ASSESSING THE AIR QUALITY REMEDIATION CAPACITY OF THE JUNGLEFY BREATHING WALL MODULAR PLANT WALL SYSTEM

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Key Research Highlights

- The efficiency of the Junglefy Breathing Wall active, modular green wall system to remove the air pollutants was tested
- Plant species selection trails indicated that *Epipremnum aureum*, *Chlorophytum cosmosum* and *Gibasis* sp. were the most efficient species in the modules for CO_2 reduction
- The lowest light required for net carbon dioxide for both *Chlorophytum* and *Epipremnum* is 2190 lux (50 □mol m^{-2} s^{-1} photosynthetically active photon flux)
- When light intensity was increased to 250 □mol m^{-2} s^{-1} (9781 lux) inside a test room, four modules removed substantial quantities of carbon dioxide, with up to 5.49 g removed per hour
- 20 modules containing *Chlorophytum* could balance the respiratory emissions of a full-time occupant
- Four modules with *Chlorophytum* could save between 0.227–0.456 kWh of energy use from reduced air conditioning costs
- Modules were tested for particulate matter removal efficiency. The modules rapidly removed all fractions of particles (fine [PM_{10}] and ultra-fine [$PM_{2.5}$]) from the atmosphere
- The modules were tested for sound attenuation. Sound recorded proximal to the modules in the pilot study indicated that a single module could reduce noise by 4.1 dBc relative to controls, with the modules facilitating a 41% lower noise reverberation than that of a hard surface
- Potential fungal and bacterial emissions from the green walls were also tested, with no significant health risks or increased bioaerosols detected

EXECUTIVE SUMMARY

With the growing need to find measures to control the growing worldwide morbidity rate associated with poor urban air quality, along with the accelerating requirements of reducing carbon emissions, there is a pressing need to find energy efficient means of improving the quality of indoor air. Many scientific studies have shown that indoor plants are capable of removing virtually all forms of air contaminant in indoor environments, whilst requiring little or no energy for their maintenance and growth. However, as the field of research develops, it is becoming clear that reasonable numbers of traditional potted plants will not have the capacity to adequately control some forms for air pollution, notable particulate matter and carbon dioxide. Consequently, in recent years, green wall technology has been proposed as a means of passively improving the capacity of botanical air cleaning methods.

Junglefy Pty Ltd have independently developed an active, modular green wall system — the Junglefy Breathing Wall (Breathing Wall) — that has the potential to accelerate the progress of horticultural means of air pollutant removal. The system consists of patterns of relatively small (0.25 m^2) composite modules containing 16 plants in the tested version, and include an axial impeller to pass indoor air across the plant growth substrate. The addition of ventilation, plus the modular nature of the system may have the potential to both increase the systems' effectiveness at reducing some air contaminants, as well as increasing its installation flexibility to as to allow increased light, through which the carbon dioxide removal potential can be increased. However ventilation also poses the potential risk of aspiration of dangerous microorganisms into indoor spaces.

We tested the biosafety and potential for the removal of a range of air pollutants of the system in a series of laboratory, office, sealed room and field trials.

The bioparticle emissions from the green walls were tested by comparing the number and diversity of fungal propagules in a vacant office with and without the modules present, and with the ventilation fans operational and off. We detected both no increase in the number of culturable fungi, and no significant change in the diversity of fungal types present, with levels in the room well below the World Health Organization recommended maximum levels for airborne fungi. Effluent air, substrate and drainage water were also tested for *Legionella* bacteria, which were found to be absent. From

these tests we can safely conclude that the modules should not present a significant health risk when used indoors, so long as they are well maintained to reasonably match the testing conditions.

The primary pollutants of concern in indoor spaces are carbon dioxide and particulate matter. We tested the specific capacity of seven common green wall plant species for the light levels at which they begin to photosynthesise, and remove carbon dioxide, identifying *Epipremnum aureum*, *Chlorophytum cosmosum* and *Gibasis* sp. as the most efficient species. When the former two species were tested in single-species module arrangements in small chamber trials, *Chlorophytum* was found to be the most effective remover of carbon dioxide, although both it and *Epipremnum* effectively removed carbon dioxide from the chamber air as long as the light supplied was greater than 2190 lux (50 □mol.m^{-2}.s^{-1} photosynthetically active photon flux). Surprisingly, ventilation fan operation increased the rate of carbon dioxide draw down, possibly due to increased leaf gas exchange rates.

