green Plants on NO_2 Levels in Homes*, Building Research Establishment Note N154/96, Watford, UK.

Darlington A, Dat J and Dixon M, 2001, The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene and xylene, *Environmental Science and Technology*, 35 (1), 240 – 246.

DECCW (Department of Environment, Climate Change and Water) NSW, 2009, http://www.environment.nsw.gov.au/aqms/index.html, viewed 04/09/09.

Degens BP and Harris JA, 1997, Development of a physiological approach to measuring the catabolic diversity of soil microbial communities, *Soil Biology and Biochemistry*, 29, 1309–1320.

Department of Health NSW, 2009, (viewed 16/04/09) – *Air Pollution Health Risks*

http://www.health.nsw.gov.au/PublicHealth/environment/air/air_pollution.asp

Dewir1 YH, Chakrabarty D, Ali MB, Hahn EJ and Paek KY, 2005, Effects of hydroponic solution EC, substrates, PPF and nutrient scheduling on growth and photosynthetic competence during acclimatization of micropropagated *Spathiphyllum* plantlets, *Plant Growth Regulation*, 46 (3) (online)

Environment Australia, 2001, Air toxics and indoor air quality in Australia, *State of Knowledge Report*, Ch. 7, viewed 12/09/09 - http://www.environment.gov.au/atmosphere/airquality/publications/sok/chapter7.html

Environment Australia (EA), 2003, BTEX *Personal Exposure Monitoring in Four Australian Cities*, Technical Paper No. 6: EA, 2003. Canberra, ACT, Australia.

Evans GW, 2003, The built environment and mental health, *Journal of Urban Health*, 80 (4), 536-555.

Fang C, Radosevich M and Fuhrmann JJ, 2001, Characterization of rhizosphere microbial community structure in five similar grass species using FAME and BIOLOG analyses. *Soil Biology and Biochemistry*, 33,679–682.

Fjeld T, 2002, The effects of plants and artificial daylight on the well-being and health of office workers, school children and health-care personnel, *Proceedings of International Plants for People Symposium*, Floriade, Amsterdam, NL.

Garland JL and Mills AL, 1991, Classification and characterization of heterotrophic microbial communities on the basis of patterns of community-level sole-carbon-source utilization. *Applied and Environmental Microbiology*, 57, 2351–2359.

GBC (Green Building Council, Australia) *Environmental Factors* http://www.gbca.org.au/ (viewed 02/09/09).

Gelsomino A, Badalucco L, Ambrosoli R, Crecchio C, Puglisi E and Meli SM, 2006, Changes in chemical and biological soil properties as induced by anthropogenic disturbance: A case study of an agricultural soil under recurrent flooding by wastewaters. *Soil Biology and Biochemistry* 38, 2069–2080.

Ghazali FM, Rahman RNZ, Salleh AB and Basri M, 2004, Biodegradation of hydrocarbons in soil by microbial consortium, *International Biodeterioration & Biodegradation* 54, 61–67.

Glimm E, Heuer H, Engelen B, Small K and Backhaus H, 1997, Statistical comparisons of community catabolic profiles, *Journal of Microbiological Methods*, 30, 71–80.

Gomez E, Ferreras L and Toresani S, 2006, Soil bacterial functional diversity as influenced by organic amendment application, *Bioresource Technology*, 97, 1484–1489.

Grayston SJ and Prescott CE, 2005, Microbial communities in forest floors under four tree species in coastal British Columbia, *Soil Biology and Biochemistry*, 37 (6), 1157-1167.

Grove JA, Kautola H, Javadpour S, Moo-Young M and Anderson WA, 2004, Assessment of changes in the microorganism community in a biofilter, *Biochemical Engineering Journal*, 18, 111–114.

Ha E-H, Hong Y-C, Lee B-E, Woo B-H, Schwartz J and Christiani DC, 2001, Is air pollution a risk factor for low birth weight in Seoul? *Epidemiology*, 12 (6), 643-648.

Höppe P and Martinac I, 1998, Indoor climate and air quality, *International Journal of Biometeorology*, 42, 1-7.

House of Representatives Standing Committee on Environment and Heritage (Australia), 2004, *Discussion Paper - Inquiry into Sustainable Cities 2025*, viewed 02/09/09,

http://www.google.com.au/search?hl=en&q=sustainable+city+living+national+policy&btnG

Hoyano A, 1988, Climatological uses of plants for solar control and effects on the thermal environment, *Energy and Building*, 11, 181-199.

