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Greening the Great Indoors for Human Health and Wellbeing

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The purpose of this Report is to present the findings of a project undertaken to further an understanding of the benefits of potted-plants on indoor air quality and wellbeing of building occupants, to contribute to 'greening the city' for sustainable urban communities. The research comprised: laboratory trials of volatile organic compound (VOC) removal, with three untried species; an office study of minimum numbers of plants required to reduce VOCs and CO_2; a preliminary examination of whether plants could, undesirably, increase airborne mould spore loads; and an investigation of effects of plants on psychological wellbeing of staff. The laboratory trials confirmed the species tested have similar capacities to remove VOCs as nine species previously tested. The office study recorded VOC and CO_2 reductions, but less marked than in our earlier studies, probably because of greater efficiency of more modern air conditioning systems, and inadequate lighting. Horticultural R&D is required to optimise plant contribution to CO_2 removal. No significant effects of plants were found on mould counts or types; indoor counts were very low – as low as one twentieth of outdoor loads. Highly significant reductions in negative mood states were found with plants – and one plant can make the difference. Recommendations for further R&D are also presented.

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GREENING THE GREAT INDOORS FOR

HUMAN HEALTH AND WELLBEING

HAL Project NY06021

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Media summary

The goal of the project was to further an understanding of the benefits of potted-plants to reduce indoor air pollution and aid wellbeing of occupants, to contribute to the national environmental goal of 'greening the city' for sustainable urban communities.

The research comprised:

- Laboratory trials of volatile organic compound (VOC) removal, with three untried species;
- Office study of the minimum numbers of plants required to reduce VOCs and CO_2;
- Examination of whether plants could, as suggested by several authors, increase airborne mould spore loads. One species associated with damp buildings, *Aspergillus fumigatus*, can potentially cause serious health problems in severely immunocompromised patients; and
- Investigation of effects of plants on psychological wellbeing of staff – first such research utilising a battery of internationally validated surveys.

Key outcomes

- Laboratory trials confirmed the species tested have similar capacities to remove VOCs as nine species previously tested. This indicates almost any species is likely to have a similarly strong VOC removal capacity.
- The office study recorded VOC and CO_2 reductions, but differences were less marked than in our earlier studies, probably because of the greater efficiency of more modern air conditioning systems, and inadequate lighting, in the buildings tested. Horticultural R&D is required to optimise plant contribution to CO_2 removal.
- From this preliminary study no significant effects were found on mould counts or types, and no *A. fumigatus* spores, in over 175 individual air samples from offices with plants. Indoor counts were very low – about one twentieth of outdoor loads.
- Highly significant reductions in negative mood states were found with plants – in anger, anxiety, depression, confusion, fatigue and stress. Just one plant can make the difference!

Future R&D

The findings provide new information on plant benefits to building occupants. R&D is needed on their potential to lower CO_2 levels and hence air-conditioner energy consumption, to contribute to sustainable urban living. More research is also needed on VOC reduction with different potting media. Meanwhile, general principles apply – place plants in accordance with stated shade tolerances, to maximise CO_2 reduction; VOC reduction will also be achieved.

Technical summary

Nature of problem

Indoor environmental quality (IEQ) is extremely important to our health, since over 80% of Australians live in urban areas and spend 90% of time indoors. Urban air pollution (UAP) causes at least 1,400 deaths and over 2000 hospital admissions p.a. in Sydney alone. Urban mental health problems are also an international concern. Indoor air pollution is almost always higher than outdoors, in particular more volatile organic compounds (VOCs) outgassing from indoor sources (furnishings, paints, etc), and more CO_2 from human respiration. Indoor plants absorb all types of UAP. We have previously laboratory-tested nine indoor species, and found they eliminate repeated high VOC doses within 24 hours. Our previous office studies showed that plants can keep VOCs down to negligible levels and s reduce CO_2 by 10 to 25%. The goal of this project was to conduct studies designed to further an understanding of the benefits of potted-plants to improve IEQ, to contribute to the national environmental goal of 'greening the city' for sustainable urban communities.

Experimental aims

The project comprised:

- Laboratory trials of VOC removal capacity in three untested species, *Aglaonema modestum, Chamaedorea elegans* and *Philodendron* 'Congo';
- Office study of minimum numbers of plants required to reduce VOCs and CO_2;
- Examination of whether plants could, as suggested by several authors, increase airborne mould spore loads. One species associated with damp buildings, *Aspergillus fumigatus*, can potentially cause serious health problems in severely immunocompromised patients; and
- Investigation of effects of plants on psychological wellbeing of staff – first such research utilising internationally validated surveys.

Results and discussion

Laboratory study Test-chamber trials with three untried species showed they have the same capacity for VOC removal as found with nine previously tested species (see Appendix). Once acclimatised ('induced') by exposure to an initial dose, they could remove repeated top-up doses within about 24 hours. *Recommendations* The evidence now with a total of 12 species, indicates the likelihood that almost any species will have a similar VOC removal capacity, but research is continuing on this matter.

Plants and office air quality We used 11 replicates with four plant treatments: 1 or 3 *Spathiphyllum* 'Petite' (200 mm pots); & 1 or 2 *Dracaena* 'Janet Craig' (300 mm pots); plus a no-plant control group. Weekly samplings were conducted over two 10-12 week periods, in 55 offices in two UTS buildings. The study recorded trends in VOC and CO_2 reductions, but differences were less marked than in our earlier studies, probably because of the greater efficiency of more modern air conditioning systems, and inadequate lighting, in the buildings tested. *Recommendations*: Indoor plants have the potential to reduce energy loads on air-conditioning systems by lowering CO_2 levels, and more horticultural R&D is required to optimise plant contribution. Meanwhile, general

principles apply – place plants in accordance with stated shade tolerances, so they can acclimatise to prevailing lighting for CO_2 reduction; VOC reduction will also be achieved.

Plants as potential source of mould-based health risks In a first-ever study on this issue, four airborne mould spore samplings were also conducted, and indoor and outdoor counts and types compared. Results showed no significant effects of plants on spore counts or species composition, and no *Aspergillus fumigatus* spores were found. Indoor counts were very low - only one twentieth of outdoor loads. *Recommendations:* No evidence was found in this preliminary study of mould-based health risks from indoor plants. To check it out further, R&D would ideally include studies in other climates (eg Brisbane and Hobart).

Plants and staff wellbeing Two psychological survey questionnaires were each administered before and after three months of plant presence (or absence). Plants were associated with 40-60% score reductions in negative mood states measured – anger, anxiety, depression, confusion, fatigue and stress. And - just one plant made all the difference. *Recommendation:* Plant presence is highly effective in improving staff satisfaction, and hence, no doubt, productivity.

Technology transfer

Progress reports have been published in NIPA Newsletters and at meetings of the Horticultural Media Association (HMA) in various states. The UTS team has also made presentations at the 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation, in Sendai, Japan, October (2007); Annual Conference of the Facility Management Association of Australia (FMAA) (2008); the Woolcock Institute of Medical Research (linked with University of Sydney and RPA Hospital) (2008); a Garden Club (2009). We have scheduled meetings this year with Industry and Garden Clubs, and are preparing this material for submission to peer-reviewed scientific journals.

1. Introduction

1.1 Project aims

International research, discussed below, clearly demonstrates that indoor plants can both reduce indoor air pollution, and directly improve occupant wellbeing over a range of tested variables. The goal of this project was to advance a scientific understanding of the capacities of indoor plant species to improve indoor environmental quality (IEQ); to enable extension of their horticultural applications to improve the wellbeing of building occupants; and to contribute to the national environmental goal of 'greening the city' for sustainable urban communities in Australia.

The project involved laboratory investigations and office studies in two buildings at UTS, to investigate effects of indoor plants on both physicochemical variables of indoor air quality (IAQ) and on psychological variables concerning feelings of wellbeing among participating staff. The experimental aims of the project have been to:

a) laboratory-test the capacities of three previously untried indoor plant species to remove volatile organic compounds (VOCs) a common class of indoor air pollutants;

b) investigate minimum numbers of plants needed to benefit IAQ in offices;

c) to make a first ever, preliminary investigation of whether, at the same time, plant presence could significantly increase or change the composition of mould spore loads in office air, which, according to several authors, could be a potential problem in the use of indoor plants in some situations;

d) explore the influence of plant presence on mood states of office occupants, including feelings of anxiety, fatigue and anger, using, for the first time, a set of internationally validated psychological survey instruments for the measurements;

e) in collaboration the National Interior Plantscape Association (NIPA) and the Nursery industry, contribute to increasing industry and public awareness of the multiple benefits of indoor-plants to urban living.

1.2 Health impacts of urban air pollution

As a result of the process of urbanisation in Australia, as in North America and western Europe, 80% of people now live in urban areas, where we spend some 90% of our time indoors (Cavallo *et al*., 1997; Environment Australia [EA] 2003). The quest for sustainable urban communities in this country must therefore include the achievement and maintenance of a sustainable building ecology.

Apart from any possible climate change implications which might exacerbate problems of city living, urban air pollution (UAP) is a world-wide health concern, including problems associated specifically with indoor air quality (Brown, 1997; WHO, 2000; EA, 2003). Ninety per cent of UAP comes from fossil fuel emissions, which comprise a mixture of carbon dioxide (CO_2) and carbon monoxide (CO); nitrogen oxides (NO_x); sulfur oxides (SO_x); organic air toxics, ie volatile organic compounds (VOCs), of which the 'big four' are benzene, toluene, ethylbenzene and xylene (the BTEX group); polyaromatic hydrocarbons (PAHs); and ozone. Health costs of urban air pollution in Australia are estimated to be about

$12 billion p.a. (Dept. of Health NSW, 2009), and air pollution in the Sydney metropolitan area alone is estimated to cause some 1,400 deaths and over 2000 hospital admissions p. a. (NSW EPA, 2006). In addition, although not generally recognised, indoor air pollution is almost always higher than outdoors. This is because as the contaminated air enters it mixes with indoor-sourced pollutants, in particular more VOCs outgassing from synthetic furnishings, finishes, paints, solvents etc. (EA, 2003; Barro *et al*., 2009; Chan *et al*., 2009), and higher CO_2 concentrations, produced by human respiration (and gas appliances). The US EPA (2000) has identified over 900 VOCs that have been found in indoor air. Even at imperceptible levels (<200 ppb), mixtures of VOCs can cause symptoms of 'sick-building-syndrome' or 'building-related-illness' (Jaakkola *et al*., 2007; Lu *et al*., 2007; Epstein, 2008).

