THE POTTED-PLANT MICROCOSM SUBSTANTIALLY REDUCES INDOOR AIR VOC POLLUTION: I. OFFICE FIELD-STUDY

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Abstract. Volatile organic compounds (VOCs) are major contaminants of indoor air, with concentrations often several times higher than outdoors. They are recognized as causative agents of "building-related illness" or "sick-building syndrome". Our previous laboratory test-chamber studies have shown that the potted-plant/root-zone microorganism microcosm can eliminate high concentrations of air-borne VOCs within 24 hours, once the removal response has been induced by an initial dose. However, the effectiveness of the potted-plant microcosm in 'real-world' indoor spaces has never previously been tested experimentally. This paper reports the results of a field-study on the effects of potted-plant presence on total VOC (TVOC) levels, measured in 60 offices (12 per treatment), over two 5–9 week periods, using three planting regimes, with two 'international indoor-plant' species. Fourteen VOCs were identified in the office air. When TVOC loads in reference offices rose above 100 ppb, large reductions, of from 50 to 75% (to <100 ppb), were found in planted offices, under all planting regimes The results indicate that air-borne TVOC levels above a threshold of about 100 ppb stimulate the graded induction of an efficient metabolic VOC-removal mechanism in the microcosm. Follow-up laboratory dose-response experiments, reported in the following paper, confirm the graded induction response, over a wide range of VOC concentrations. The findings together demonstrate that potted-plants can provide an efficient, self-regulating, low-cost, sustainable, bioremediation system for indoor air pollution, which can effectively complement engineering measures to reduce indoor air pollution, and hence improve human wellbeing and productivity.

Keywords: indoor air pollution, VOC, TVOC, "sick-building syndrome", "building-related illness" environmental biotechnology, bioremediation, phytoremediation, potted-plant

1. Introduction

Urban-dwellers generally spend about 90% of their time indoors, where the air is likely to be significantly more polluted than outdoors. The possible effects of indoor air pollution on human health are therefore an issue of international concern (Fisk, 2000; Heslop, 2002; Mendell *et al.*, 2002; Environment Australia [EA], 2003; Mølhave and Krzyzanowski, 2003; Wolkoff, 2003). Volatile organic compounds (VOCs) are a major class of contaminants of indoor air (Sullivan *et al.*, 2001; Wolkoff, 2003), where levels may be up to 10 times higher than those outdoors (Rehwagen *et al.*, 2003). These chemical cocktails are recognized as causative

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agents of "building-related illness" or "sick-building syndrome" (Carpenter, 1998; Brasche *et al*., 1999; Carrer *et al*., 1999; Sullivan Jr *et al*., 2001).

A number of studies have shown that potted-plants have a capacity to contribute to the improvement of indoor air quality, by reducing air-borne contaminants such as VOCs, nitrogen oxides and dust (Wolverton and Wolverton, 1993; Giese *et al*., 1994; Coward *et al*., 1996; Lohr and Pearson-Mims, 1996), as well as by aiding humidity, temperature and noise control (Costa and James, 1999). It has also been shown that staff wellbeing (as measured by questionnaire surveys and interviews) and productivity (as reductions in sick-leave rates) are improved where indoor plants have been installed (Burchett *et al*., 1999; Bergs, 2002; Fjeld, 2002).

Our previous laboratory studies, using sealed bench-top test chambers with seven indoor plant species, have shown that the potted-plant microcosm can eliminate repeated daily doses of benzene or *n*-hexane (as model VOCs) applied at up to 50 and 150 ppm respectively, over test periods of two to four weeks (Tarran *et al*., 2002; Wood *et al*., 2002; Orwell *et al*., 2004). These concentrations are, respectively, 10 and 3 times the specified Australian maximum allowable time-weighted average 8-hour occupational exposure concentrations, and hence are several orders of magnitude higher than any concentrations likely to be encountered in indoor air (National Occupational Health and Safety Commission, Aust., 1991). The VOC doses were repeatedly removed within 24 hours once the potted-plant system had been induced to accelerated removal rates by an initial dose of the compound. The induced VOC removal rates could, depending on dose, rise to more than 10 times higher than the initial, unstimulated rates. The heightened removal rates were maintained under light or dark conditions, and rose further in response to increased dose concentrations.

Our studies also showed that the primary VOC removal agents were microorganisms of the potting mixtures. This was evidenced initially by the fact that taking the plant from the pot, and replacing the potting mix in the chamber, commonly had no significant effect on VOC removal rates over a further week of daily dosing, although, with some species, the plants did make a small direct contribution to VOC removal rates (Wood *et al.*, 2002; Orwell *et al.*, 2004). We also showed that bacterial cultures derived from the potting mixes could be induced to similar VOC removal rates within three days (3 doses) after initial exposure to the compound (Wood *et al.*, 2002; Orwell *et al.*, 2004). We isolated over 50 common soil bacterial species from these potting-mix-derived cultures (Wood *et al.*, 2002; Torpy, unpub. data), and research is proceeding to analyse the potting-mix microbial species/alliances involved in the VOC degradation. The findings are in line with those of other studies, which have shown that plants, apparently universally, establish and maintain species-specific communities ofroot-zone (rhizosphere) microorganisms, as a mutually beneficial microcosm (Atwell *et al.*, 1999; Darlington *et al.*, 2000; Nemergut *et al.*, 2000; Pucci *et al.*, 2000; Kowalchuk *et al.*, 2002; Siciliano *et al.*, 2003). It is also well known that many species of soil microorganisms can degrade liquid-phase petroleum hydrocarbons as

nutrient sources, the capacity forming the basis of bioremediation technologies for oil spills (eg., Leigh *et al.*, 2003; Margesin *et al.*, 2003; Chaianeau *et al.*, 2005).

However, although our own and earlier laboratory studies have demonstrated the ability of the potted-plant microcosm to remove VOCs, no experimental field-study has previously been made to investigate whether, in 'real-world' environments, the potted-plant microcosm can bring about significant reductions in indoor air-borne VOC pollution. The aim of this study, therefore, was to make a quantitative investigation of the capacity of the potted-plant microcosm to reduce TVOC pollution in office air, in particular examining:

(a) whether realistic numbers of potted-plants could bring about significant reductions in TVOC loads;
(b) if so, how many potted-plants, of what size, would be required;
(c) whether the presence or absence of air-conditio- ning affects potted-plant performance;
(d) the identity of individual VOCs encountered in the office air;
(e) any interactions that the potted-plants might have with other physicochemical variables in the office environment.