IPCC, 2009, Predictions of CO_2 concentrations, viewed 02/09/09.

http://probaway.files.wordpress.com/2008/04/ipccco2concentrations.jpg

Jørgensen KS, Puustinen J, and Suortti A-M, 2000, Bioremediation of petroleum hydrocarbon-contaminated soil by composting in biopiles, *Environmental Pollution*, 107 (2), 245-254.

Kanaly RA and Harayama S, 2000, Biodegradation of high-molecular-weight polycyclic aromatic hydrocarbons by bacteria, *Journal of Bacteriology*, 182: 8, 2059-2067.

Kittel T, Geiger TA, Chetami Y, Lai M-Y, Liew L and Madad A, 2001, *Environmental Control of Photosynthesis, SEE-U 2001 Mod B*, http://www.see-u-org (viewed 02/09/09).

Leahy JG and Colwell RR, 1990, Microbial degradation of hydrocarbons in the environment. *Microbial Reviews*, 54 (3), 305–315.

Leather P, Pyrgas M and Beale D, 1998, Windows in the workplace: sunlight, view and occupational stress, *Environment and Behaviour*, 30 (6), 739-762.

Lee J-H and Sim W-K, 1999, Biological absorption of SO_2 by Korean native indoor species, In, M.D. Burchett *et al.* (eds) *Towards a New Millennium in People-Plant Relationships, Contributions from International People-Plant Symposium*, Sydney, 101-108.

Lim YW, Kim HH, Kim KJ *et al*., 2006, The health effect of houseplant on the symptoms of Sick Building Syndrome, *Epidemiology*, 17 (6), 16.

Lohr VI and Pearson-Mims CH, 2000, Physical discomfort may be reduced in the presence of interior plants, *HortTechnology* 10 (1), 53-58.

Marcelis LFM, Broekhuijsen AGM, Meinen E, Nijs E and Raaphorst M, 2005, Quantification of the growth response to light quantity of greenhouse grown crops, *Acta Horticulturae*, 711, V International Symposium on Artificial Lighting in Horticulture.

Microsoft, 2001, *Excel Version 11.3.5* Microsoft Australia

Mølhave L and Krzyzanowski M, 2003, The right to healthy indoor air: status by 2002, *Indoor Air*, 13, Supplement 6, 50-53.

Niklińska M, Chodak M and Laskowski R, 2006, Pollution-induced community tolerance of microorganisms from forest soil organic layers polluted with Zn or Cu, *Applied Soil Ecology*, 32, 265–272.

Okpokwasili GC and Olisa AO, 1991, River-water biodegradation of surfactants in liquid detergents and shampoos. *Water Research* 25, 1425–1429.

Ohura T, Amagai T, Senga Y and Fusaya M, 2006, Organic air pollutants inside and outside residences in Shimizu, Japan: Levels, sources and risks, *Science of the Total Environment*, 366, 485–499.

Östberg TL, Jonsson AP and Lundström US, 2006, Accelerated biodegradation of *n*-alkanes in aqueous solution by the addition of fermented whey. *International Biodeterioration & Biodegradation*, 57, 190–194.

Orwell, R, Wood R, Burchett M, Tarran J and Torpy F, 2006, The potted-plant microcosm substantially reduces indoor air VOC pollution: II. Laboratory study, *Water, Air, and Soil Pollution*, 177, 59-80.

Orwell, R, Wood R, Tarran J, Torpy F and Burchett M, 2004, Removal of benzene by the indoor plant/substrate microcosm and implications for air quality, *Water, Soil and Air Pollution*, 157, 193–207.

Park S-H, Mattson RH and Kim E, 2002, Pain tolerance effects of ornamental plants in a simulated hospital patient room, *ActaHorticulturae*, 639, 50-52.

Pesce, SF and Wunderlin DA, 2004, Biodegradation of lindane by a native bacterial consortium isolated from contaminated river sediment, *International Biodeterioration & Biodegradation* 54: 255–260.

Preston GM, Haubold B and Rainey PB, 1998, Bacterial genomics and adaptation to life on plants: implications for the evolution of pathogenicity and symbiosis, *Current Opinion in Microbiology*, 1, 589-597.

Preston-Mafham J, Boddy L and Randerson PF, 2002, Analysis of microbial community function diversity using sole-carbon-source utilisation profiles – a critique, *FEMS Microbiology Ecology*, 42, 1–14.

Radwan SS, Al-Mailem D, El-Nemr I and Salamah S, 2000, Enhanced remediation of hydrocarbon contaminated desert soil fertilized with organic carbons, *International Biodeterioration & Biodegradation*, 46 (2), 129-132.