Green walls were then tested in a 15.65 m^3 sealed test room. Once again, *Chlorophytum* outperformed *Epipremnum* in these trials, and fan operation increased the removal of carbon dioxide. Rates of carbon dioxide draw down were modest but effective at 50 □mol m^{-2} s^{-1}, however when light intensity was increased to 250 □mol.m^{-2} .s^{-1} (9781 lux), four modules were capable of removing substantial quantities of atmospheric carbon dioxide, with up to 5.49 g of carbon dioxide removed per hour. These are some of the highest photosynthetic carbon dioxide removal rates detected for indoor plants in the literature. It was estimated that 20 modules of *Chlorophytum* could balance the respiratory emissions of a full-time occupant, and four modules could save between 0.227–0.456 kWh of energy use from reduced air conditioning costs. These values could be increased if plant specific lighting could also perform some of the function of general room lighting.

Our carbon dioxide removal trials indicate that, given sufficient light, the Breathing Wall system has the capacity for very high efficiency removal of respiratory emissions in indoor applications.

Airborne particulate matter has been linked to a growing rate of morbidity and mortality worldwide, even when present at what are often considered low concentrations. The removal of particulate matter by indoor plants has received little study, thus we tested the particulate matter removal capacity of the Breathing Wall modules, with smoke produced from burning diesel fuel. Once corrected for natural sedimentation of the generated particulates, the modules rapidly removed both fine (PM_{10}) and ultra-fine ($PM_{2.5}$)

particles from chamber air, indicating clear potential as an effective system for the maintenance of low particulate levels indoors. Further experimentation is required to determine the capacity of the system to remove large quantities of particulate matter over a long period, and for direct comparison with existing mechanical filtration methods.

As an adjunct trial, we performed a test to determine whether the Breathing Wall system had noise attenuation qualities, finding that a single module could reduce a mixed-frequency sound signal by up to 4 dB relative to a flat screen. This test is indicative that the Breathing Wall system also has valuable properties in noise reduction, and is worthy of further trials.

The first stages of this research project have thus demonstrated the significant potential of the Breathing Wall system for indoor air quality remediation, with biosafety equivalent to, and pollutant removal capacity considerably greater than systems previously studied. Whilst testing is ongoing, at this point we can confidently claim that the Breathing Wall system will not produce harmful bioaerosol emissions if reasonably well maintained, will remove some indoor carbon dioxide if supplied with modest additional light or large quantities of carbon dioxide with higher light levels, and will maintain airborne particulate matter density at a low level. Further research will target additional air contaminants, before attempting to develop characteristics of the system so as to improve its performance. The Breathing Wall system is a genuine step forward in the performance of botanical air cleaning systems, and the extent to which it can be developed holds great promise.

The research encompassed by this report will be used to produce three manuscripts for submission to peer reviewed scientific journals.

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RATIONALE

Whilst it is well known that traditional indoor plants have the capacity to improve almost all aspects of indoor environmental quality, newer developments in horticultural technology, in particular green wall systems, have received far less research. The increased plant density, vertical alignment, exposure of the substrate to the atmosphere, and the potential for the addition of active atmospheric filtering through the addition of mechanical ventilation to the plant walls are all major departures from traditional pot plant arrangements, and are all likely to change the environmental impact of these systems from the effects identified in previous research on potted plants.

The development of the Junglefy Breathing Wall modular green wall system has presented a unique opportunity to test the capabilities of a cutting edge living infrastructure design. This report represents the initial stages of a research collaboration between Junglefy Pty Ltd and the Plants and Environmental Quality Research group at the University of Technology Sydney, the aim of which is to test and develop the Breathing Wall system to maximise its capacity to phytoremediate indoor air. The stages of this research documented here relate to testing the biosafety and basic air quality remediation capabilities of the system as it was developed, to provide baseline understanding of the performance of the existing system. Future research will determine whether modifications to the system can be made to maximise its air cleaning and energy reduction capabilities.