1.3 Health benefits of indoor plants

1.3.1 Potted plants reduce indoor air pollution

International research has shown that indoor plants can reduce all types of urban air pollutants (Wolverton *et al*., 1989, 1991, 1993; Coward *et al*., 1996; Lee & Sim, 1999; King & Crosby, 2002, Yoneyama *et al*., 2002; Yoo *et al*., 2006; Kim *et al*., 2008). As is discussed further in Sections 2 and 3, our UTS research has clearly demonstrated that potted-plants can be used to reduce indoor concentrations of VOCs and CO_2, two classes of contaminant almost always in higher concentrations indoors than outside. Our research approach is in line with the general methodology of environmental toxicology, which involves the study of plants (and animals) to indicate and/or remediate pollution. A triad approach is commonly adopted (Dagnino *et al*., 2007; Iannuzzi *et al*., 2008), the three investigative strands comprising:

- *field studies* to establish correlations between pollutants of concern and responses in 'target' organisms of interest (which may include either toxic or adaptive responses);
- *laboratory studies* to elucidate and confirm cause-effect relationships between pollutant presence and concentrations, and organism responses; and
- *physicochemical analyses* to bring results together to provide a coherent understanding of dose-response relationships and their mechanisms.

All three strands have been used in the research reported here.

1.3.2 Direct health benefits of indoor plants

Indoor plants have also been shown to yield directly measurable benefits to the health and wellbeing of building occupants. Fjeld and colleagues (1998, 2002) found that staff sick leave was reduced by over 60% when indoor plants were installed. They also found less sick leave absences among school children with plants in their classroom, and that staff with plants in offices showed significantly fewer health and discomfort problems, including 37% less coughing, 30% less fatigue, and a 23% reduction in symptoms such as headaches, sore eyes, nose or throat, 'heavy-headedness' or lowered concentration. Better performance and behaviour among junior high school children with plants in their classroom was reported in a Taiwanese study (Han, 2008). USA studies by Lohr and colleagues (1996a,b; 2000) also showed productivity gains, and reductions in perceptions of pain and discomfort, when plants were present. A Texan survey with some 450 respondents (Dravigne *et al*., 2008) found that job satisfaction rose significantly on all 10 criteria tested among staff with indoor plants, and that indoor plants were preferred to window views of planted exteriors. The psychological survey responses of UTS staff participants in the current project are reported in Section 5.

2. Laboratory studies - VOC removal

2.1 Background

We have previously laboratory-tested VOC removal capacity in nine indoor plant species (see Appendix 1 for complete list of species tested) (Wood *et al*., 2002, 2008; Orwell *et al*., 2004, 2006; Tarran *et al*., 2002, 2007; Burchett *et al*., 2005, 2009). We have used four test VOCs in the studies, three from the BTEX group - benzene, toluene and xylene, found from both outdoor and indoor sources, since they are used as industrial solvents for furnishings, finishes etc.; and *n*-hexane, also used as a solvent. The potted-plants were tested in bench-top chambers, with repeated top-up doses of one or other of the test VOCs, under both light and dark conditions. In summary, our results have shown that all species tested are about equally effective in VOC removal, as follows:

- Removal rates are stimulated by an initial dose the VOC;
- When fully adapted ('induced') by exposure to the VOC, usually achieved by the third top-up dose, the potted-plant microcosm can consistently remove repeated doses within about 24 h;
- If the dose concentration is increased, the rate of removal rises in response to the challenge (ie, approximates first-order kinetics);
- The system also removes very low, residual concentrations of VOCs, to below detection limits of the gas chromatograph (GC) instrumentation (< 20 ppb);
- The system is equally effective in light or dark;
- The main VOC removal agents are normal potting-mix bacteria, however the plant is also involved, and has a role in nourishing its root-zone microorganisms;
- VOC removal is thus achieved by the plant/potting-mix symbiotic (or mutualistic) microcosm.

Subsequent testing with three of the test species showed that pot size is less critical in VOC removal rates than might be supposed. We found that potted-plants in 200 mm diameter pots removed repeated doses of benzene at the same rates as those in 250 or 300 mm pots; and that three 125 mm pots were as effective as one 200 mm pot (Burchett *et al.*, 2009). That is, there is clearly abundant capacity in the potted-plant microcosm for VOC removal. The plant materials used have been supplied in a variety of potting mixtures, in accordance with the judgement of the suppliers as to the horticultural requirements of the species concerned. The results therefore indicate that if the plant is well tended, the root zone microorganisms involved in VOC removal will also be in a healthy state (Burchett *et al.*, 2009).

2.2 Aim

The strong similarities among results with all the plant species investigated suggest that most indoor species are likely to show the same VOC removal propensities. Nevertheless, the aim of the laboratory experiments in this project was to test that hypothesis further, by trialling three previously unexplored species.

2.3 Methods

2.3.1 Plant materials

The selection of the three test species was based on discussions with NIPA: *Aglaonema modestum*, *Chamaedorea elegans* and *Philodendron* 'Congo'. Plant materials were arranged by NIPA (supplied by TLC Indoor Gardens, Sydney) in 200 mm pots. Plants were therefore of a size normally supplied to offices by plant hirers, and were growing in standard potting mixes for those species. Four replicate plants were used in each trial.

2.3.2 Test VOC and dosages

Benzene was used as the test VOC. Apart from its being a component of general UAP, benzene is used as a solvent in the manufacture of pesticides, detergents, synthetic rubber, lubricants, dyes and other materials (US EPA, 2010). Three successive (top-up) doses of 5 ppm benzene (16 mg m^{-3} at 1 atm, 23ºC) were applied, to provide for full induction of VOC removal response at this concentration. This dosage was chosen because it is equal to the Australian 8-hour-averaged occupational exposure maximum concentration (Australian Safety & Compensation Council [ASCC], 2006). A final 25 ppm dose was then applied, to test further the responsiveness and capacity of the potted-plant microcosm.

2.3.3 Equipment

As in our previous studies (eg. Orwell *et al*., 2006; Burchett *et al*., 2009), eight 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 steel frames, sealed with foam-rubber tape and adjustable metal clamps (Figure 1). The chambers 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^oC; 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), with variable intensity to a maximum of ~50 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 were used to obtain chamber air samples at regular 24 h intervals. Chamber VOC concentrations were measured 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).

2.3.4 Procedures

For each species, the set of replicate pot-plants was first watered to saturation and allowed to drain for 1 h before being placed one per chamber, with lids sealed and lights on. A 5 ppm dose of benzene (AR grade, Sigma) was then injected into each chamber and left for 30 min for complete evaporation before an initial air sample was taken. Subsequent air samples were taken over the next several days. Each of the two top-up doses of 5 ppm was injected into the chambers after 95% of the previous dose had been removed; then a final 25 ppm dose was applied to test the vigour of the microcosm.

2.3.5 Leak tests

Chamber leak tests were conducted before and after each trial, applying a 5 ppm benzene dose. A beaker containing 500 mL water was placed in each chamber to simulate pot-plant evapotranspiration. These tests corrected for any loss of VOC from the chambers not directly attributable to the plants, eg. from leakage past the door seals or absorption into the perspex.

Figure 1. Plants in test chambers.

2.3.6 Data analysis

From the results of the leak tests corrections were applied to the data; VOC losses in blank chambers were 5–10% per day. Statistical comparisons were performed using one-factor ANOVA (Excel 2001, Microsoft, Australia Corp.) and pair-wise Tukey's HSD tests. Differences between rates are reported as statistically significant where $p \leq 0.05$.

2.4 Results

Figures 2-4 present the results for the three species. It can be seen that the patterns of response were very similar in each case. In each species, removal rates were initially slow in response to the first 5 ppm dose of benzene, but started to increase in response to that dose, and rose further with each of the two top-up doses. Also, in all species, with the five-fold increase in concentration with the final 25 ppm dose, there were further increases in removal rates in response. A comparison of VOC removal rates for the three species is presented in Table 1.

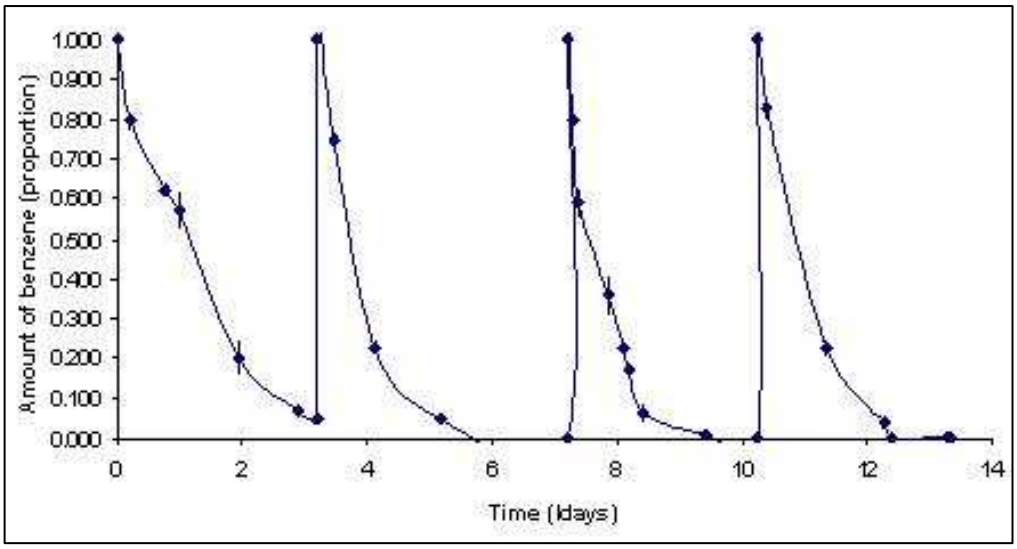

Figure 2. Removal from test-chamber air of three doses of 5 ppm benzene, and one 25 ppm dose, with *Aglaonema modestum* (means ± standard error, SE; N=4).