The project involved two experimental investigations, using staff offices in three buildings of the University of Technology, Sydney (UTS) (Australia). The experimental period was from June to November 2003 (winter/spring). On the basis of the results obtained in this field-study, a series of laboratory dose-response experiments was conducted to throw further light on the responses observed and the mechanisms involved. A report of these associated laboratory studies is presented in the following paper (Orwell *et al*., this volume, pp. 193–207).

2. Materials and Methods

2.1. Building descriptions

Two of the three selected UTS buildings were air-conditioned and located in Sydney's central business district (CBD) (south of Sydney Harbour). The third was naturally ventilated, located in a leafy inner suburb, but next to Sydney's main northern highway (Gore Hill; north of Sydney Harbour). The seven-storey building referred to here as "Building 1" (UTS designation: Bldg.10; CBD) was approximately 50 years old, and was refurbished about six years ago. This is an administration building, comprising mainly single-occupant offices, plus several conference rooms. The nine offices selected (Investigation 1) were all on Level 6 (top floor); however, because of the building's previous history, the offices were variously supplied from three separate air-conditioning systems.

"Building 2" (UTS designation: Tower Bldg.; CBD*),* was purpose-built for UTS in 1970, has 26 storeys, and is supplied by a single air-conditioning system. It comprises a mixture of offices, lecture theatres, seminar rooms, and laboratories, The eight offices selected (Investigation 2) were located on the 10th to 15th storeys. In accordance with international standards (J. Kraefft, UTS, pers. comm.), the air-conditioning systems in both buildings supply 6–8 air changes per hour to each office, of which 10–15% of the supply is fresh (external) air input. None of the air-conditioning systems adjusted humidity levels in the incoming air.

"Building 3" (UTS designation: Dunbar Bldg., Gore Hill), was built for tertiary science education in the 1960s, has six storeys, and is naturally ventilated. This building also comprises a mixture of offices, lecture theatres, seminar rooms and laboratories. It has hollow ceilings throughout, and opening windows in all rooms, for ventilation. However, during the period of these investigations, windows were almost always closed, it being winter/early spring. The offices selected (nine for Investigation 1; eight for Investigation 2) were scattered among the six storeys.

2.2. Office selection

In each building, initial contact was made with the Head of Section concerned, who suggested possible volunteers, who were then approached individually. Considerably more staff volunteered than could be accommodated in the investigations, and offices were selected from the group at random. The offices were not of consistent dimensions, although they had all been designed for single occupancy, ranging from 10 to 12 m^2 floor area, with ceiling heights 3–4 m (volumes ~30–50 m^3).

2.3. Experimental design

Investigation 1. A comparison was made of the effects of two plantings of potted floor-specimens of *Dracaena deremensis* 'Janet Craig' plants (300 mm diameter pots) on concentrations of TVOCs in office air, under air-conditioned and non-air-conditioned circumstances. Two sets of nine offices were used, in Buildings 1 and 3 respectively. In each building, after one month of weekly pre-testing for range-finding of indoor air parameters, subsets of three replicate offices were randomly supplied with 0 (reference), 3, or 6 potted-plants. Six floor specimens of this type were thought to be most probably too much plant material for the average office, however the density was included to try and ensure that at least one treatment would yield significant differences in TVOC concentrations, and hence represent a starting point for the further development of the potted-plant microcosm for indoor air remediation functions. Weekly measurements of air quality variables, listed below, were then carried out over a nine-week period, after which the potted-plants were randomly reassigned among the offices for a second nine-week period. (3 treatments × 3 replicates/treatment × 2 buildings × 2 experimental periods = Combined total of 36 office-experimental-units; 12 offices per treatment.)

Investigation 2. The aim of this study was to compare the (possible) impact of the two planting regimes above, with that of a regime utilizing smaller potted-plants and a mixture of two species. Two sets of eight offices (different from the above) were used, this time in Buildings 2 and 3 respectively. In each building, after one month of preliminary air testing, subsets of four replicate offices were randomly supplied, respectively, with 0 (reference) or 6 'table-sized' potted-plants (200 mm diameter pots) comprising five of *Spathiphyllum* 'Sweet Chico' (Peace Lily) plus one of *D.* 'Janet Craig'. Air quality variables in this case were measured during successive nine- and five-week experimental periods in Building 2, and a single nine-week period in Building 3. (2 treatments $\times$ 4 replicates/treatment $\times$ 1 set of (2) buildings, $\times$ 3 experimental periods = Combined total of 24 office-experimental-units; again, 12 offices per treatment).

2.4. Air quality monitoring

For weekly TVOC samplings a Portable Photoionisation Detector, ppbRAE was used (Rae Systems Inc., USA), sensitivity 0-999 ppb at 1 ppb resolution (calibrated with isobutylene standard); with correction factors from a list of >250 chemicals (supplier, Active Environmental Solutions, Melbourne, Aust.). Sampling was conducted in all offices between 10.00 am and noon, ie over a period of peak activity in the buildings, to reduce any possible effects of diurnal fluctuations in the system. Five-minute samplings in each office were made, comprising ten 30-sec readings, which were taken from all parts of the office, by moving slowly with the instrument around the room, from the middle of the floor space, and reaching over desk, past computer, into corners with shelves or cabinets, etc., depending on the particular layout of furniture and fittings. Weekly samplings of CO_2, CO, relative humidity and temperature were made at the same time, using a Portable IAQ-Calc Indoor Air Quality Meter (TSI Inc., MN, USA) (ten 30-sec readings of each variable).

Four weeks of pre-testing of all selected offices were carried out before plant placements, to establish levels and variability of TVOCs and other measured air variables among offices in each building, prior to plant placements. They were found to be similar in all three buildings and in the same range as those of the reference offices throughout the experimental periods. Following one week of acclimation of the potted-plants after placement for each experimental period (Wood *et al.*, 2002; Orwell *et al.*, 2004), results are reported from the commencement of the second week of each period.