The ultimate aim of this research is to develop a plant-based system that can maintain a healthy, safe and energy efficient indoor environment, whilst concurrently allowing a major reduction in building energy use through reduced air conditioning and mechanical ventilation requirements, and thus building carbon footprint.

INTRODUCTION

About 80% of the residents of developed countries live in urbanised areas and spend on average 90% of their time indoors (Environment Australia 2003). The quest for sustainable urban communities must therefore include the achievement and maintenance of a healthy indoor environment. With growing development and population density, the quality of the air in cities is having a progressively greater influence on human health. Whilst air quality varies between geographical locations, there is no known 'safe' level of air pollution (Brunekreef and Holgate 2002), thus all initiatives to improve city air need prioritisation in urban development planning.

Urban air pollution has now become a world-wide health concern. Global health care and associated costs for developed countries associated with just the indoor component of air pollution have been estimated at nearly US$90 trillion (Hutton 2013). Health problems associated with indoor air pollution may have led to as many as 150,000 mortalities per year in the US alone (Guieyesse 2008). Indoor air quality has thus become a major international health issue (Brown 1997, WHO 2000, Environment Australia 2003), and has been designated as a significant health concern in both the USA and Europe (Morey et al 2001, Bernstein et al 2008).

Indoor air pollution is almost always more concentrated than outdoors — as outdoor-sourced contaminated air enters through natural or mechanical ventilation, it mixes with indoor-sourced pollutants, in particular higher carbon dioxide (CO_2) from human respiratory emissions (Norbäck and Nordström 2008), and also volatile organic compounds (VOCs) released from plastics and most other petrochemical-derived materials (Environment Australia 2003, Sakai et al 2004, Barro et al 2009; Chan et al 2009). Most modern buildings are tightly sealed against the external environment, with ventilation fully dependent on mechanical air conditioning systems which incorporate a small fresh air input into the ventilation cycle. This has further added to problems associated with indoor air pollution. There is thus an emerging need to develop means of maintaining a safe and healthy indoor atmosphere, whilst simultaneously reducing building energy use so as to lower carbon emissions.

Research over the past three decades has demonstrated that indoor plants can improve indoor air quality, as they are capable of reducing all types of urban air pollutants (e.g., Wood et al 2002, Tarran et al 2007, Irga et al 2013, Torpy et al 2013, Torpy et al 2014). There is also an international body of evidence that demonstrates direct beneficial effects of indoor plants on human health, psychological wellbeing, and work productivity (e.g. Lohr et al 2000; Bergs 2002, Fjeld 2002, Park et al 2002, Bringslimark et al 2007).

Currently, indoor environmental quality is maintained in most city buildings through the use of the mechanical ventilation component of heating, ventilation and air conditioning (HVAC) systems. Whilst these systems can be effective at maintaining a healthy indoor environment, they draw substantial quantities of electrical energy to do so. Replacing all or part of this energy with plant-based systems would be a major step in reducing city carbon footprints, thus contributing to global sustainability.

Module design

The project used Breathing Wall modules (Junglefy Pty Ltd, Sydney), which are designed for use in vertical plant-walls. The module's material construction is composed of recycled plastic, supplied with a growth medium high in coconut fibre content, supplemented with a liquid fertilizer and periodic watering supplied via channels at the top of each module, connected to a receiving trough at the base. The dimensions of each module are 500 mm^2 and ~100 mm deep, which holds 16 plants horizontally in circular compartments. Each module includes a small electric axial impeller which, when activated, provides a uniform flow of air up through the growth medium and past the plant leaves, at a rate of 3.5 m/s at full velocity (measured detached from the modules). All planted modules had been nursery grown for 8 months before being used in the trials. Further details of the Breathing Wall modules are protected by a non-disclosure agreement, for which patents have been applied and are pending.