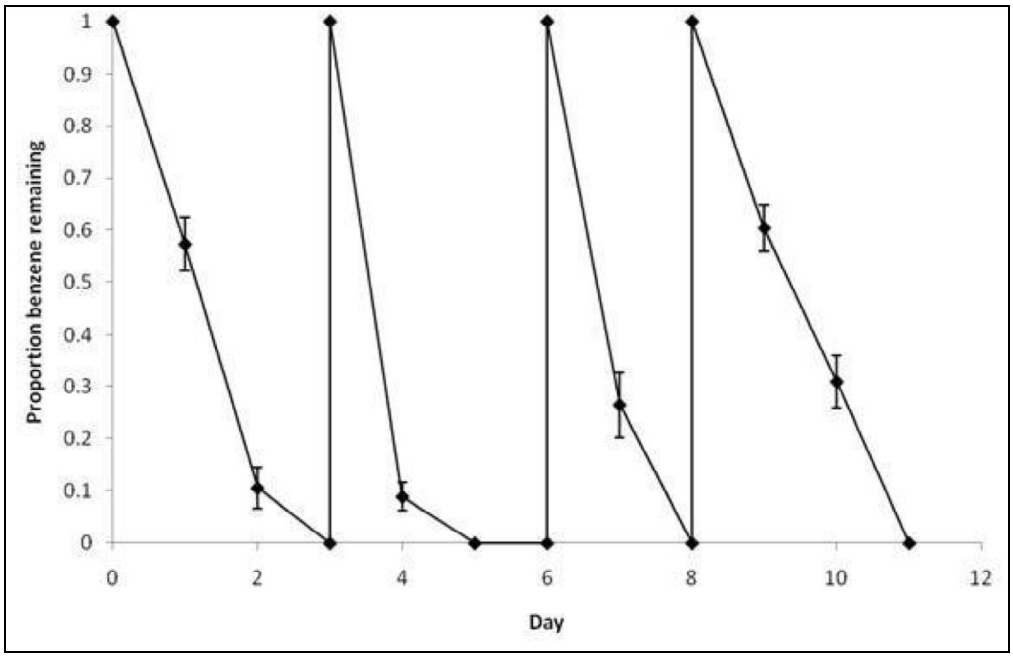

Figure 3. Removal from test-chamber air of three doses of 5 ppm benzene, and one 25 ppm dose, with *Chamaedorea elegans* (means ± SE; N=4).

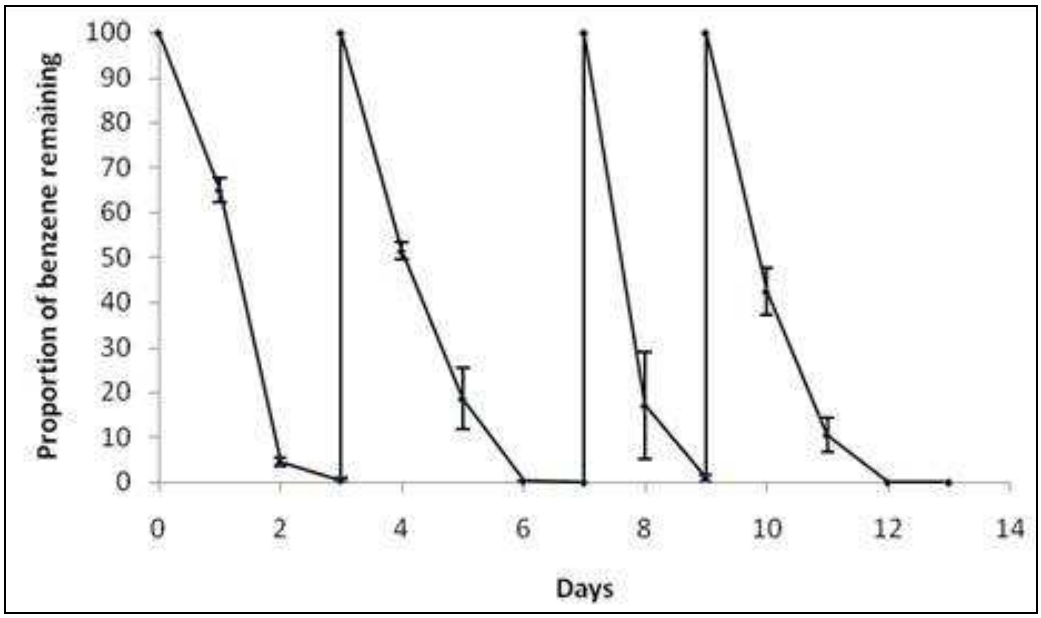

Figure 4. Removal from test-chamber air of three doses of 5 ppm benzene, and one 25 ppm dose, with *Philodendron* 'Congo' (means ± SE; N=4).

Table 1. Time (h) taken to remove 80% of first and third 5 ppm dose, and subsequent 25 ppm dose.

Species/Times	1st 5 ppm dose 80% removal	3rd 5 ppm dose 80% removal	Calculated Time to remove 1 ppm	25 ppm dose 80% removal	Calculated Time to remove 1 ppm
Aglaonema	46	18.5	4.6	24	1.2
Chamaedorea	38	29	7.3	62	3
Philodendron	43	28.5	7	51	2.6

2.5 Discussion

The general pattern in VOC removal response in these three species is very similar to those found with the other nine species tested, although once again species-specific variation was present. These variations point to a direct plant involvement in the removal process and also, no doubt, to differences among plant material stocks and potting mix formulations (and their attendant microorganisms). The strong similarities among results for the three species provide clear confirmation of the view that the great majority of indoor plant species is likely to show comparable VOC removal capacity. Our findings therefore extend and modify those obtained in the pioneering screening studies of Wolverton and colleagues (1989, 1991, 1993), who reported removal rates among a large number of species, varying from about 14 to 90% in 24 hours, but from tests conducted over short time periods. They were not aware of the induction period necessary for any species to show full response rates at any particular VOC dosage, thus removal rates we have detected are generally far higher than Wolverton's.

In an earlier UTS study, using toluene and xylene as test VOCs, we showed step-wise inductions of higher removal rates with each of four increases in dosage, through a 500-fold

concentration range (from 0.2 to 100 ppm; Orwell *et al.*, 2006). The results show a very robust capacity for VOC reduction in the potted-plant microcosm. This is not surprising, since the bacteria involved (see Burchett *et al.,* 2009) are among the normal decomposing microorganisms of soil/potting mixtures, and similar to those routinely cultured for use in bioremediation of oil spills and groundwater contamination. They are clearly also capable of responding to the relatively minute, though from a human health point of view significant, airborne concentrations of VOCs - digesting them as nutrients.

2.6 Significance to industry

With the results reported here, we have now laboratory-tested 12 commonly used indoor plant species for VOC removal capacity. All the species show very similar capacities for VOC removal, and their response is very robust, rates generally rising to meet any increases in concentrations of air-borne VOCs. The new results add confirmation to the view that it is likely that any indoor plant species would show comparable VOC removal capacity. It is hoped that in future studies we can include examples of woody dicots and succulents such as bromeliads, to determine whether removal capacity extends in the same measure to these taxonomically disparate plant groups.

3. Office study - effects of plants on indoor air quality (IAQ)

3.1 Aim

The aim of this component of the project was to conduct an office field study to investigate the minimum numbers and/or sizes of plants needed to quantifiably benefit IAQ variables, particularly total VOC loads (TVOCs) and CO_2..

3.2 Background

3.2.1 Previous UTS studies

In our previous office study we found mixtures of 10 to 15 different individual VOCs in sampled offices (Wood *et al*., 2006; Orwell *et al*., 2006). TVOC loads in unplanted (reference/control) offices ranged from about 60 to 400 ppb over two nine-week experimental periods. However, in offices with any of three plant treatments, TVOC concentrations were always below 100 ppb (considered to be of negligible respiratory health risk). The three plant treatments included: three or six floor specimens (300 mm pots) of *Dracaena deremensis* 'Janet Craig'; and six desk plants in 200 mm pots - five *Spathiphyllum wallisii* 'Petite' plus one *D.* 'Janet Craig'. The results showed that the induction of VOC removal response was 'switched on' whenever indoor concentrations of TVOCs rose above about 100 ppb, so TVOCs in planted offices were maintained below that level. The fact that three plants were as effective as six in maintaining low TVOC levels suggested that three plants were more than enough to achieve the result. Thus the minimum number of plants needed for VOC cleansing must be three or fewer – and of what size? The current project sought to answer these questions.

In the first office study we had found that in offices with three or more pots of *D.* 'Janet Craig', CO_2 levels were reduced by 10% in an air-conditioned building, and by 25% in a non-air-conditioned building (to below external concentrations) (Tarran *et al*., 2007). The current project therefore also aimed to examine the effects of plants on CO_2 levels in UTS offices, in two newer air-conditioned buildings than sampled in the previous study.

3.2.2 Potential for indoor plants to reduce building ventilation costs

In a recent article reported by the US National Institutes of Health, Epstein (2008) stated that: "Over the last 50 years a new man-made ecosystem has developed – the controlled indoor environment within the sealed exterior shells of modern non-industrial buildings. Emitted toxic volatile compounds from building materials, furnishings and equipment, and inappropriate ventilation (…to reduce expenses) contribute to reduce indoor air quality (IAQ)…[H]ealth problems related to this ecosystem have emerged…'Building Related Illness'… or …'Sick Building Syndrome',….symptoms including irritation of…eyes, nose and throat, headache, fatigue and difficulty concentrating,….symptoms reduce productivity and increase absenteeism…"

In this 'sealed chamber' ecosystem, building air-conditioning (A/C) systems have a twofold purpose –air refreshment (ventilation) and temperature control. Refreshment rates from outside air are generally in the range of 11-15% p. h. The trigger for increased ventilation is to reduce CO_2 concentrations, rather than to refresh O_2 levels. Raised CO_2 concentrations have been used as an indicator of total indoor air pollution, and because they are directly

associated with: increased respiratory symptoms, decreased productivity (Erdmann and Apte, 2003; Clements-Croome, 2008), loss of concentration (Seppänen *et al*., 2006), and lowered student performance (Shaughnessy *et al*., 2006). Australia follows the WHO and American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) standards for indoor CO_2 levels, which specify a maximum acceptable indoor air concentration of 1,000 ppm. Some organisations (including UTS) use 800 ppm CO_2 as the maximum level. Many city buildings have A/C ventilation rates pre-set to ensure indoor CO_2 levels below 600 ppm (which requires constant energy input), while some have variable flows, with sensors that switch in extra ventilation when CO_2 concentrations rise above acceptable values. Global warming forecasts predict that outdoor CO_2 levels, now at ~380 ppm, could rise to above 500 ppm over the next 25-30 years (IPCC, 2009), which would narrow the gap between outdoor and indoor CO_2 concentrations, and hence the degree to which extra A/C ventilation is required.

Indoor plants could potentially play an important role in lowering indoor CO_2 levels, hence reducing the energy requirements of city buildings, and contributing to the goal of sustainable cities in Australia. However, achieving adequate light levels for effective photosynthesis inside buildings, even for shade-tolerant plants, can be problematic. Plant CO_2 uptake also depends on species' attributes including foliage area and degree of shade tolerance, as well as light intensity. Baseline information of plant performance under current building conditions is required, as a first step towards the horticultural development and deployment of indoor plants to reduce CO_2 concentrations, and hence the load on city A/C systems.