Passive Organic Vapour Monitors (OVMs; 3M, Sydney, New South Wales) were used to identify likely predominant individual VOCs found in the office air. An OVM was placed in each of two reference and two 6-plant offices, in each building involved, near the end of first nine-week experimental period of each investigation, (August and October respectively). Each OVM was left on a shelf in sampled offices for approximately one week (exact number of minutes calculated for analysis), and were then analysed by WorkCover, the NSW Occupational Health

and Safety Agency. Analyses were by gas chromatography (GC/MS) against a standard suite of >200 compounds which had been identified by the Agency as being the commonest indoor VOCs in the Sydney urban area. Their stated detection limits were: hydrocarbons, 0.1 μg; alcohols/ketones, 0.2 μg; aliphatic chlorinated hydrocarbons, 0.2 μg. Final values are converted by WorkCover to estimated aerial concentrations (ppb) for reporting results to clients. The OVM method and sample numbers provided a relatively inexpensive means of profiling the main VOCs in the air mixtures in the three buildings sampled. However, since the OVMs are designed to be worn by staff members for a single day (to obtain worker 8-hour average exposure estimates), WorkCover advised that, while the data would indicate relative concentrations of contaminants in the office air in the weeks sampled, they would not give reliable estimates of 'real' prevailing levels of individual VOCs in the sampled air.

2.5. POTTED-PLANTS SELECTED

The two potted-plant species were chosen because they are commonly used internationally, and in our test-chamber studies had been found to be reliably effective in removing high air-borne concentrations of benzene and *n*-hexane (Tarran *et al.*, 2002; Wood *et al.*, 2002; Orwell *et al.*, 2004). In *Investigation 1*, the floor-specimens of *D.* 'Janet Craig' were of height 1.3 m, in 30 cm diameter plastic pots, inside decorative outer containers also of plastic (plants from Tropical Plant Rentals, Sydney, NSW; containers from Northshore Office Landscaping, Sydney). In *Investigation 2*, the 'shelf" or 'table-sized' specimens of *S.* 'Sweet Chico' (Figtree Nursery, Sydney) and *D.* 'Janet Craig', were of height 30–40 cm, in 20 cm diameter pots, in plastic pots, inside decorative outer containers of light metal (Container Connection, Sydney).

The potting mixes were made up by the two suppliers individually, and hence were of slightly different materials, but both consisted of a standard, light 'indoor mix', of composted hardwood sawdust, composted bark fines, and coarse river sand ($\sim$2:2:1) (bulk density $\sim$0.6 g mL^{-1}; air-filled porosity $\sim$30%), with a '9-month slow-release' fertilizer including trace elements (Macrocote, Sydney, NSW). The pots for the *D.* 'Janet Craig' floor specimens contained 9–10 L of potting mix, while those for both species of table specimens contained $\sim$3 L of potting mix.

2.6. DATA ANALYSIS

For each experimental investigation, the weekly values obtained for the air variables were subjected to Repeated Measures-ANOVA analysis (Systat, SPSS Inc., 1998) and pair-wise Tukey's HSD test. Differences between treatments are reported as statistically significant where $p \leq 0.05$. In some cases, possible trends in results (where $0.05 \leq p < 0.1$) are also discussed, for reasons outlined in the text. For each investigation, weekly sets of data means were first plotted individually for

TABLE I

Physicochemical characteristics of office air with various numbers and types of potted-plants per office, and ambient outdoor air, over two investigations, each involving two of three buildings

Investigation; Building; and No. of plants per office/ Ambient outdoor air	Temperature (°C)	Relative Humidity (%)	Carbon dioxide (ppm)	Carbon monoxide (ppm)
Investigation 1				
Building 1				
0 plants	22.8 ± 0.2	44 ± 2	365 ± 17	0
3 plants	22.8 ± 0.3	44 ± 2	375 ± 15	0
6 plants	22.5 ± 0.1	45 ± 2	365 ± 18	0
Outdoor	21.2 ± 1.1	48 ± 2	*ns	ns
Building 3				
0 plants	21.4 ± 0.4	46 ± 3	370 ± 60	0.01 ± 0.01
3 plants	20.8 ± 0.4	47 ± 3	280 ± 15	0.02 ± 0.02
6 plants	20.5 ± 0.5	48 ± 4	285 ± 12	0.02 ± 0.03
Outdoor	18.0 ± 1.0	51 ± 6	ns	ns
Investigation 2				
Building 2				
0 plants	23.0 ± 0.2	44 ± 4	370 ± 17	0
6 plants	22.8 ± 0.2	45 ± 3	320 ± 7	0
Outdoor	22.7 ± 1.5	56 ± 5	ns	ns
Building 3				
0 plants	21.8 ± 0.5	47 ± 4	375 ± 70	0.02 ± 0.02
6 plants	21.1 ± 0.6	49 ± 5	420 ± 80	0.10 ± 0.01
Outdoor	20.7 ± 1.3	47 ± 7	ns	ns

Values are means ± S.E.; *Inv. 1*, $n = 36$ *Inv. 2*, $n = 23$; *ns = not sampled.

each building, for each set of treatments, so as to reveal response patterns in detail (60 sets of plots). The results below are presented in summary form, namely as means for each investigation period, for each treatment, for the buildings involved, under specified conditions.

3. Results

3.1. Office environment—physicochemical conditions

Values for physicochemical variables other than TVOCs are presented in Table I. Temperatures remained steady and comfortable (21–23°C) in the three study buildings during the experimental period, with outdoor temperatures only a little lower (mild Sydney winter/spring). External CO_2 concentrations in the metropolitan region range from 340–370 ppb, depending on local winds and other weather-related pollution levels in the Sydney basin (NSW EPA, verbal comm.). The plants had no significant effect on internal carbon dioxide concentrations, indicating that, in these buildings, any CO_2 removed by photosynthetic fixation was insignificant

compared with the effects of human exhalation in the offices, and that illumination levels might well have been below the light-compensation point for photosynthesis (Atwell *et al.,* 1999a). Traces of carbon monoxide were detected only in Building 3 (Table I) where, in the absence of air-conditioning, some staff were using flueless gas heaters.

Relative humidities in Buildings 1 and 2 were similar to those in the naturally ventilated Building 3, all being slightly lower than outdoor values. Humidity values were not significantly affected by the presence of potted-plants (plant evapotranspiration rates tend to be self-adjusting, varying inversely with ambient humidity levels; Atwell *et al*., 1999b). Humidities were generally in the 'optimum range' for occupants (30–60%) (ASHRAE, 2001).