The current report documents the first steps in developing the Breathing Wall system explicitly for improving indoor environmental quality. The stages of this research were as follows:

1. Testing the biological particulate emissions from the active plant modules to determine whether potentially dangerous microorganisms were being released, including an *in situ* study of previously installed green walls in Sydney

2. Determining which plant species were most effective at reducing CO_2
3. Testing the effects of light and ventilation rate on CO_2 draw down
4. Testing the capacity of the green wall system to remove CO_2 on a room scale, so as to allow calculation of the potential energy savings from reduced requirements on HVAC ventilation
5. Testing the capacity of the modules to remove particulate matter
6. Pilot testing the capacity of the modules to reduce indoor noise levels
7. Testing the capacity of the modules to remove VOCs (to be conducted January 2016)

Units

The units used for the amount of light supplied to plants in this report are generally referred to in terms of Photosynthetically Active Radiation (PAR), which is a measure of the photosynthetic photon flux density. This is an SI unit, and refers to the amount of light available (in micromoles of photons) of the wavelengths directly usable in the process of photosynthesis. The units of PAR are thus μmol.m^{-2}.s^{-1}. Whilst PAR is used in the field of plant science, we are aware that the horticultural industry uses the SI unit of illuminance or luminous emittance, lux (lx). The primary difference between these two scales is that PAR measures photosynthetically available light only, whilst lux weights all wavelengths of visible light equally, thus all light sources need to be measured independently for both lux and PAR. We have supplied data in both units in this report.

PART I: Indoor bioparticle assessment

Background

The inclusion of indoor plants in confined workspaces has led some authors (Staib et al 1978, Summerbell et al 1989, Hedayati et al 2004) to question whether they have the potential to emit airborne bioparticulate matter, such as fungal spores or bacteria, in the buildings concerned, to the point where is has been argued that indoor plants should never be used in any building. For example, the natural habitat of the pathogenic fungal species *Aspergillus fumigatus* is soil, where it decomposes dead organic matter, but it is also prevalent in buildings in which moisture and dampness are problems. Several authors have hence raised the possibility that indoor plants could be a significant contributor the presence of this species, and thus to the prevalence of serious fungal respiratory disease from infection by this mould species (Staib et al 1978a, b, Summerbell et al 1989, Hedayati et al 2004). Indoor airborne fungal spores and other propagules have also been linked with less serious health issues such as sick building syndrome (SBS; Takeda et al 2009; Meyer et al 2004). Fischer and Dott (2003) claimed that fungi in indoor air should be considered as potential health hazards because some species infect humans, many common types act as allergens, and under some circumstances they can be genotoxic.

The first targeted study on the effects of indoor plants on airborne bioparticles was conducted by Torpy et al (2013), over two seasons (autumn and spring) in Sydney, Australia. Potted-plants of two of the most commonly used indoor plants, *Spathiphyllum wallisii* 'Petite' (Peace Lily) and *Dracaena deremensis* 'Janet Craig' were used in the trials, with treatments of 0, 1, 2, or 3 of either species allocated per single-occupant office, with a total of 55 offices. It was found that the potted plants of neither species produced airborne fungal counts in the office environment of a higher than acceptable level; mean fungal counts were in the range 46–126 colony forming units (cfu)/m^3, which are well below the WHO (1990) maximum of 500 cfu/m^3 for plant and soil fungi. There were also no seasonal differences in indoor counts between autumn and spring, and the indoor fungal aerosol loads were significantly lower than outdoor levels, despite the indoor plant presence. These results were attributed to the heating, ventilation and air conditioning (HVAC) system in the sampled building, which apparently efficiently filtered a considerable portion of outdoor-sourced fungal spores from the incoming air. Pathogenic species such as *A. fumigatus* were detected in only very low concentrations, and the indoor fungal samples presented a mixed species composition of both indoor and outdoor taxa, thus presenting no apparent aberrant health risks to building occupants. In summary, the study found the inclusion of this plant material within the indoor environment did not

significantly increase the number or potential hazards of airborne fungal propagules.

Despite these findings, we believe it is prudent to safety test major alterations to the traditional potted plant system if they are to find widespread use in indoor environments, especially those where occupants with immune system disorders may exist, such as hospitals and child care centres. Further, it has not been fully established whether the addition of active aeration of plant materials via fan-forced air induction to their substrates has the capacity to increase airborne bioparticle release. Darlington et al (2000) conducted a biosafety assessment of a proprietary aerated active green wall system. The authors found a moderate increase in overall airborne propagule density, however not of a magnitude to cause a health concern. Whilst Darlington's (2000) study was performed *in situ*, in a Toronto, Canada office building, the lack of replication of this study precludes an indication of the likely consistency of these observations. Wang and Zhang (2011) were not able to culture microbial growth successfully from their biological air filtration system, but concluded that more research was required before it could be ruled out that such systems do not contribute to high bioparticle matter indoors. Biological air filtration systems, specifically those that use forced air in their operation, have the potential to generate problematic bioaerosols, and concerns have been raised over whether these microbial biopollutants indeed negate any benefits of the air treatments these systems are intended to provide (Lu et al 2012). A study by Adan and Samson (2011) linked an increase in humidity levels with that of fungal release from a point source, with 80% relative humidity apt to cause significant problems. The microenvironment near the growth substrate of indoor plants might be expected to reach this level. Thus a part of the current work was devoted to testing the bioparticle emissions from the Junglefy Breathing Wall modules.