3.3 Methods

3.3.1 Buildings sampled

Two air-conditioned UTS buildings were used, located in Sydney's central business district, on the southern side of Sydney Harbour. Both buildings are of brick and concrete, both are of seven storeys, and accommodate a mixture of lecture rooms, workrooms or laboratories, and staff offices (mainly single-occupant; average areas 10-12 m^2, average volume = 43±2 m^3, although several Head of Section offices were up to 145 m^3**).** Building A is about 18 years old, and houses the Faculty of Design, Architecture and Building (UTS designation: Building 6). Building B, housing the Faculty of Science, is four years old (UTS designation: Building 4). The A/C systems in each building supply an average of 6-8 air changes per hour to each office, with a 10-15% fresh (external) air input (J. Kraefft, UTS, pers. comm.). These A/Cs do not adjust humidity levels in the incoming air.

3.3.2 Participants

Approval was first gained for the project from the UTS Human Research Ethics Committee, since the research involved psychological assessment as well as air quality sampling (see Section 5). For each building, initial contact was then made with the Dean of the Faculty concerned, after which staff either were approached individually, or, hearing of the project, volunteered to take part. A total of 55 staff participated in the project, which was conducted between March and October 2008.

3.3.3 Experimental design

Offices were randomly assigned among five treatments, with 11 offices per treatment, comprising: 1 or 2 floor specimens (F1 & F2) of *Dracaena* 'Janet Craig' in 300 mm pots; 1 or 3 desk specimens (D1 & D3) of *Spathiphyllum* 'Petite' in 200 mm pots; and one control

group (RO) with no plants. Plant materials were organised by NIPA and supplied by TLC Indoor Gardens, Sydney. Air quality monitoring was conducted weekly over two 10-12 week sampling periods during teaching semesters - from March to June, and August to October respectively, with plants rested in a shaded greenhouse between semesters. Plants and treatments were randomly reassigned among offices for the second Round, except that participants who had had no plants in Round 1 were first randomly assigned to one of the four plant treatments for Round 2. All participants received one or more plants at the end of Round 2, in thanks for their participation.

3.3.4 Air quality sampling

Weekly TVOC samplings were conducted using a Portable Photoionisation Detector, ppbRAE (Rae Systems Inc., USA; supplier, Active Environmental Solutions, Melbourne, Aust.), with sensitivity 0–999 ppb at 1 ppb resolution (calibrated with isobutylene standard), and with correction factors from a list of >250 VOCs. Five-minute samplings were taken in each office, comprising ten 30-sec readings, which were taken from all parts of the office. At the same time samplings of CO_2, CO, relative humidity (RH) and temperature were made, ten 30-sec readings of each variable, using a Portable IAQ-Calc Indoor Air Quality Meter (TSI Inc., MN, USA).

3.3.5 Data analysis

For each experimental Round, 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 considered statistically significant where $p \leq 0.05$. In some cases, possible trends in results (where $0.05 < p < 0.1$) are also discussed, for reasons outlined below.

3.4 Results

3.4.1 Overview

We did not find the strong plant-associated reductions in either TVOC or CO_2 levels as were obtained in our first office study. This was no doubt the result of the fact that the two buildings sampled are considerably newer than the buildings used in the previous study, with more efficient A/C systems, and with overall VOC and CO_2 levels being far smaller than previously encountered. Larger numbers of offices would be needed to confirm any trends in the data. However, trends were recorded with respect to both TVOC and CO_2 reductions, and the implications of this for future horticultural technology and building management are discussed below.

3.4.2 General building conditions

Temperatures were kept steady by the A/C systems through both Rounds in both buildings – at a comfortable level of 22.2±0.07 ^{o}C in Round 1 and 22.5± 0.1^{o}C in Round 2. RH was also steady in each Round, but varied more between Rounds, being 55.4±0.7% in Round 1, and 48.7±1.1% in Round 2. Both RH values are within the optimum range for building occupants, ie between 40 and 60% (OHS Reps. Information, 2010).

3.4.3 Effects of plants on TVOC and CO_2 levels

Results for the effects of plant treatments on both TVOC and CO_2 concentrations are presented in Table 2. The ambient indoor TVOC levels recorded in this study, with means in control offices of 20 and 35 ppb in the two Rounds respectively, were much lower than those encountered our first office study. Individual readings in the current study rarely exceeded 100 ppm, which was the concentration above which clear stimulation of the VOC removal response was observed in our first office study. The results indicate the use of materials with lower VOC contents in these buildings than in the older buildings. Nevertheless, in Round 1 (Table 2) recorded means for TVOCs were 15% lower in offices with three desk plants (D3) and 9% lower with two floor plants (F2), than in reference offices (R0). Although the differences are not statistically significant ($p > 0.05$), they are interesting, indicating the need for further research, because in laboratory trials we have repeatedly recorded removal of remnant VOC concentrations to below detection limits of the GC (<20 ppb). Future laboratory trials should include an investigation of the minimum concentrations at which induction of VOC removal can be observed, which is a matter that has received no study to date. Also in Round 1, all four plant treatments recorded means for CO_2 concentrations of between 3 and 10% lower than those in control offices, but again the differences were not statistically significant.

Table 2. Average TVOC and CO_2 concentrations over two 10-12 week rounds of sampling, in offices with four plant treatments, plus reference offices. Code: D1 and D3: 1 or 3 desk plants respectively; F1 and F2: 1 or 2 floor plants respectively; RO: reference/control –no plants. (Values are Means ± SE; N=110 per treatment per Round.)

Round/ Item	TVOCs (ppm)	CO_2 (ppm)
Round 1		
D1	22.6 ± 3.0	503 ± 7.2
D3	17.1 ± 2.0	497 ± 8.3
F1	25.0 ± 3.5	509 ± 10
F2	18.1 ± 2.4	504 ± 7.4
R0	20.0 ± 2.1	517 ± 13
Round 2		
D1	37.7 ± 2.3	401 ± 12
D3	36.0 ± 2.0	401 ± 11
F1	37.0 ± 2.4	386 ± 9.1
F2	34.7 ± 2.4	389 ± 9.0
R0	35.5 ± 5.6	386 ± 11

In Round 2 no reductions were recorded with any plant treatment for either TVOCs or CO_2. There were seasonal differences in average levels of both types of pollutant. TVOC levels in Round 2 were almost twice as high as in Round 1, which may reflect higher ambient city levels at increased temperatures. And CO_2 levels were 20% lower in Round 2, suggesting higher ventilation rates in response to rising external temperatures over the spring period.

Reduced staff occupancy in spring semester associated, eg, with more site or field excursions, may also have lowered CO_2 levels, but no data on such matters were recorded.

3.5 Discussion

3.5.1 VOC reduction

The results obtained here were quite different from those of our first office study, with respect to reduction of TVOCs. The species used were the same, and office sizes were in the same range as in the previous project. The reason for the differences may be because the plant numbers used in the current project were (deliberately) fewer than in treatments used in the first project, and were therefore insufficient to bring about significant reductions in these two classes of contaminant. However, this seems unlikely to be the case, as the ambient TVOC levels were clearly far lower in the current study, and this is most likely to be the cause of the difference. The results of our laboratory trials with three species, mentioned above (Burchett *et al*., 2009), showed efficient VOC removal and no differences in removal rates between plants in 200 mm and 300mm pots, suggesting it is more likely that what was being measured here was the result of more efficient A/C systems, which better decontaminate the indoor air. This is good news for occupants in such buildings, but comes at considerable energy costs. We cannot conclusively state whether the smaller numbers of plants tested here would be adequate to substantially improve office IAQ with respect to TVOCs. However, the results of one of our recent laboratory studies, where the effects of varying numbers of plants on benzene bioremediation was tested (Burchett *et al*. 2009), indicated that there is a considerable increase in removal between one and two plants, but a smaller difference between two and three plants. We are therefore confident that at most two plants will be sufficient to provide VOC air cleaning capability similar to that of the three plants tested in our first office study.

3.5.2 CO_2 reduction

The results concerning the effects of plants on CO_2 removal were again much weaker than in our first office study. However, it is universally recognised that, given adequate lighting green plants photosynthesise, absorbing CO_2 and reciprocally emitting O_2. ‘Shade’ plants achieve effective photosynthesis at very low light levels compared with crop and other ‘high light’ plants (Givnish 1988) and, as mentioned earlier, our first field study showed statistically significant reductions in CO_2 levels in offices with plants.

For urban environmental sustainability to be achieved, indoor plant species can and should be developed to play a significant role in reducing indoor CO_2 levels, reducing mechanical ventilation rates, or helping to keep them below the trigger point at which extra ventilation by A/C systems must switch in. TVOC levels would be reduced by the potted-plant microcosm at the same time. However, no systematic research has been conducted on the photosynthetic capacities of indoor species. The lighting requirements of indoor plants (in the total potted-plant microcosm, the potting-mix contents of which also respire in light or dark) must be established first. In laboratory studies recently reported to HAL (Burchett *et al.,* 2009) we have profiled the light-response curves of CO_2 uptake in two species, *Spathiphyllum* ‘Petite and *Epipremnum aureum* (Pothos), as part of a basic study into the lighting requirements of

indoor plant species. We plan to extend this research with different test species, and a variety of plant growth media.

3.6 Significance to industry

Both our field and laboratory studies have clearly shown that indoor plants have the capacity to reduce indoor air pollution from VOCs and excess CO_2. There are concerns in Australia in regard to increasing global CO_2 levels, urban air pollution, and the need for 'green technology' in building design and maintenance, to advance the goal of 'sustainable urban communities' (House of Representatives, 2004). Meanwhile, placing indoor species in accordance with their stated shade tolerances will optimise CO_2 reduction benefits that can be obtained from the plants. It is also timely that the horticultural development of indoor plants as standard installations in city building for air pollution reduction and refreshment and energy conservation be undertaken, including lighting technology and design where appropriate.

Figure 5. Participants became very attached to their plants.

4. Does plant presence affect mould spore loads in office air?

4.1 Background

As outlined above, there is a considerable international body of evidence on the direct beneficial effects of indoor plants on human health and wellbeing (eg., Lohr *et al*., 2000; Bergs, 2002; Fjeld, 2002; Park et *al*., 2002; Bringslimark *et al*., 2007). However, several authors, though their conclusions were not justified by the evidence they adduced, have raised the possibility that indoor plants could be a significant contributor to fungal respiratory disease in extremely immunocompromised patients, resulting from infection, by the mould *Aspergillus fumigatus* in particular (Staib *et al*., 1978a and b; Summerbell *et al*., 1989; Hedayati *et al.,* 2004). The natural habitat of *A. fumigatus* is soil, where it decomposes dead organic matter, but it is also prevalent in buildings where moisture/dampness is a problem. Its airborne spores are found around the world, both outdoors and inside, since it is one of the most cosmopolitan of mould species, though not the most abundant in terms of numbers. It is estimated from world data that all humans will inhale several hundred *A. fumigatus* and many other mould spores daily during normal activities, with no adverse effects in those with a functioning immune system (Debeaupuis *et al*., 1997; Latgé, 1999; Smith and Kagan, 2005). However, the spores of this species can cause Acute Bronchiopulmonary Aspergillosis (ABPA) and other diseases in severely immunocompromised individuals, such as in transplant, chemotherapy, or HIV/AIDS patients. In such individuals the immune system is insufficient to prevent many types of opportunist infection, and ABPA, if contracted, then has a high mortality rate (over 40%) (Latgé, 1999; Salvin, 2002; Terr, 2004; Smith and Kagan, 2005).