3.2. Investigation 1-with floor-specimens of *D.* 'Janet Craig'

From the weekly ppbRAE samplings, the range of TVOC concentrations in the two buildings (Figures 1–3) was found to be similar to those reported from other studies, and, as also reported, higher than the ambient air in the streets outside the buildings (Brown *et al.*, 1994; Brown, 1997; EA, 2003)**.**

To compare the overall effects of the two planting densities on TVOC levels, combined results for Buildings 1 and 3 are presented in Figure 1. Figure 1a presents means of all results for each of the three experimental treatments (0, 3, or 6 plants) over the two nine-week experimental periods, along with average outdoor TVOC concentrations over the 18-weeks. Indoor TVOC levels, with or without plants, were significantly higher than outdoor concentrations. However, indoors (Figure 1a), a trend was in evidence ($p < 0.09$) of a possible reduction in TVOC levels in the presence of plants, the recorded mean TVOC concentration in reference offices (0 plants) being 110 ± 15 ppb, whereas the mean in offices with either 3 or 6 plants was 80 ± 7 ppb (a 30% reduction). (In the mixture of VOCs identified in office air, Table II, it is estimated at a TVOC level of 100 ppb would equal a pollutant load of about 350–380 mg m^{-3}).

Figure 1b also presents pooled results from both buildings over both experimental periods, but, in this case, only for those weeks in which TVOC concentrations in reference offices were higher than 100 ppb (9 of the 18 weeks). Under these circumstances, substantial TVOC reductions were found in the planted offices ($p < 0.05$). With a mean TVOC concentration in reference offices of 190 ± 40 ppb, in those with either 3 or 6 potted-plants, means were approximately equal, 105 ± 15 ppb and 100 ± 10 ppb respectively. That is, when the average reference TVOC load was greater than about 100 ppb, the presence of either 3 or 6 potted-plants resulted in a reduction in TVOC pollution of approximately 50%. In contrast, in weeks in which reference offices recorded TVOC concentrations lower than 100 ppb, no significant differences in concentrations were found between planted and unplanted offices ($p > 0.05$; data not shown). Reasons for these results are considered later (Section 4).

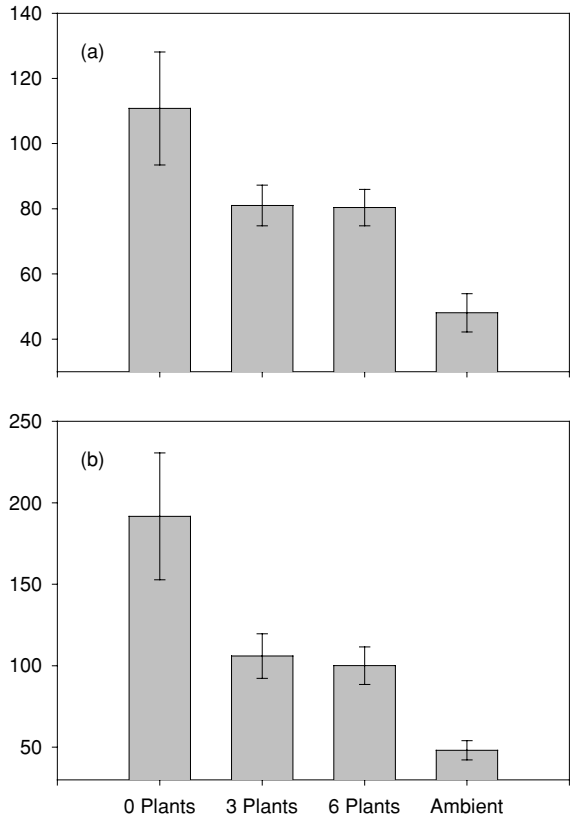

Figure 1. Investigation I., Combined results of TVOC levels in Buildings 1 and 3, over two successive nine-week experimental periods. (a) Means of all weekly readings, in offices with 0, 3, or 6 potted floor specimens of *Dracaena* 'Janet Craig', and outdoor levels. (b) Means of readings for those weeks in which TVOC levels were >100 ppb in reference offices (0 plants). Values are e means ± S.E. ($n = 36$).

To compare potted-plant effectiveness under air-conditioned and non-air-conditioned circumstances, the results for Building 1 (air-conditioned) and Building 3 (naturally ventilated) are presented individually in Figures 2 and 3. Figures 2a and 3a show TVOC levels for all 18 weeks for each building, where there were no significant differences between the two buildings in reference-office TVOC levels, nor between reference and planted offices in either building, although downward trends were observed for planted offices. External TVOC levels were similar around the two buildings (50 ± 25 ppb). In weeks when TVOC levels in reference offices were higher than 100 ppb (Figures 2b, 3b), more pronounced reductions in concentrations were evidenced in both buildings in the presence of plants. In Building 1 (Figure 2b), the trend was not statistically significant ($0.05 < p < 0.10$), however in Building 3 (Figure 3b), the presence of potted-plants resulted in a highly significant reduction in TVOC concentrations (from 280 ± 120 ppb to 65 ± 10 ppb)