Bacterial bioparticles — *Legionella*

Bacteria from the genus *Legionella* are strongly associated in the public understanding with air conditioning systems. Water is the major habitat of most *Legionella* spp., and these bacterial are found in both a range of natural waters, and also in artificial aquatic environments such as cooling towers; water systems in hotels, homes, ships and factories; respiratory therapy equipment; fountains; misting devices; and spa pools (CDC 2005). Despite the longstanding recognition of soils and potting mix as a source of legionellae, especially the species *L. longbeachae*, there has been little research carried out to determine whether indoor plants and their growth substrates could be a source of contamination by species of bacteria.

The disease legionellosis has two main clinical syndromes: Legionnaires' disease (*L. pneumophilia*) and Pontiac fever (*L. longbeachae*). Legionnaires' disease is characterised by severe pneumonia with a ~10% lethality, whereas Pontiac fever usually causes a milder, influenza-like illness (Vic. Gov. Aust., 2015). The primary method of contracting legionellosis is via the inhalation of aerosols containing the *Legionella* bacterium. A study by Hedges and Roser (1991) found *Legionella* spp. to be distributed throughout much of the New South Wales' built environment, with no seasonal variations, leading to the possibility of outbreaks throughout the year. Steele et al (1990) studied the distribution of *L. longbeachae* in potting soils in Australia, and found the species in 73% of the potting soils tested, but it was not detected in potting soils which had been manufactured in Greece, Switzerland or the UK. Hughes and Steele (1994) found *L. longbeachae*, which had been linked to human infections in South Australia, in composted plant matter obtained from home gardeners and bulk composting facilities. Koide et al (2001) discovered various species of *Legionella* in samples of composted wood products and potting mixes. The presence of *Legionella,* particularly *L. longbeachae,* in horticultural substrates is therefore commonplace in this country. However, Grimes (1991) reported that the optimal habitat conditions for the proliferation of *Legionella* spp. includes a carbohydrate nutritional source, a surrounding temperature of ~38˚C, and a non-moving water body. Normal indoor potted-plants conditions would thus present a low probability of *Legionella* spp. proliferation (Burchett et al 2007). However given the aeration component of the Breathing Wall modules, we added *Legionella* testing to this research for surety.

The aim of this research was to test the biosafety of the Breathing Wall plant-wall module design as a possible point source of culturable airborne fungal propagules and *Legionella* spp. The study involved three complementary investigations;

(a) a controlled study of module fungal bioparticle emission, with and without active plant-wall fan aeration, in a university office;
(b) testing for *Legionella* spp. in the growth substrate, effluent air and water leachate of two plant species (*Chlorophytum cosmosum* and *Epipremnum aureum*);
(c) an *in situ* study of fungal spore distribution in seven commercial buildings in central Sydney, Australia, each of which contained a plant-wall (of various sizes) which were comprised of these modules

Methods

The building containing the test office used for this study is located in Sydney, and houses the UTS Faculty of Science. The building is 7 storeys tall and contains staff offices, laboratories, lecture rooms and conference rooms. The average sized staff office is 10–12 m^2 with an average volume of 43 ± 2 m^3. The HVAC system in the building supplies an average of 6–8 air changes per hour to each office, with a 20% filtered fresh air intake mixed with 80% recycled air (J. Kraefft — building manager pers. comm). The HVAC system does not adjust humidity levels of the air inflow. A single air-conditioned office was used for the trials. The selected office was unoccupied for several weeks prior to the experiments. The office contained a desk and chair only, and was thoroughly cleaned with disinfectant and ventilated for several days immediately before experimentation. Experimental replication was achieved with time-for-space substitution with a period of thorough ventilation between tests. Air samples were taken to determine that the airing period was sufficient to preclude carry-over of bioparticles from previous tests.