Raghavan PU and Vivekanandan M, 1999, Bioremediation of oil-spilled sites through seeding of naturally adapted *Pseudomonas putida*, *International Biodeterioration & Biodegredation*, 44 (1), 29-32.

Reuther G, 1987, Comparative anatomical and physiological studies with ornamental plants under in vitro and greenhouse conditions, *Acta Horticulturae* 226, *International Symposium on Propagation of Ornamental Plants*.

Seppänen O, Fisk WJ and Lei QH, 2006, Ventilation and performance in office work, *Indoor Air*, 16, 28-36.

Shaughnessy RJ, Shaughnessy UH, Nevalainen A and, Moschandreas D, 2006, A preliminary study on the association between ventilation rates in classrooms and student performance, *Indoor Air*, 16 (6), 465-468.

Shibata S and Suzuki N, 2002, Effects of foliage plants on task performance and mood, *J. Environmental Psychologyi*, 22 (3), 265-272.

Siciliano SD, Germida JJ, Banks K and Greer, CW, 2003, Changes in microbial community composition and function during a polyaromatic hydrocarbon phytoremediation field trial, *Applied and Environmental Microbiology*, 69 (1), 483-489.

Spain JC and Van Veld PA, 1983, Adaptation of natural microbial communities to degradation of xenobiotic compounds: Effects of concentration, exposure time, inoculum, and chemical structure, *Applied and Environmental Microbiology*, 45 (2), 428-435.

Tarran, J, Orwell R, Burchett M and Wood R, 2002, *Quantification of the Capacity of Indoor Plants to Remove Volatile Organic Compounds under Flow-through Conditions*, Final Report to Horticulture Australia Ltd, Sydney.

Tarran J, Torpy F and Burchett M, 2007, Use of living pot-plants to cleanse indoor air – research review, *Proceedings Of 6th Internat. Conf. On Indoor Air Quality, Ventilation & Energy Conservation, - Sustainable Built Environment*, Sendai, Japan, Oct., Vol III, pp 249-256.

Thompson WA, Huang LK, and Kriedemann PE, 1992, Photosynthetic response to light and nutrients in sun-tolerant and shade-tolerant rainforest trees. II. Leaf gas exchange and component processes of photosynthesis, *Australian Journal of Plant Physiology*, 19(1), 19 - 42

US EPA, 1989, *Report to Congress on Indoor Air Quality, Vol II: Assessment and Control of Indoor Air: Effects of Individual Pollutants, Volatile Organic Compounds*, p. 3-6,

US EPA, 2000, *Healthy Buildings, Healthy People: A Vision For The 21st Century*, Office of Air and Radiation. *Air: VOCs*, 3-6, 29.

US EPA, 2009, *Indoor Air Quality Scientific Findings Resource Bank*, Lawrence Berkeley National Laboratory, http://eetd.lbl.gov/ied/sfrb/ , viewed 17/09/09.

Van Huylenbroeck JM, Huygens H and P. C. Debergh PC, 1995, Photoinhibition during acclimatization of micropropagated *Spathiphyllum* 'Petite' plantlets, *Journal In Vitro Cellular & Developmental Biology – Plant*, 31 (3), (Online).

Vidal D, Griera E, Marin P and Sabido J, 1990, Anatomical and physiological acclimation of *Fatsia japonica* leaves to irradiance, *American Journal of Botany*, 77 (9), 1149 – 1158.

Viñas M, Sabaté J, José Espuny M, and Solanas AM, 2005, Bacterial community dynamics and polycyclic aromatic hydrocarbon degradation during bioremediation of heavily creosote-contaminated soil, *Applied and Environmental Microbiology*, 71(11), 7008-7018.

Westover KM, Kennedy AC and Kelley SE, 1997, Patterns of rhizosphere microbial community structure associated with co-occurring plant species, *Journal of Ecology*, 85, 863-873.

Wolverton BC, Johnson A and Bounds K, 1989, *Interior Landscape Plants for Indoor Air Pollution Abatement*, Final Report, NASA Stennis Space Centre MS, USA.

Wolverton Environmental Services Inc., 1991, *Removal of Formaldehyde from Sealed Experimental Chambers, by* Azalea, *Poinsettia and* Dieffenbachia, Res. Rep. No. WES/100/01-91/005.

Wolverton BC and Wolverton JD, 1993, Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment, *Journal of Mississippi Academy of Sci*ence, 38 (2), 11-15.