The several researchers referred to above concluded from this situation that indoor plants represent an unacceptable hazard to building occupants, especially to the immunocompromised and vulnerable, and that therefore indoor plants should never be used (Staib *et al*., 1978a and b; Summerbell *et al*., 1989; Hedayati *et al*., 2004). However, there is no evidence that indoor potted-plants have in fact been involved in any reported cases of the disease, and there is also debate as to where most ABPA victims contract their infection—whether it is in hospital (ie a 'nosocomial' illness) or 'community-acquired', ie, environmentally acquired (Warris and Verweij, 2007). The main demonstrated sources of *Aspergillus* spores in indoor air are damp building materials (Gravesen *et al*., 1999; Terr, 2004), damp carpets and furnishings (lounges, mattresses), and sometimes water supplies (Gerson *et al*., 1994; Anaissie *et al*., 2001, 2002; Alberti *et al*., 2001; Smith and Kagan, 2005). As Nieminen *et al.* (2002) put it: "*A. fumigatus* belongs to a group of indicator organisms typical of moisture-damaged buildings". Extra dust clouds from nearby demolitions of damp-affected buildings have also been associated with hospital outbreaks of ABPA (Horner, 2006).

4.2 Aim

Research was needed to bridge the gap in understanding of the epidemiology of ABPA, in particular examining the possible role of indoor plants as a source of mould infection. We therefore undertook a preliminary, first-ever study designed to test directly any influence of plant presence on indoor airborne mould spore counts or types. The experimental aims of the study were to investigate whether the presence of pot-plants in offices:

- affects the species composition of airborne mould spores;
- increases mould spore loads (counts);
- contributes to an increase in the incidence of *A fumigatus* or other species of this genus; and
- investigate indoor/outdoor ratios and species composition of mould spore loads.

4.3 Methods

4.3.1 Treatments and sampling

Mould spore sampling was conducted twice in Round 1 and in Round 2 of the office study (total 244 samples), samples being taken at the same times as other air quality variables were being sampled; and also from outdoors, near the A/C inlets of the two buildings tested.

4.3.2 Sampling methods

A Reuter Centrifugal Air Sampler (RCS) (impeller type) was used, fitted with strips of agar gel containing Sabouraud's dextrose, fungal-selective growth medium. Single samples of 80 L of air were taken from every office in each sampling, and a set of four replicate 20 L samples from near each of two A/C inlets for external air samplings. The agar strips were then incubated at office temperature (23^{o}C) in the dark for 7-20 days for mould colonies to develop, and then were stored at 2-4^{o}C until they could be identified.

4.3.3 Counting and identification

For each strip, the number of colony-forming units (cfu) was first scored, and their appearance described. An adhesive tape 'lift' was then taken from the strip and stained with lactophenol cotton-blue, a fungal-specific stain. The tape was then transferred to a slide and examined under the microscope for identification, using a range of keys (Klich and Pitt, 1988; Ellis, 1994; Dugan, 2006; Ellis *et al*., 2007; Univ. Adelaide, 2008-10; DoctorFungus Corp., 2008-10). Identification was generally made to genus level, but to species for any type of *Aspergillus* present. Yeast types, also observed, were described and counted but not otherwise identified taxonomically.

4.3.4 Data analysis

The average number of all types of fungi obtained from office air was compared across plant and control treatment groups, using a general linear model, repeated measures analysis of variance (SPSS v 17.0.0, SPSS Inc. 2008). Data were log-transformed before analysis to improve homogeneity of variance. The ANOVA was followed with a Dunnett's two-sided *post hoc* test to compare spore numbers between plant treatment groups and the control samples.

4.4 Results

A total of 51 mould types, plus 11 yeasts, were identified among the 55 offices over the four samplings (Table 3). The most prevalent mould types were species of *Cladosporium*, *Penicillium*, *Alternaria* and *Rhizopus*, which are among the most common of genera world-wide, and regarded as generally harmless. There were also, as commonly found in mould spore sampling, some 25 types that were unidentifiable because, although their hyphal masses were distinguishable from one another they did not produce fruiting bodies, which are essential for taxonomic identification. It can be seen from Table 3 that *A fumigatus* was not

found in any sampling, and that any of the other six *Aspergillus* species detected were found extremely rarely, values ranging from 0 to 5 among totals of 100 to 200 cfu/80 L for the sampling run as a whole. As expected, there were variations in counts among sampling runs (range 26 – 43 cfu m^{-3}).

Table 3. Mould species and spore counts from four samplings in 55 offices (all plant treatments and control offices), and three samplings externally near A/C inlets.

Round/ Types	**Round 1, 1st *Inside***	**Round 1, 2nd *Inside***	**Round 2, 1st *Inside***	**Round 2, 2nd Inside**		**Round 1, 2nd *Outside***	**Round 2, 1st *Outside***	**Round 2, 2nd *Outside***
DATE	Apr	May	Aug	Sept		May	Aug	Sept
Acremonium sp.			4	1		1	1	
Actinomycetes	2	2	1	1				
Alternaria sp.	1	21	5	14		8		4
Arthrobotrys 2 spp.			1				1	
Aspergillus candidus							1	
Aspergillus niger	1	2	3	4		2		1
Aspergillus nivius			1					
Aspergillus ochraeceous	1		1	2				
Aspergillus parasiticus		1						
Aspergillus versicolor			1					
Aureobasidium sp.	7	2	1	5			1	1
Bipolaris sp.	2							
Botrytis sp.			1					
Chaetomium sp.				1				
Cladophialophora sp.		2	1	7		1		
Cladosporium 5spp.	14	46	31	36		17	1	4
Curvularia sp.	1		1					
Epicoccum sp.	3	8	23	10				1
Fusarium sp.	2		1				1	
Geotricitum sp.	2							
Gymnascella hyalinospora			3				1	
Malbranchea 2 spp.		10	5	3		3		1
Mucor sp.		1	1					
Nigrospora sp.	1	1				1		
Candida	1							
Oidiodendron sp.	1							
Penicillium 4 spp.	8	19	21	7		3	1	
Pithomyces sp.	3	8	1	8		4		1
Rhizopus stolonifer	10	6	10	6				
Rhodotorula	1							
Scopulariopsis 2 spp.		5	5					
Scytalidium 5 spp.	2	10	17	5		1	2	
Trichosporum	1							
Ulocladium sp	1							
Wallemia 2 spp.		2	11	4		4	2	
Unidentifiable	27	5	14	3		1	4	
Yeasts (11 types)	23	17	21	13		2	5	4

Figure 6 presents the average mould spore loads (cfu m^{-3}) for each of the five treatments (four with plants, plus control offices), and matching outside air samples. The overall indoor/outdoor ratio was 1:20; ie, the outdoor load was 20 times higher than that indoors. The results of the analysis for the indoor treatment groups are shown in Table 4. There were no significant differences among any of the treatment groups, nor between the two sampling Rounds. Although these are preliminary data only, it appears that the presence of plants has no detectable effect on the air-borne mould loads in the buildings sampled. The outdoor spore load was higher in winter than at either of the two spring samplings (Table 3, Figure 6). Species diversity (Table 3) as scored by the RCS instrument used is generally lower than with some other mould sampling systems (Tavora *et al*. 2003). But this one is portable and the only practicable method for quantitative comparisons among treatments and sampling occasions. In addition, the equipment also captures *Aspergillus* spores with an efficiency equal to that of most other systems (Tavora *et al*. 2003).

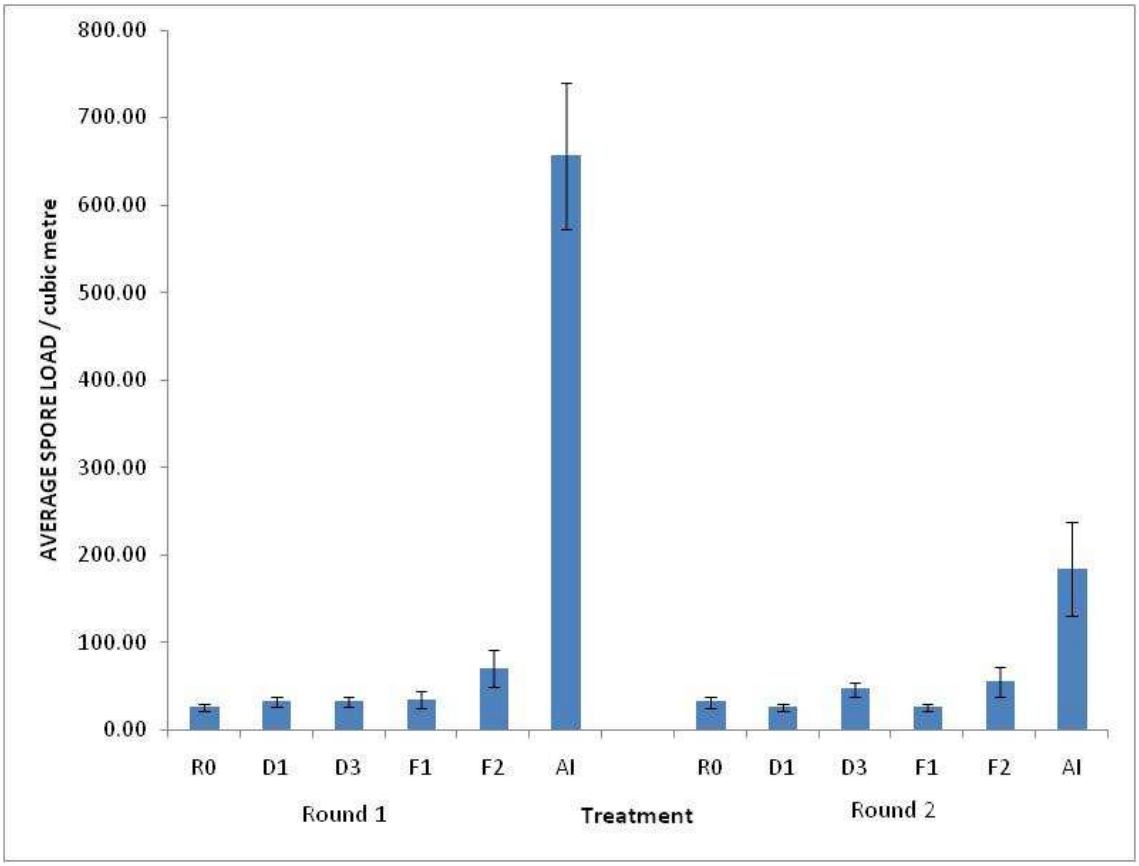

Figure 6. Average mould spore numbers (cfu m^{-3}) in air of offices among five treatments, plus outside air (Code: R0: reference/control – no plants; D1 and D3: 1 or 3 desk plants respectively; F1 and F2: 1 or 2 floor plants respectively; AI: outside air (samples taken near Air Intakes for A/C system). Values are means ± SE, N=11.