Test office

As a pilot trial, single modules were first tested in the office to determine the potential change in bioparticle density with the presence of single modules when fans were in active or passive states. As no changes in air quality were detected, two modules were used for the remainder of the investigation.

Each office trial was assigned a randomly chosen pair of modules containing the same plant species, either *Chlorophytum cosmosum* or *Epipremnum aureum*. Modules were watered to field capacity and excess water drained prior to testing. Prior to installation, a reference fungal air sample was taken in the office, to provide a background concentration and diversity estimate for the ambient airborne fungi in the room.

Modules were installed side by side, 600 mm from the rear wall, with the plants extending out towards the centre of the room. The photoperiod for the office was 12:12 hours, with a light level of ~50 µmol m^{-2} s^{-1} (2300 lux), evenly distributed across both modules. Module fans were set to run 30 minutes on, 30 minutes off, for 5 hours, to replicate the predicted operational pattern in a commercial installation. fan operation commenced once modules had been placed in the office.

After the 5 h fan operation cycle was complete a second fungal air sample was taken. The office air was then left to stabilise undisturbed (ie. the module fans were not running) for 2 h before a final sample was taken. The modules were

then removed and the office door left open, with a pedestal fan in operation overnight (>12 h) to ventilate fungi released during the tests (any fungi not removed by this process would be detected by the subsequent reference air sample). The test was repeated 4 times for each plant species.

Airborne fungal samples

Air samples were taken using a Reuter Centrifugal air sampler (RCS; Biotest Diagnostics Corp., Denville, NJ, USA), which works on the principle of airborne fungal spores accelerating through a calibrated impeller before impacting onto an agar medium strip (Zhen et al 2009). We used Sabouraud's dextrose agar for these tests, which is a fungal-specific growth medium with which we have substantial experience. Samples were taken for 2 minutes, which is equivalent to 80 L of air. The strips were aseptically removed from the sampler, re-sealed into their original plastic cases and incubated in the dark at 23°C. Fungi growing on the media after 7 days incubation were identified. Any fungi not identifiable after 7 days were subcultured onto Sabouraud's dextrose agar and incubated for up to 21 days. Organisms not identifiable at this time were classified as 'sterile mycelia', by convention.

Fungal colonies were sampled from the strips using cellotape and stained with lactophenol cotton blue, before identification to genus level using gross microscopic morphology, with references provided by Alexopoulos et al (1996), Ellis et al (2007) and Klich and Pitt (1988). *Aspergillus* species were further identified to species, as there are a number of pathogens in this genus.

Legionella testing

We followed a different procedure for testing the modules for the presence of *Legionella* spp., sampling the modules directly rather than the air within a room containing the modules. Whilst this method dramatically increases the likelihood of detecting *Legionella* if present, and may not represent accurately the capacity of the modules to release *Legionella* into the air, given the pathogenic potential of these bacteria, a rigorous test to exclude their presence as far as possible was considered prudent.

Air samples

Two modules of each plant species were sampled. Air samples were taken using agar plates with buffered charcoal yeast extract (BCYE), containing the growth supplement L-cysteine. Four BCYE plates were suspended in a vertical position in front of the modules with lids removed at the plant canopy edge for 2 minutes while the fans were running. The plates were then incubated at 37°C at pH 6.9 under 2.5% CO_2 for 96 hours in anaerobic incubation jars.

Substrate samples

For each plant species, two randomly selected modules were sampled based on the methods described in the Centres for Disease Control guidelines (CDC 2005). A composite sample composed of five 5 g substrate samples from each module was collected. Subsamples were pooled and mixed in a sterile sample jar. For culturing, the substrate was diluted with sterilised ultrapure water to 10^{-4}. Diluted samples were then acidified with 0.2 M KCl–HCl at room temperature for 10 minutes, since acid treatment has been shown to reduce the number of bacterial colonies other than *Legionella* spp. (CDC 2005) The samples were then spread onto BCYE agar plates containing the L-cysteine growth supplement, and incubated as described above.