WHO (World Health Organisation), 2000, *The Right to Healthy Indoor Air – Report on a WHO Meeting, Bilthoven*, NL, European Health Targets 10, 13.

WHO, 2003, *Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide*. Report of WHO Working Group, Bonn, Germany.

WHO, 2005, *Indoor Air Pollution and Health*, Fact Sheet No. 292.

Wood RA, Burchett MD, Alquezar R, Orwell R, Tarran J and Torpy F, 2006, The potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-study, *Water, Air, and Soil Pollution*, 175, 163-180..

Wood RA, Orwell RL and Burchett MD, 1997, Rates of absorption of VOCs by commonly used indoor plants. *Proceedings of healthy buildings / IAQ 1997, global issues and regional solutions*, Woods JE, Grimsrud DT and Boschi N (eds), Washington, D.C., Vol. 2, 59–64.

Wood RA, Orwell R, Tarran J, Torpy F and Burchett M D, 2002, Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air, *Journal of Horticultural Science and Biotechnology*, 77, 120–129.

Yeh DM, Yang WJ, Chang FC, Chung MC, Chen Wl , and Huang HW,2007, Breeding and micropropagation of *Aglaonema, Acta Horticulturae* 755: ISHS International Conference on Quality Management in Supply Chains of Ornamentals.

Yoneyama T, Kim HY, Morikawa H and Srivastava HS, 2002, Metabolism and detoxification of nitrogen dioxide and ammonia in plants, In, K. Omasa *et al*. (eds) *Air Pollution and Plant Biotechnology – Prospects for Phytomonitoring and Phytoremediation*, Springer, Tokyo, Japan, 221-234.

Zak JC, Willig MR, Moorhead DL and Wildman HG, 1994, Functional diversity of microbial communities: A quantitative approach, *Soil Biology and Biochemistry,* 26, 1101–1108.

Appendix 1

List of indoor plant species UTS laboratory-tested for VOC removal

- *Aglaonema modestum* (Fam. Araceae)
- *Chamaedorea elegans* (Fam. Palmae)
- *Dracaena deremensis* 'Janet Craig' (Fam. Dracaenaceae; prev. Liliaceae)
- *Dracaena marginata*
- *Epipremnum aureum* (syn. *Scindap(s)us aureus)* (Pothos; Devil's Ivy) (Fam. Araceae)
- *Howea forsteriana* (Kentia palm) (Fam. Palmae)
- *Philodendron* 'Congo' (Fam. Araceae)
- *Sansevieria trifasciata* (Mother-in-law's tongue) (Fam. Ruscaceae/Dracaenaceae)
- *Schefflera* 'Amate' (Qld. Umbrella Tree) (Fam. Araliaceae)
- *Spathiphyllum* 'Petite' (& 'Sweet Chico') (Peace Lily) (Fam. Araceae)
- *Spathiphyllum* 'Sensation'
- *Zamioculcas zamiifolia* (Zanzibar; ZZ) (Fam. Araceae)

They were all found to be just about equally effective in removing a standard dose within about 24 hours, after a week of acclimatization (induction) to exposure to the VOC.

APPENDIX 2

Technology transfer

We have been and will continue to be, actively engaged in technology transfer of information derived from this research.

Talks/Seminars During the course of this project we have made presentations on our indoor plant research at:

- Ambius staff training sessions,
- Meetings of the Horticultural Media Association (HMA) in Brisbane, Sydney and Melbourne.
- Annual Conference of the Facility Management Association of Australia (FMAA) (2008)
- Woolcock Institute of Medical Research (linked with the University of Sydney and RPA Hospital)
- International meeting of Science educators at UTS
- North Shore branch of the Garden Clubs of Australia
- About 12 radio interviews, mainly arising from talks at HMA
- Participated in 'Speed-meet-a-geek', UTS/ABC public event for Science Week (Aug. '09) (armed with a potted *Spathiphyllum* 'Petite' as symbol of area of expertise)

Articles on the work have been published in:
Industry publications-
Newsletters of the National Interior Plantscape Association
Brochures and online advice of Ambius
Proceedings of Ideaction'08 – Enabling Sustainable Communities (HMAA Conf.); 7-9 May 2008, Qld.

Peer-reviewed international journals-
We have two in preparation:
Torpy F, Brennan J & Burchett MD, Relationship between container size and VOC removal capacity of indoor pot-.
Burchett MD, Torpy F, & Brennan J, Indoor plant installations – an increasing necessity for urban sustainability.