Table 4. Results of repeated-measures analysis of variance comparing average spore numbers in offices among different treatment groups (note: p >>0.05).

Treatment	p
Sampling run	0.782
Treatment	0.111
Run x Treatment	0.933

4.5 Discussion

The number of species, and the most common types of indoor mould species found in this study, are similar to those reported in overseas studies (Beguin and Nolard, 1994; Górny and Dutkiewicz, 2002; Choo *et al*., 2008). The species *A fumigatus*, identified as the commonest causative agent of ABPA, was not found, and the frequency of spores from other species of the genus was extremely low (Table 3). The indoor spore counts were also low (Table 3, Figure 6), and compare very favourably with the WHO guideline for maximum indoor airborne spore loads of phylloplane (leaf-surface associated) fungi, of 500 cfu m^{-3} (cited in Environment Australia, 2001). Also, no statistically significant differences in spore counts between planted and unplanted offices or among plant treatment groups (Table 5). The indoor/outdoor ratios (avr. 1:4) were also as expected, since A/C systems are designed to filter out particulates from the entering air (though not gaseous pollutants). The air in these two buildings, in offices with or without plants, had less than one twentieth the number of fungal spores in the surrounding city air.

In North America and Europe chronic building dampness problems are severe, and are apparently much more prevalent than in basically warm, dry New South Wales, Australia. The relationship between general mould-related illness (including asthma, coughing etc.) and water-damaged or under-ventilated, damp air-conditioned buildings, has been extensively researched in the northern hemisphere (eg Fisk, 1999; Park *et al*., 2004). However, no direct relationship between potted-plants and either air-borne mould spore loads or mould-related illness has ever been shown, and the current study found that potted-plants make no significant difference to mould spore counts or types in the two buildings investigated. This research is continuing; in future studies we aim to investigate the mould species present in the potting mixes of the two species used in this office study, to elucidate similarities or differences between their fungal communities and the distribution of airborne mould types in the two buildings sampled.

4.6 Significance to industry

From this preliminary study there appear to be no effects of indoor potted-plants on the airborne mould species composition or spore loads in the two office buildings tested, in the city of Sydney. The loads were found to be very low in comparison with internationally recommended maximum indoor total concentrations, and about one twentieth of those in the air outside the buildings. This information can be made available to clients with some confidence if queries are raised on the matter.

5. Do office plants improve the psychological status of occupants?

5.1 Background

There is an increasing body of evidence on the direct health and psychological wellbeing benefits of indoor plants. For example, a Swedish study (Rappe and Linden, 2002) using surveys of staff in 10 nursing homes for patients with dementia, reported beneficial impacts of indoor plants, including better-stimulated senses and more positive emotional states among residents. A USA Medical Group Management Association newsletter (Gilhooley and Rice, 2002) reported that the literature showed that "Plants…are likely to enhance patients' perceptions of their surroundings upon entering a health care facility - as an interior viewed as welcoming and relaxing helps accelerate the healing process". A British study (Smith and Pitt, 2009) found from a questionnaire survey that "…occupants of planted offices feel more comfortable, more productive, healthier and more creative, and feel less pressure than occupants in unplanted offices". A Dutch experiment by Dijkstra *et al*. (2008), which involved showing photos of hospital rooms to participants, and afterwards measuring their stress levels, found that those shown rooms with plants recorded less stress than those shown rooms with a painting on the wall. Kaplan and Kaplan (1990, 1995) researching the psychological benefits of greenery in building occupants' surroundings, concluded plants act as a restorative environment by providing four qualities: attracting effortless attention; giving a feeling of momentary 'awayness' from normal preoccupations; extending 'scope' - a reminder of being part of a wider whole; and 'flowing with one's inclinations' (a brief intermission from 'busy thoughts'). Without necessarily consciously noticing the plant material, such glances relieve 'attention fatigue', resetting a feeling of calm.

5.2 Aim

The purpose of this investigation was to examine the extent to which plants in offices can significantly improve occupants' mood states and create a positive sense of wellbeing. This component of the project was conducted under the guidance and collaboration of Professor Ashley Craig, formerly Professor of Behavioural Sciences at UTS, now a Professor in the Rehabilitation Studies Unit, Northern Clinical School, Faculty of Medicine, University of Sydney. This is the first such study undertaken using standard psychological survey instruments with internationally demonstrated reliability and validity, to assess the effects of office plants on occupants' mood states and wellbeing.

5.3 Method and assessments

5.3.1 Approach

The study involved a group cohort design involving repeated measures over time. One baseline survey questionnaire was administered at the commencement of the office project to provide a demographic profile and general assessment of health and stress among participants. As well, two questionnaires of mood states were each administered twice: once at the commencement of Round 1, and again in the final week of Round 2, to evaluate any

changes in mood associated with plant presence. To ensure confidentiality and validity of assessment, participants were asked to complete the questionnaires and place them in coded, sealed envelopes, on their desks or near a plant, for pick-up the following week when air sampling was to be conducted. Forty of the 55 participants completed all measures.

5.3.2 Lifestyle Appraisal Questionnaire (LAQ)

The LAQ was administered once, at the commencement of Round 1. The instrument has been shown to be reliable and valid, and was developed by Craig *et al.* (1996) as a means of determining health risk status and perceived levels of stress, in the general population as well as in groups with major health problems (eg cancer, coronary heart disease, hypertension). Items in the LAQ are designed to assess 'lifestyle' from a multifactorial perspective. One series of questions relates to possible longer-term lifestyle health risk factors (Part I), for instance prevalence of alcohol use, cigarette smoking behaviour, whether the participant is overweight, exercise behaviour, family history of disease, and so on, while questions in Part II are aimed to assess the participant's perceived pressures and life demands.

5.3.3 Profile of Mood States (POMS)

This instrument was administered twice, before and after plant placements. It has been used over a span of more than 30 years and has been shown to have acceptable reliability and validity (McNair *et al*., 2005). It is available in several versions and languages, and has been found to be a useful instrument for measuring factors affecting psychological/ mood states in a number of situations of health, illness or psychopathology (eg., Wells *et al*, 1998; Dritsas *et al*., 2006; Craig *et al.,* 2008). The POMS is composed of six sub-tests, plus a composite measure from the totals. In this project, the six sub-tests were analysed, including tension (anxiety), depressive mood, feelings of anger, levels of fatigue, levels of confusion, and feelings of vigour, plus composite total scores. The POMS was administered first as the plants were placed in the offices, and secondly after about three months of plant presence, as well as in the no-plant control group. Participants were asked to respond to 65 items, on a scale of 0 – 4, with 0 being 'not at all like me' to 'extremely like me', with adjective descriptors such as 'Friendly', 'Hopeless', 'Energetic', 'Sympathetic', etc.

5.3.4 General Health Questionnaire (GHQ)

This survey instrument was also administered twice, before and after plant placements. The GHQ was developed by David Goldberg in 1972, and has been shown to be reliable and valid since that time (eg, Goldberg *et al*., 1996). It was designed as a psychiatric screen (Dale *et al*., 2009; Sweeting *et al*., 2009). In this project the GHQ-30 was used, a 'short form', 30-question version without items relating to physical illness. The questionnaire assesses the participant's recent or present feelings, for instance the ability to concentrate, sleep, make decisions. It uses a four-point scale: 'better than usual', 'same as usual', 'less than usual' and 'much less than usual', the last two responses indicating increasing stress, and being summed for final scores. The GHQ was administered at the same times as the POMS questionnaire.

5.4 Results

5.4.1 Lifestyle appraisal of participant group

The LAQ results (Tables 5 and 6) confirm that the participants were a relatively healthy group, both physically and mentally. They generally had LAQ Part I scores of less than 20, suggesting they were within the normal range of health risks as measured by this instrument, while the Part II scores, relating to perceived current stresses or life demands, were also within the normal range (Craig *et al*., 1996).

Table 5. Part 1 LAQ scores (from questions relating to general lifestyle health risk factors) (Means ± SE; N = number in that group).

Part I	Group	Mean	SE	N
Sex	Female	16.67	1.95	18
	Male	13.95	1.39	22
Age group	<40	11.22	0.89	9
	40-50	13.42	1.62	12
	50-60	20.33	2.44	12
	>60	14.43	3.22	7
Marital status	Defacto	13.43	1.70	7
	Married	15.58	1.42	24
	Separated	11.00	2.83	5
	Single	14.67	0.88	3
	Widowed	40.00	-	1
Employment	Academic	16.38	1.62	26
	Administration	14.50	1.65	6
	Lab management	12.00	2.92	5
	Researcher	11.33	2.40	3
Dwelling	Alone	25.33	7.54	3
	Couple+children	14.61	1.72	18
	Couple	14.19	1.49	16
	Share/Group	13.67	1.20	3

Table 6. Part II LAQ scores (from questions relating to current feelings of stress).
(Means ± SE; N = number in that group).

Part II	Group	Mean	SE	N
Sex	Female	23.22	2.89	18
	Male	23.14	1.96	22
Age group	<40	14.33	1.41	9
	40-50	24.67	1.78	12
	50-60	28.75	3.20	12
	>60	22.43	5.58	7
Marital status	Defacto	24.86	4.95	7
	Married	21.79	2.09	24
	Separated	23.00	4.09	5
	Single	25.00	5.86	3
	Widowed	40.00	-	1
Employment	Academic	25.31	2.01	26
	Administration	24.17	5.17	6
	Lab management	15.40	3.23	5
	Researcher	15.67	3.93	3
Dwelling	Alone	37.33	1.33	3
	Couple+children	24.28	2.37	18
	Couple	20.38	2.65	16
	Share/Group	17.33	2.96	3

5.4.2 Changes in POMS scores with plant presence

The results for mean total scores among the four plant treatments and control group, on the two rounds of POMS questionnaires are shown in Figure 7, and a summary of analyses for the six POMS sub-categories, for overall plant presence or absence, is presented in Table 7. The Table shows significant reductions were found with plant presence in all POMS scores across the five negative mood states, as well as in the POMS total score. There was also a non-significant trend for vitality (‘vigour’) to increase in the one desk and one floor plant conditions, although there were no significant differences found between these two groups. In contrast, there were trends in the control group of reduction in vigour and increase in total negative feelings, though again, not statistically significant.