Leachate samples

A 1 L composite leachate water sample was collected from two randomly selected modules of each plant species and used to inoculate BCYE agar plates. Samples were diluted to 10^{-4}, acid treated, and incubated as above.

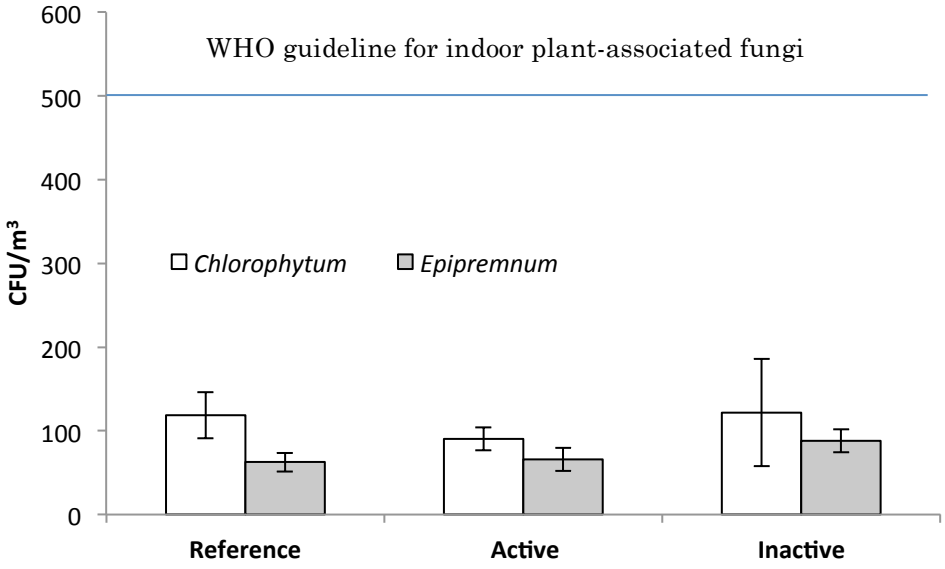
Results and Discussion

Airborne fungi in office trials

The bioparticle counts in all samples were very low, with an overall mean fungal propagule density of 90.6 ± 11.5 cfu/m^3. The result compares favourably with the WHO guideline for maximum indoor airborne spore loads of phylloplane fungi of 500 cfu/m^3 (Environment Australia 2001).

Figure 1 presents the mean fungal spore loads (as colony forming units per cubic metre; cfu/m^3) for the three sampling stages. No significant differences were found among either the sampling stages (ANOVA; P = 0.834), or the plant species (ANOVA; P = 0.381) in the modules. These findings indicate that the presence of the modules, with or without the assisted aeration system, had no significant effect on airborne fungal loads in the office sampled. This is in line with our previous findings (Torpy et al 2013), which found that the presence of indoor potted-plants did not increase total indoor fungi. These findings should be applicable to *in situ* installations of the modules, as long as maintenance and watering are appropriate.

Figure 1: Fungal bioparticle emissions from two modules in an office. 'Reference' indicates the samples that were taken in the ventilated office, before installation of the modules; 'Active' indicates samples taken directly after 5 h of intermittent fan operation; 'Inactive' indicates samples that were taken after a further 2 h with the module fans off. Values are means ± SEM, n = 4.



Fungal diversity in office trials

The diversity of fungal genera detected in the samples is shown in Table 1. There were no significant differences in fungal diversity between plant species for these trials (ANOVA; $P = 0.539$), thus the data for both species has been pooled for clarity. There were minor changes in the types of fungi detected in the air after the modules were installed, with an increase in the number of yeasts, and the appearance of several organisms not detected in reference samples: *Chaetomium* sp., *Chrysosporium* sp., *Cladophialophora* sp., *Curvularia* sp., and *Aspergillus niger*. Other than yeasts, all of these genera were present in such small numbers that their appearance only in the active and inactive samples was likely due to chance. Whilst *A. niger* has been implicated in human disease, the extremely small number of particles detected does not represent a health concern, and is 80–90% lower than the number of aspergilli normally detected in outdoor air in Sydney (Irga and Torpy 2015). The highly pathogenic species *Aspergillus fumigatus* was not found in any sample.