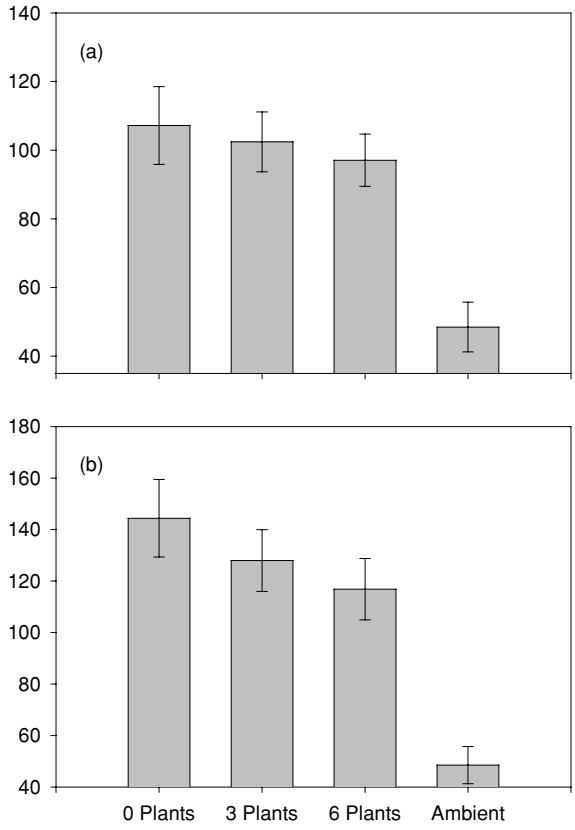

Figure 2. Investigation I., TVOC levels in Building 1 over two successive nine-week experimental periods. (a) Means of all weekly readings, in offices with 0, 3, or 6 potted floor specimens of *Dracaena* 'Janet Craig', and outdoor levels. (b) Means of readings for those weeks in which TVOC levels were >100 ppb in reference offices (0 plants). Values are means ± S.E. ($n = 18$).

i.e. a reduction of about 75% ($p < 0.05$). It was also clear that three potted-plants were as effective as six in bringing about the large TVOC reductions. Reasons for differences in strength of response between the two buildings are discussed in Section 4.

3.3. Investigation 2- with mixed table specimens of *S.* 'sweet chico' and *D.* 'janet craig'

The results for the second investigation, for Buildings 2 and 3, are presented in Figures 4 and 5. In Building 2 (air-conditioned; Figure 4) average indoor TVOC levels were, again, higher than outdoor levels, but in Building 3 (Figure 5) indoor levels were not significantly different from those outdoors ($p > 0.05$). In each building, with the combined results for all weeks sampled (Figures 4a and 5) no

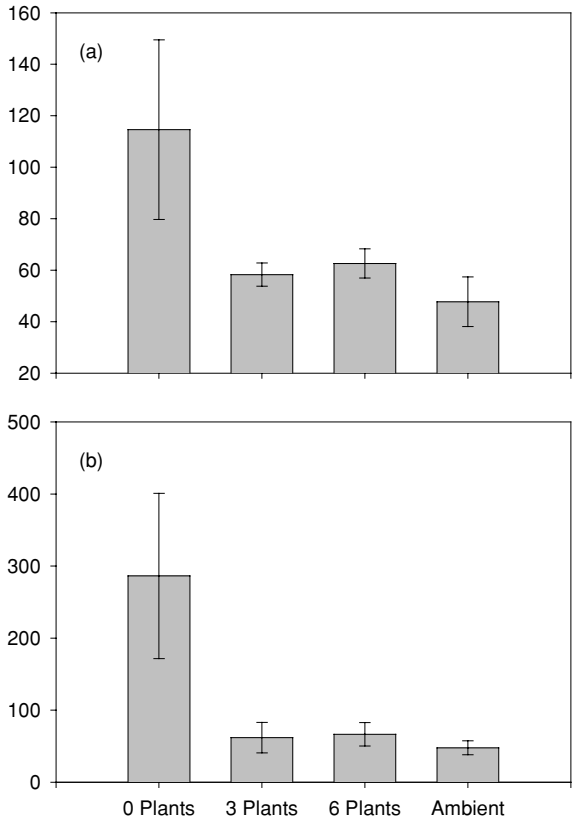

Figure 3. Investigation I., TVOC levels in Building 3 over two nine week experimental periods. (a) Means of all weekly readings, in offices with 0, 3, or 6 potted floor specimens of *Dracaena* 'Janet Craig', and outdoor levels (b) Means of readings for those weeks in which TVOC levels were >100 ppb in reference offices (0 plants). Values are the means $\pm$ S.E ($n = 18$).

significant difference in TVOC levels were distiguished between reference and planted offices, although recorded levels in planted offices were slightly higher than in unplanted offices. This was no doubt because the *S.* 'Sweet Chico', which was in flower over the period, i.e. producing its own VOCs. However, in Building 2 (Figure 4b) in weeks when TVOC concentrations in reference offices were higher than 100 ppb (3 of 14 weeks; mean 210 ± 25 ppb), there was again a large reduction in TVOC concentrations in the presence of potted-plants (to 65 ± 20 ppb), i.e. a fall of approximately 70% ($p < 0.05$). The results thus also clearly show that the six smaller, mixed, table-sized potted-plants were as effective in bringing about TVOC reduction as three (or six) of the larger floor specimens of *D.* 'Janet Craig' used in Investigation 1 (cf Figures 1–3). In Building 3 (Figure 5), over the single nine-week sampling period, there was no week in which mean reference TVOC concentrations were higher than 100 ppb.

TABLE II

Distributions and estimates (WorkCover NSW analyses) of aerial concentrations (ppb) of VOCs detected from analysis of Organic Vapour Monitors, with one week's exposure after placing in offices at the end of 8 weeks of the presence of either 0 or 6 potted-plants, in two investigations, each in two of three buildings

	Investigation; Building; and No. plants per office							
	Investigation 1*				Investigation 2*			
	Building 1		Building 3		Building 2		Building 3	
VOCs	0 plants	6 plants	0 plants	6 plants	0 plants	6 plants	0 plants	6 plants
Ethanol	7.1	7.0	6.2	3.9	24.5	11.5	2.1	4.8
Methylbutane	4.8	5	1.4	1.1	2.6	2.2	1.8	1.5
Toluene	2.8	3.0	5.0	1.3	2.1	2.1	1.1	1.2
Xylenes	1.8	2.1	3.0	0.8	1.5	1.9	0.7	‡ nd
Methylbenzenes	1.9	2.0	0.3	0.2	Nd	nd	nd	nd
n-Pentane	0.9	1.0	0.9	0.4	Nd	nd	nd	nd
n-Hexane	0.9	1. 0	0.8	0.7	0.75	0.7	0.6	0.7
2-Methylpantane	1.08	1.0	0.6	0.45	0.6	0.6	0.4	nd
Methylcyclopentane	0.18	0.22	nd	nd	Nd	nd	nd	nd
Ethylbenzene	0.45	0.45	0.5	nd	Nd	nd	nd	nd
Dodecane	1.7	nd	0.35	0.3	0.6	nd	nd	nd
Limonene	nd	1.08	0.9	2.25	0.8	0.3	0.3	0.5
Acetone	nd	0.40	nd	nd	Nd	nd	nd	nd
n-Decane	nd	nd	nd	nd	Nd	nd	nd	0.30
Totals	23.6	24.3	19.9	11.3	33.5	19.3	7.0	9.0

Values are means ($n = 2$) *Sampled August and October, 2003, (winter & spring, respectively) ‡ nd = not detected.