Table 7 also shows percent change over time as a function of plant versus no plants for all the POMS measures. Inspection of the Table makes it clear that the presence of plants was associated with greater reductions on negative mood compared to the no-plant controls.

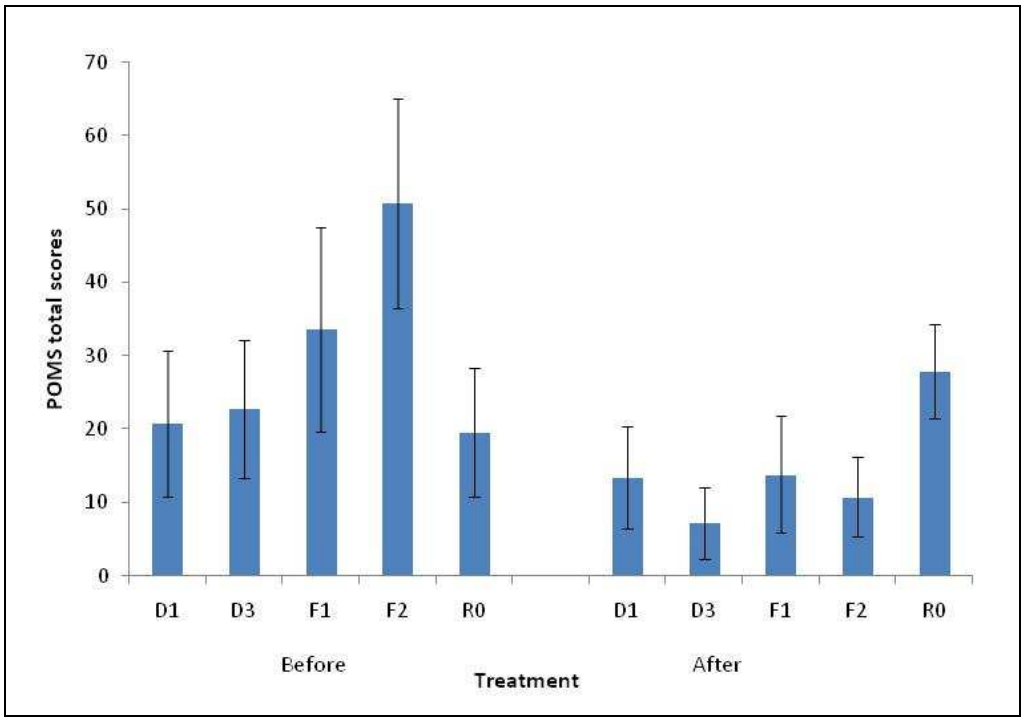

Figure 7. Differences in POMS score in the five treatment groups before and after plant placement. (Code: D1 and D3: 1 or 3 desk plants respectively; F1 and F2: 1 or 2 floor plants respectively; R0: control – no plants. Data are means ± SE, n = 11).

Table 7. Summary of scores for POMS, sub-categories and totals, for participants before and after plant presence placement, plus control group. Code: SD = significant difference ($p \leq 0.05$); NSD = no significant difference ($p > 0.05$). (N with plants = 31; N with no plants = 9)

Sub-category/ Score difference plants	Means (± SE) Before plants	Means (± SE) After plants	% Difference	Significance/ Probability*
With plants				
Tension/Anxiety	9.5 ± 0.9	6.0 ± 0.6	37% reduction	0.027*
Depression/Dejection	9.5 ± 1.5	4.0 ± 0.7	58% reduction	0.006**
Anger/Hostility	9.9 ± 1.2	5.5 ± 1.0	44% reduction	0.006**
Fatigue	10.2 ± 1.0	6.3 ± 0.7	38% reduction	0.006*
Confusion	7.7 ± 0.6	5.4 ± 0.5	30% reduction	0.022*
Vigour	15.4 ± 0.7	16.1 ± 0.9	4.5% increase	0.520
Total	31.1 ± 4.8	11.1 ± 3.1	64% reduction	0.003**
No plants				
Tension/Anxiety	9.4 ± 1.9	9.2 ± 1.2	2% reduction	0.850
Depression/Dejection	10.5 ± 3.2	7.1 ± 1.5	32% reduction	0.461
Anger/Hostility	9.6 ± 2.5	8.4 ± 2.2	12% reduction	0.631
Fatigue	9.3 ± 2.0	8.3 ± 1.4	11% reduction	0.504
Confusion	7.9 ± 1.2	7.6 ± 1.1	4% reduction	0.983
Vigour	17.7 ± 1.4	12.8 ± 1.9	28% reduction	0.186
Total	20.0 ± 8.8	27.9 ± 6.4	42% increase	0.445

*Difference is significant; **Difference is highly significant; no asterisk – difference not significant.

5.4.3 Changes in GHQ scores with plant presence

The results for mean total scores for "more stressed" plus "very stressed" responses among the four plant treatment and reference groups, on the two rounds of GHQ questionnaires are shown in Figure 8. Table 8 presents the summary of results for the GHQ measure, which assesses levels of general mental health, such as feelings of being stressed, for the pre- and post- measures for the two groups. The results are similar in direction to those found for the POMS questionnaire. That is – the presence of plants was again associated with significant improvements (reductions) in feelings of stress or anxiety. The presence of plants resulted in a 50% reduction in negative mental health as measured by this instrument. In contrast, a 20% increase in GHQ scores was recorded in the group with no plants, although because of the variability in the group, (as indicated by the standard error, SE), this trend was not statistically significant at $p \leq 0.05$.

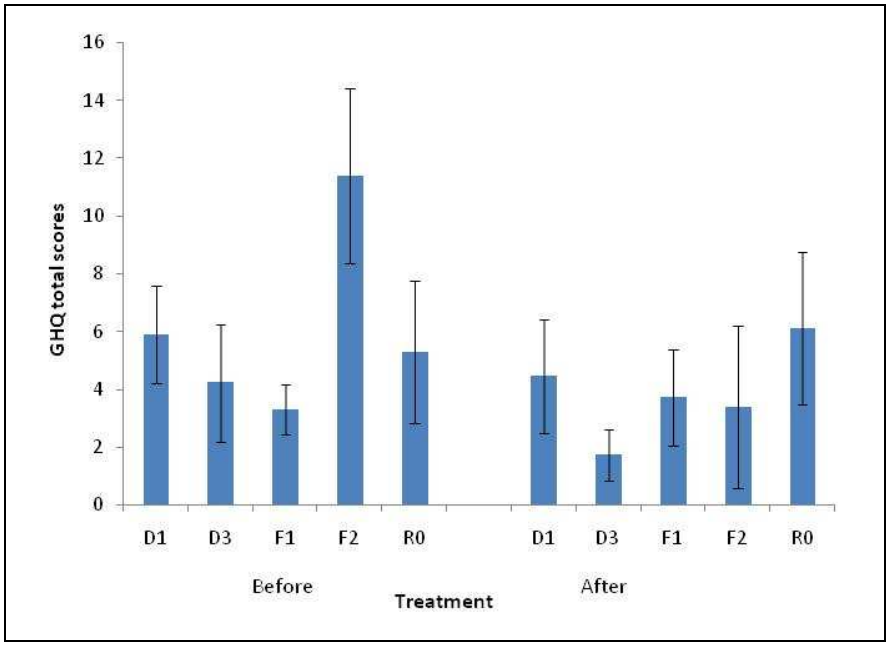

Figure 8. Differences in total GHQ scores in the five treatment groups before and after plant placement. (Code: D1 and D3: 1 or 3 desk plants respectively; F1 and F2: 1 or 2 floor plants respectively; R0: reference/control – no plants. Data are means ± SE, n = 11).

Table 8. Summary of GHQ scores for participants before and after plant placement, plus no-plant control group. (N with plants = 31; N with no plants = 9)

Group/ Score	Means (± SE) Before plants	Means (± SE) After plants	% Difference	Significance/ Probability*
Plant presence	6.3 ± 0.8	3.2 ± 0.8	50% reduction	0.003**
No plants	5.1 ± 1.5	6.1 ± 1.7	20% increase	0.684

**Difference highly significant.

5.5 Discussion

The staff participants in this study were (as would be hoped), a group of people of normal physical and mental health, as indicated by the LAQ scores. Nevertheless, the presence of plants was associated with significant reductions in negative mood states, which are considered to reduce worker satisfaction and productivity. These included psychological states of anxiety (POMS-Tension and GHQ), feeling sad and depressive, feeling fatigued and confused, and feelings of anger. The extent of change in these psychological states was considerable. Reductions ranged from 65% and 50% (on POMS Total score and GHQ respectively), down to 30% for confusion. Inspection of the no-plant control scores showed no significant change over time, although an increase in stress of 20% was recorded for this group with the GHQ. The results demonstrated that benefits can be gained from placing a plant, either on the desk or floor, in the office. In this study no additional psychological benefit was found from having more than one plant in the office, ie. just one was enough to make the difference (though more might be more aesthetically appealing). Over the same period, recorded scores for negative feelings in the control groups increased.

Limitations of this study included a poor return of completed assessments from the no-plant (control) participants. This low return limited the ability of the study to comment further on the psychological benefits of plants in the workplace. Nevertheless, the POMS Total scores and GHQ scores were found to be significantly changed in a positive direction. The POMS total is a composite measure of negative mood, while the GHQ is a general screen for mental health. To have achieved psychological improvements in these two composite measures suggests the participants are happier and more satisfied people in the workplace when a plant is placed in their presence (at least over a 3-month test period). The social environment of the workplace with plants can therefore be assumed to be of benefit, and more conducive to health and wellbeing. Further research is needed to explore the dynamics of just how these beneficial changes occur, however, this study has demonstrated the psychological, social and mental health value of strategically placing plants in the office.

5.6 Significance to industry

The study found significant reductions (by 30 – 60%) in negative mood states and feelings of stress among participants with plants in their offices, whereas such scores did not decline among participants with no plants, rather there were trends over the period for increased feelings of stress (by 20 to 40%) in the no-plant group. The results add further evidence on the benefits of indoor plants for occupant wellbeing, and can be confidently marketed for such benefits, not only in office buildings but in almost any other type of building as well.

6. Discussion

6.1 Summary overview

The laboratory studies of VOC removal in three previously untried species bring to twelve the species tested in this laboratory (for full list see Appendix). The results further confirm the abundant capacity of the indoor plant microcosm to remove VOCs and hence improve indoor air quality, and the likelihood that most indoor species would have a similar capacity.