3.4. VOCS DETECTED

Table II presents the results of the WorkCover analyses of the OVM absorption badges, for both investigations. Fourteen VOCs were identified, with no clear differences in types being found among the buildings, or between planted and unplanted offices. As mentioned in ther Methods section, the values provide an indication of the relative concentrations among the VOCs detected during the sampled weeks, but not actual aerial concentrations.

4. Discussion

4.1. MECHANISM OF POTTED-PLANT RESPONSE TO TVOC POLLUTION

The results of both investigations showed that, when mean TVOC loads in the air of reference offices exceeded 100 ppb, concentrations were greatly reduced in the presence of any of the three potted-plant regimes trialled, by from 50–75%.

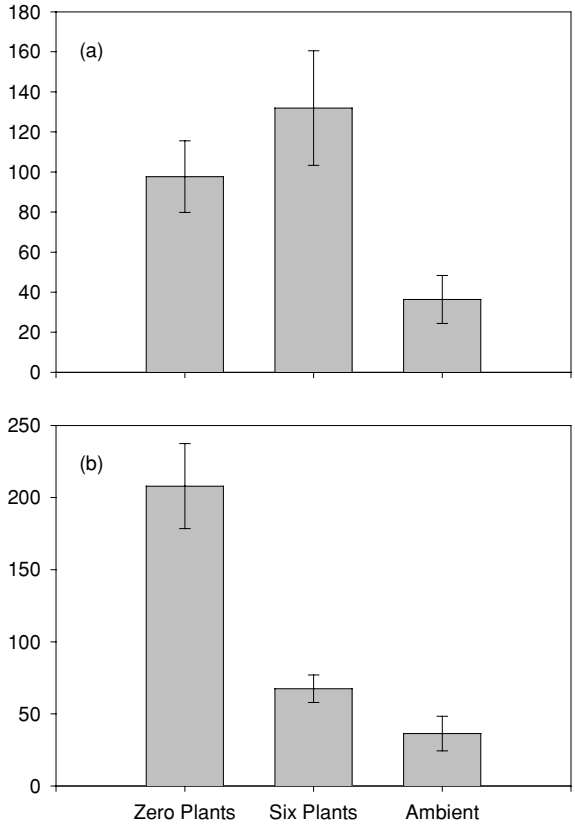

Figure 4. *Investigation 2*., TVOC levels in Building 2 over a nine- and a 5-week experimental period. (a) Means of all weekly readings, in offices with 0, or 5 potted-plants of *S.* 'Sweet Chico' plus 1 *Dracaena* 'Janet Craig'. (b) Means of readings for those weeks in which TVOC levels were >100 ppb in reference offices (0 plants). Values are means $\pm$ S.E ($n = 16$).

The results thereby also showed that the smallest amount of plant/potting-mix microcosm material trialled, was sufficient (and perhaps more than enough, since no minimum was evidenced), to produce effective VOC removal in the indoor air. The results, though they were not necessarily predictable in terms of the exact amount of microcosm-material required, are consistent with our previous findings. There we showed that a metabolic VOC removal response mechanism was induced by exposure to a single dose of VOC, and that the removal capacity was maintained when the system was challenged with repeated daily top-up doses of the compound (Tarran *et al.*, 2002; Wood *et al.*, 2002; Orwell *et al.*, 2004). In those laboratory test-chamber studies, however, the (single-compound) VOC dosages used (5–50 ppm benzene; 50–150 ppm *n*-hexane), were several orders of magnitude higher than the concentrations encountered here. Those laboratory studies also showed that, once induced, the system could remove very low residual concentrations of VOC, to

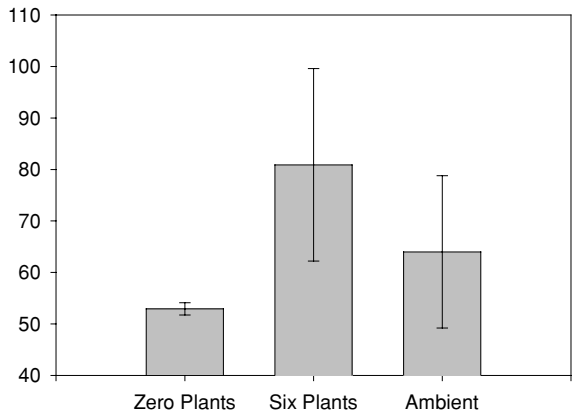

Figure 5. *Investigation 2*. TVOC levels in Building 3 over one nine-week experimental period; means of all weekly readings, in offices with 0, or 5 potted-plants of *S.* 'Sweet Chico' plus 1 *Dracaena* 'Janet Craig'. (In this Building there were no weeks in which reference office TVOC levels >100 ppb). Values are means ± S.E ($n = 8$).

below GC detection limits (i.e. <20 ppb). However, we have not previously made any laboratory investigation of a possible threshold limit of response, i.e the lowest concentration at which accelerated removal of air-borne VOCs can be stimulated *de novo*. The laboratory studies reported in the next paper specifically address this issue (Orwell et al., this volume, pp. 193–207).

As outlined above, it is well established that many soil bacterial species can degrade liquid-phase petroleum hydrocarbons. From the current study it would appear that VOCs in the gaseous phase in contact with the potted-plant microcosm can be degraded by substrate microorganisms via the same metabolic pathways as those involved in the bioremediation of oil spills or the degradation of other soil-borne aromatic hydrocarbons (by partitioning into adsorbed water on the potting mix particles, and thus become available to the microorganisms). The most interesting aspect of the results reported here, then, is not the evident over-abundance of capacity in the microcosm to deal with such extremely low VOC concentrations (smaller and smaller volumes of potted-plant material being found equally effective), but rather that the induction of the VOC removal response can be triggered at such low levels. However, our subsequent laboratory dose-response studies (see following paper), confirm the induction of the VOC removal mechanism within the range of the concentrations found in the offices.

The results of this office study indicate, conversely, that TVOC concentrations below a threshold of about 100 ppb do not stimulate a VOC removal induction. The lower effectiveness of the potted-plants in Building 1 than in Building 3 (Investigation 1), or than in Building 2 (Investigation 2), can be analysed further on this basis. A comparison of Figures 2b, 3b and 4b, shows that, in Building 1, even in weeks where TVOC concentrations in reference offices were higher than 100 ppb,

the levels were still significantly lower than in the corresponding reference offices in the other buildings under such circumstances. Reference levels in Building 1 (145 ± 15 ppb) were 30% lower than in Building 2 (210 ± 25 ppb; Figure 4b), and 50% lower than in Building 3 (290 ± 110 ppb; Figure 3b). It would appear that the weaker response in the planted offices of Building 1 was because TVOC levels did not rise sufficiently far above 100 ppb, or for sufficiently long, to stimulate a stronger induction of the VOC-removal response, such as was found in the other two buildings. In Buildings 2 and 3, when TVOC concentrations were more than twice as high as the apparent threshold of $\sim$100 ppb, all of the three planting regimes reduced levels to below 100 ppb once more (60–70 ppb). The findings are in line with those of our previous studies, showing rises in induction levels with increasing concentrations. Such a graded response is consistent with well-established principles of enzyme induction and Michaelis-Menton theory, which predicts near-first-order kinetics with respect to substrate (here VOC) concentrations at levels below saturation of enzymic active sites. The results of the laboratory dose-response studies (next paper) provide confirmation of this explanation of the strength of response in the face of rising TVOC levels.

4.2. VOCs IDENTIFIED

The VOCs detected in the offices (Table II) are among those commonly reported from other indoor air studies (see, eg, Sullivan Jr. *et al.*, 2001). Three of the predominant compounds detected, toluene (monomethylbenzene), ethylbenzene and xylenes (dimethylbenzenes) are referred to collectively, with benzene, as BTEX. The health hazards of this group of compounds, released in vehicle fuel emissions, are well known from international studies (eg Sullivan Jr. *et al.*, 2001, Rehwagen *et al.*, 2003; EA, 2003). Short-term exposure to any of them may produce symptoms including dizziness, loss of concentration, nausea and respiratory difficulties. Chronic exposures to any of them can result in neurotoxicities, respiratory disease and possible teratogenic effects, while benzene and xylene are confirmed carcinogens. Human exposures to BTEX have recently been studied in four cities in Australia (EA, 2003). The study found, *inter alia*, that the urban participants, even in Australia's warm-temperate climate, nevertheless spent 80–90% of their time indoors, where TVOC levels were higher than outdoors, and in the same range as those found in the present study ($<$100–300 ppb). This range is classified as within the limits for "clean air", defined as that in which the "TVOC load is much less than 1 mg per m^3, and individual VOCs less than 1% of any exposure standard" (Sullivan Jr. *et al.*, 2001). However, the health hazards of long-term exposures to such air pollution loads are of international concern as a human health issue (WHO, 2000; Mølhave and Krzyzanowski, 2003; Daisey *et al.*, 2003; Wyon, 2004).

4.3. SUMMARY OF FINDINGS

The results of the two office field-studies show that:

- When indoor average TVOC concentrations rise above about 100 ppb, the presence of potted-plants of the types, numbers and sizes used here, brings about highly significant reductions in TVOC levels, of up to 75% (to below 100 ppb)
- Three floor-specimens of *D.* 'Janet Craig' are as effective as six
- Six table-sized potted-plants, comprising five *S.* 'Sweet Chico' and one *D.* 'Janet Craig' (a feasible amount of plant material in any office, or other room-type), are as effective as 3 (or 6) of the larger *D.* 'Janet Craig' specimens
- From the above, the smallest amount of potted-plant material trialled (six 'table' specimens) may still be more than is required to bring about the TVOC reductions achieved in the sampled offices (since no minimum was found)
- The potted-plants appeared equally effective under air-conditioned and non-air-conditioned circumstances

These findings from the office field-study are confirmed and elucidated further by the results of the laboratory dose-response study reported in the following paper. Together, the findings indicate that the potted-plant microcosm represents an adaptive, self-regulating, low-cost, sustainable system for bioremediation of VOC pollution in indoor air, which can complement engineering measures in any type of building. The findings also have wider implications for air pollution reduction, including applications of phytoremediation to reduce outdoor air pollution.

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References

ASHRAE (American Society for Heating, Refrigeration, and Air-Conditioning Engineers): (2001). ANSI/ASHRAE Standard 62-2001, Ventilation for acceptable Indoor Air Quality. Atlanta: ASHRAE Inc., GA, USA.

Atwell, B., Kriedemann, P., & Turnbull, C. (eds) (1999a). *Plants in Action, Adaptation in Nature, Performance in Cultivation* (pp 383–392). Melbourne, Australia: Macmillan Education Australia Pty Ltd.

Atwell, B. et al. (eds) (1999) (b) *Ibid.*, 460–468.

Bergs, J. (2002). The effect of healthy workplaces on the well-being and productivity of office workers. In: Proceedings of International Plants for People Symposium, Floriade, Amsterdam, NL, June, 2002, Flower Council of Holland, NL.

Brasche, S., Bullinger, M., Gebhardt, H., Herzog, V., Hornung, P., Kruppa, B., Meyer, E., Morfield, M., Schwab, R. V., Mackensen, S., Winkens, A. & Bischof, W. (1999). Factors determining different symptom patterns of sick building syndrome—results from a multivariate analysis. In: *Proceedings of Indoor Air '99*. The 8th International Conference on Indoor Air Quality and Climate, August, 1999, Edinburgh, Scotland, August, UK, *5*, 402–407.

Brown, S. K. (1997). Volatile organic compounds in indoor air: sources and control. Chem. in Australia, January/February, 10–13.

Brown, S. K., Sim, M. R., Abramson, M. J., & Gray, C. N. (1994). Concentrations of volatile organic compounds in indoor air — a review. *Indoor Air*, *4*, 123–134.

Burchett, M. D., Tarran, J., & Wood, R., (Eds) (1999). Towards a New Millennium in People-Plant Relationships – Contributions from the International People-Plant Symposium, Sydney, July, 1998. Sydney, NSW, Australia: UTS Printing Services.