This office study, in contrast to the first such study conducted at UTS, did not show significant reductions in either total VOC loads, or CO_2 concentrations, although consistent trends were recorded with plant presence. The findings appear to be the result of more efficient A/C systems in the two buildings sampled, both of which were much newer than those in our previous study. However, the earlier results, together with our laboratory studies, show clearly that pot-plants can contribute to cleansing indoor air by reducing both these classes of urban pollutants, which are almost always higher indoors than outside. Overall the results of the two office studies, taken together, clearly point to the need for strategic R&D to be undertaken on CO_2 removal capacities among indoor plant species with different shade tolerances, a matter on which there has been no systematic research published to date. Their use could then be optimised by the provision of adequate lighting for effective net photosynthesis, and they could be utilised routinely as a means of significantly reducing indoor CO_2 levels, hence reducing the AC energy loads on city buildings.

While the many benefits of indoor plants to building occupants have been demonstrated in an increasing number of international studies, including those from UTS, doubts have been raised concerning their potential as a source of airborne pathogenic mould spores. But the results of the preliminary study conducted here do not support this hypothesis. No statistically significant differences were detected of indoor plant presence on either airborne mould species composition or spore loads, in two buildings tested. Furthermore, the spore loads were found to be very low in comparison with internationally recommended maximum total concentrations, and far lower than those in the outside air.

The findings on the effects of plant presence on the psychological status of building occupants are also very encouraging. The significant reductions in negative mood states among participants with planted offices add new evidence as to the direct benefits of indoor plants to the wellbeing of building occupants. These are the first such findings related to indoor plant benefits from research conducted in Australia, and the first resulting from a study utilising standard psychological instruments that have been shown internationally to be reliable and valid across sub-populations ranging greatly in health or illness, physical and mental.

Overall, the findings add to the body of evidence that the potted-plant microcosm can significantly improve many aspects of indoor environmental quality (IEQ), providing cleaner air and lower stress levels among occupants. Targeted horticultural technology can now be developed so as to optimise the use of indoor plants to complement any engineering measures to improve IEQ in any type of building.

6.2 Recommendations for future R & D

6.2.1 VOC reduction

i. From the laboratory-based experimental evidence now obtained with 12 commonly used species, it appears likely that most indoor plants would have similar VOC removal capacity. However, as outlined in a recent report to HAL (Burchett *et al*., 2009), there remain several more plant groups to be investigated for this air-cleansing capacity, such as Bromeliads, Crassulaceae, Cacti, and woody dicots. These species have a range of different root/shoot ratios and general metabolic styles, which could result in different root-zone microbial communities, which could in turn affect VOC uptake rates.

ii. The office study findings provide supporting evidence for the potential for efficient VOC uptake by indoor plants. There is now a need for research comparing VOC reduction in plants grown in conventional potting mixtures with those grown in various hydroculture media. There is a move in the northern hemisphere in favour of hydroculture of indoor plants, on inert inorganic media fertilised with pelletised or liquid growth media. Claimed advantages are that such media are cleaner; odour-free and pest-free; need watering only at 3-4 week intervals and fertilising two to three times per year. There is no systematic scientific literature available on these claims, and none on the effects of different potting media on VOC removal capacities of indoor plants

6.2.2 CO_2 reduction

On the evidence of our past and current studies, and the depth of world knowledge on plant photosynthetic function, it is clear that indoor plants have the potential to achieve considerable reductions in A/C power consumption of city buildings, by reducing rates of extra ventilation to lower excess CO_2 levels. However, before this can be accomplished further baseline research is needed, to elucidate the photosynthetic characteristics of indoor species, including:

i. Profiling light responses in a range of species so as to find the optimum intensity range for net photosynthesis for each;

ii. Establishing responses also to different CO_2 concentrations, so as to identify species most suitablefor use in reducing building ventilation loads.

The information could be used to recommend the most suitable species/varieties for various lighting conditions, and would provide a basis for collaboration with lighting and design experts on how to achieve maximum benefit from interior plantscapes of the future.

6.2.3 Effects of pot-plants on mould spore loads of indoor air

When addressing industry meetings over the last two years concerned with the benefits of indoor plants, both in Australia and overseas, members of the UTS group have been challenged by critics either hostile to the use of plants altogether, or querying their health risks. The study reported here is the first conducted to examine the effects of indoor plants on airborne mould spore loads and types. The results showed no significant effects of indoor potted-plants on either mould spore loads or species composition, in the two Sydney city office buildings sampled. The spore loads were also very low in comparison with internationally recommended maximum indoor concentrations, and with outdoor aerial loads.

More extensive studies are needed to elucidate:

i. Mould species present in the potting mixes of commonly used indoor plants, to establish similarities or differences between their fungal complements and the airborne mould types we found in air inside and outside Sydney buildings;

ii. The extent to which finishes, eg crushed glass or coconut fibre on the surface of the potting mix could in practice significantly reduce numbers and/or types of spores that might be dispersed from the surfaces;

iii. Differences in airborne mould species consortia that might be found indoors/outdoors in more tropical (eg Brisbane) and cooler (eg Hobart) climates, which are of course also associated with different potential urban sources of moulds.

6.2.4 Occupant wellbeing

The results of the 'before-and-after' psychological survey measurements were very pleasing – further confirmation of the direct benefits of plants in the workspace. There were limitations to the findings because of low replicate numbers in the various treatments, and especially the smaller number of returns from the 'no-plant' control group (who, although weekly air sampling was conducted in their offices, appeared less engaged with the project than those with plants, which is in itself a finding from the project).

It would be valuable to conduct a much larger survey using the same internationally validated measurement instruments, in several city buildings, with some floors or areas with plant installations and some without, to explore whether different plant numbers or arrangements may have differential effectiveness in lifting mood states of occupants.. The plant-hire industry might be able to assist in identifying such buildings in which cooperation would be likely to available.

6.2.5 In summary

The major national environmental goal of Australia is that of producing sustainable urban communities (House of Representatives, 2004), satisfying the 'triple bottom line' of environmental, social and economic considerations. Indoor plants have the potential to contribute to that goal, since they can assist in attaining all of the objectives of that triple bottom line. However, in order for indoor plants to become standard installation elements of urban building (or 'facility') ecology, further targeted research is needed on a number of fronts.

6.3 Recommendations for Industry

6.3.1 Laboratory study -VOC removal

From ast and current studies, we have now laboratory-tested a total of 12 commonly used indoor plant species (see Appendix) for VOC removal capacity, and all show similar, strong VOC removal capacities, namely:

- When fully adapted ('induced') by exposure to a VOC, usually achieved by the third top-up dose, the potted-plant microcosm can consistently remove repeated doses within about 24 h;

- If the dose concentration is increased, the rate of removal rises in response to the challenge — there is plenty of spare capacity in the potted-plant microcosm;
- The microcosm can also remove very low, residual concentrations of VOCs, effectively to zero;
- The system works equally well for VOC removal in light or dark;
- VOC removal rate with 200 mm diameter pot-plants is equal to that of 300 mm plants, at concentrations encountered in indoor air;
- The main VOC removal agents are normal potting-mix bacteria, however the plant is also involved; if the plant is kept healthy, the symbiotic microcosm will be effective;
- The results indicate it is likely that any indoor plant species would show comparable VOC removal capacity, though work is continuing to test more types;
- This evidence suggests that the choice of species for use in VOC removal can also include aesthetic or design considerations, not just particular species.
-

6.3.2 Office field study – VOC and CO_2 reduction

- Our previous office study found that indoor plants maintained TVOC loads at very low levels (below 100 ppb), and –
- Reductions in CO_2 concentrations by 10% in an air-conditioned building and by 25% in a naturally ventilated building;
- However the current study, in two newer air-conditioned buildings, recorded only slight trends in VOC and CO_2 reduction. The results indicate that what was being measured this time was the efficiency of the air-conditioning systems; but—
- Indoor plants could be developed to maximise their CO_2 reduction capacities, to help lower the air-conditioning ventilation requirements of urban buildings, hence contributing to urban sustainability. (And they would lower VOC levels at the same time.)
- Considerably more research is needed to achieve this goal (see R&D Section above).
- Meanwhile, indoor plants can be placed to optimise their contribution – general principles apply — position them in accordance with their stated light/shade tolerances; and maximise their foliage area.

6.3.3 Effects of indoor plants on airborne mould spore loads?

Since mould-related illnesses in the northern hemisphere have been strongly linked with damp buildings, building materials, furnishings and carpets, it seems intrinsically unlikely that potted-plants, with comparatively very small pot surface areas, would be a significant cause of mould health problems. The results of this preliminary office study found no effects of indoor potted-plants on the airborne mould spore loads or species composition in two Sydney city office buildings sampled, and the spore loads were very low in comparison with internationally recommended maximum indoor concentrations, and with outdoor aerial loads. We aim to continue confirmatory research on this issue.

6.3.4 Psychological wellbeing

- The results of the psychological survey testing showed clear reductions in feelings of stress, anxiety, depression, anger, fatigue, confusion and overall negativity among participants with plants in their offices (by 30 – 60%), and one plant was enough to make the difference.
- In contrast, participants with no plants (control group) showed no significant changes over the three-month experimental period, but a trend was recorded towards increased feelings of stress (by 20%).
- This is the first such study of the effects of indoor plants on wellbeing conducted in Australia, and the first on this matter in the world utilising standard, internationally recognised psychological instruments that have been shown to be reliable and valid in sub-populations ranging across the spectrum of health and illness (physical and mental).
- The findings show that indoor plants can be marketed for their demonstrated benefits to staff wellbeing, which research shows are also associated with improved work performance.

7. Technology transfer

The UTS team have been and will continue to be actively involved in technology transfer of information derived from this research. We list activities we have undertaken in association with this project.

Talks/Seminars

We have made presentations on our indoor plant research at:

- 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. 2009)
- Meetings with NIPA Committee in Brisbane

We have also scheduled meetings with the HMA, Green Building Council, and Garden Clubs during 2010.

Industry publications

Contributions to newsletters of the National Interior Plantscape Association.

Conference presentations

Two team members (F Torpy and J Tarran) attended the 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation, - Sustainable Built Environment, in Sendai, Japan, October 2007, and presented a paper:

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.

M Burchett presented a paper at the HMAA annual Conference in Queensland, May 2008:

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

Peer-reviewed international journals

We are preparing the research material as a series of papers for submission to international scientific journals.

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Appendix

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; only dicot tested) (Fam. Araliaceae)
- *Spathiphyllum* 'Petite' (& 'Sweet Chico') (Peace Lily) (Fam. Araceae)
- *Spathiphyllum* 'Sensation'
- *Zamioculcas zamiifolia* (Zanzibar; ZZ) (Fam. Araceae)

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