Carpenter, D. O. (1998). Human health effects of environmental pollutants: new insights. *Environ. Monit. Assessmt.*, *53*, 245–258.

Carrer, P., Alcini, D., Cavallo, D., Visigalli, F., Bollini, D., & Maroni, M. (1999). Home and workplace complaints and symptoms in office workers and correlation with indoor air pollution. In Proceedings of Indoor Air '99. The 8th International Conference on Indoor Air Quality and Climate, August, 1999, Edinburgh, Scotland, UK, *1*, 129–134.

Chaianeau, C. H., Rougeux, G., Ye-premiain, C., & Oudot, J. (2005). Effects of nutrient concentration on the biodegradation of crude oil and associated microbial populations in the soil. *Soil Biol. Biochem.* (in press)

Costa, P. R. & James, R. W. (1999). Air conditioning and noise control using vegetation, In Proceedings of Indoor Air '99, Edinburgh, International Conference on Indoor Air Quality and Climate, Vol. 3, pp 234–239.

Coward, M., Ross, D., Coward, S., Cayless, S., & Raw, G. (1996). Pilot Study to Assess the Impact of Green Plants on NO2 Levels in Homes. Building Research Establishment Note N154/96, Watford, UK.

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003). Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor Air*, *13*, 1, 53–64.

Darlington, A. B., Chan, M., Malloch, D., Pilger, C., & Dixon, M. A. (2000). The biofiltration of indoor air: implications for air quality. *Indoor Air*, *10*, 39–46.

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

Fisk, W. J. (2000) Review of health and productivity gains from better IEQ. In Proceedings of Healthy Buildings 2000, Helsinki, Finland, *4*, 22–34.

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. In *Proceedings of International Plants for People Symposium*, Floriade, Amsterdam, NL, June, 2002, Flower Council of Holland, NL.

Giese, M., Bauer-Doranth, U., Langebartels, C., & Sandermann Jr., H. (1994). Detoxification of formaldehyde by the spider plant (*Chlorophytum comosum* L.) and by soybean (*Glycine max* L.) cell-suspension cultures. *Plant Physiology*, *104*, 1301–1309.

Heslop, K. (2002). Personal and environmental characteristics, occupational factors and psychosocial correlates of sick building syndrome. In *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Monterey, CA, USA, pp. 432–437.

Kowalchuk, G. A., Buma, D. S., & van Veen, J. A. (2002). Linkages between aboveground plant communities and soil-borne microbial diversity. *Abs. Gen. Meet. Amer. Soc. Microbiol*., *102*, 309.

Leigh, M. B., Fletcher, J. S., Nagle, D. P., Prouzova, P., Mackova, M., & Macek, T. (2003). Field evidence of rhizosphere enrichment of PCB-degrading bacteria. *Abs. Gen. Meet. Amer. Soc. Microbiol.*, *103*, 117.

Lohr, V. I., & Pearson-Mims, C. H. (1996). Particulate matter accumulation on horizontal surfaces in interiors: influence of foliage plants. *Atmospheric Environment*, *30*, 2565–8.

Margesin, R., Gander, S., Zacke, G., Gounot, A. M., & Schinner, F. (2003). Hydrocarbon degradation and enzyme activities of cold-adapted bacteria and yeasts. *Extremophiles*, *7*(6), 415–458.

Mendell, M. J., Fisk, W. J., & Kreiss, K. (2002). Improving the health of workers in indoor environments: priority research needs for a National Occupational Research Agenda. *American Journal of Public Health, 92*(9), 1430–1440.

Mølhave, L., & Krzyzanowski, M. (2003). The right to healthy indoor air: status by 2002. *Indoor Air*, *13*(Suppl. 6), 50–53.

National Occupational Health and Safety Commission (Australia) (1991). Exposure Standards for Atmospheric Contaminants in the Occupational Environment. Canberra, ACT, Australia: Australian Government Publishing Service.

Nemergut, D. R., Wunch, K. G., Johnson, R. M., & Bennett, J. W. (2000). Benzo(a)pyrene removal by *Marasmiellus troyanus* in soil microcosms. *Journal of Industrial Microbiology & Biotechnology*, *25*(2), 116–119.

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

Pucci, O. H., Bak, M. A., Perressutti, S. R., Klein, I., Haertig, C., Alverez, H. M., and Wuensche, L. (2000). Influence of crude oil contamination on the bacterial community of semiarid soils of Patagonia (Argentina). *Acta Biotechnology*, *20*(2), 129–146.

Rehwagen, M., Schlink, U., & Herbarth, O. (2003). Seasonal cycle of VOCs in apartments. *Indoor Air*, *13*(3), 283–291.

Siciliano, S. D., Germida, J. J., Banks, K., and Greer, C. W. (2003). Changes in microbial community composition and function during a polyaromatic hydrocarbon phytoremediation field trial. *Applied and Environmental Microbiology*, *69*(1), 483–489.

Sullivan Jr., J. B., Van Ert, M. D., Krieger, G. R., & Brooks, B. O. (2001). Indoor environmental quality and health.. In: J. B. Sullivan Jr., & G. R. Krieger (Eds.), *Clinical environmental health and toxic exposures* (2nd ed., pp. 669–704). Philadelphia, PA, USA: Lippincott Williams & Wilkins, a Walter Kluwer Co.

Tarran, J., Orwell, R., Burchett, M., Wood, R., & Torpy, F. (2002). Quantification of the Capacity of Indoor Plants to Remove Volatile Organic Compounds under Flow-through Conditions. Final Report to Horticulture Australia Ltd, HAL, Sydney, NSW, Australia.

Wolkoff, P. (2003). Trends in Europe to reduce the indoor air pollution of VOCs. *Indoor Air*, *13*(Suppl. 6), 5–11.

Wolverton, B. C., & Wolverton, J. D. (1993). Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *Journal of Mississippi Academic Science*, *38*, 2, 11–15.

Wood, R. A., Orwell, R. L., Tarran, J., Torpy, F., & Burchett, M. (2002). Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. *Journal of Horticultural Science and Biotechnology*, *77*(1), 120–129.

Wyon, D. P. (2004). The effects of indoor air quality on performance and productivity. *Indoor Air*, *14* (Suppl 7), 92–101.