We are unsure of the reason behind the increase in yeast propagule density, although once again the numbers detected are too small to warrant health concern, with mean outdoor yeast density in Sydney many times higher, at ~47 cfu.m^2 (Irga and Torpy 2015). All of the yeasts encountered were further tested for the possibility that they were pathogenic *Cryptococcus* spp., however no yeasts of this genus were observed.

Several genera of fungi were only present in air samples taken when the modules were not present. The removal of the potentially pathogenic *A. ochraceous*, *Scedosporium* sp. and *Aureobasidium* sp. is noteworthy, although once again the small numbers of these organisms was insufficient to warrant concern prior to installation of the modules, and their appearance in these samples was likely due to natural random variability.

Table. 1: Mean percentage incidence and SEM of airborne fungal genera detected in an office with two plant-wall modules. 'Reference' indicates the samples that were taken in the office before installation of the modules; 'Active' indicates samples taken directly after 5 h of intermittent fan operation; 'Inactive' indicates samples that were taken after a further 2 h with the module fans off. Means with no SEM are samples for which only a single observation of that genus was made. Values are means ± SEM, n = 8.

	Density of fungal colonies in samples (cfu/m^3)		
Fungal genera	Reference	Active	Inactive
Cladosporium	46.02 ± 9.62	44.20 ± 7.64	32.27 ± 11.45
Alternaria	20.46 ± 7.91	21.60 ± 9.66	21.45 ± 8.00
Penicillium	9.90 ± 6.20	7.81 ± 4.05	5.39 ± 2.67
Sterile mycelia	8.60 ± 4.21	15.10 ± 8.77	19.08 ± 7.43
Aspergillus ochraceus	4.20	_	_
Veronea	2.08	1.25	_
Scedosporium	2.08	_	_
Aureobasidium	1.79	_	_
Yeast	1.79	4.17	8.75 ± 4.58
Geotrichum	1.60	_	_
Phoma	1.60	_	_
Rhizopus	_	3.13	_
Chaetomium	_	_	4.17
Chrysosporium	_	_	2.08
Cladophialophora	_	_	2.78
Curvularia	_	_	2.50
Aspergillus niger	_	2.81 ± 1.86	1.52

The number of species, and the most common types of indoor fungi found in this study, namely *Cladosporium, Alternaria* and *Penicillium*, are similar to those that have been reported in previous studies in airborne fungal diversity in indoor spaces (Beguin and Nolard 1994, Górny and Dutkiewicz 2002, Choo et al 2008). These are among the most commonly encountered fungal genera worldwide, and are regarded as generally harmless. In addition, these three genera were the most prevalent fungi whether in the background reference samples or when fans were active or inactive, indicating no effect of the modules.

Legionella samples

The leachate water and air samples collected from the modules showed no colonies with morphologies consistent with the appearance of *Legionella* spp. However, samples of the solid substrate collected from two of the modules showed colony growth on one BCYE agar plate. After 3 days incubation, the colonies had a white to grey colouration, with a smooth, shiny, raised surface with precise edges. This is consistent with *Legionella* spp. morphology (CDC 2005). In order to acquire a presumptive identification of *Legionella*, a subculture was made onto a 'negative' BCYE agar plate, which did not contain the growth supplement L-cysteine. If the subculture fails to be produced, the result would provide strong evidence that the original sample was a *Legionella* species, and the presumptive *Legionella* colonies must be examined further (CDC 2005). However, the subcultures tested produced positive colony growth on the negative agar, indicating a strong probability that they were not of *Legionella* spp.
The findings thus indicate that the modules are unlikely to be a major source of *Legionella* bacteria. However, as is the case with any indoor plant system, under extremely poor maintenance conditions the potential remains for the proliferation of pathogens, including *Legionella*. As was the case for fungal bioparticles, we thus reiterate our recommendation to ensure that all indoor plant installations are well maintained. Specifically regarding *Legionella*, no components of the green wall system should be allowed to reach 37°C to minimise the chances of proliferation of these bacteria.

IN SITU SAMPLES

Whilst our previous office experiment indicated no fungal particle emissions from the modules, the modules used were new and maintained in the university glasshouse. To determine whether fungal bioparticle emissions were different for older installations, we conducted a field trial of previously installed green walls.

Methods

Seven commercial buildings in inner Sydney that contained a plant-wall installation made up of Breathing Wall modules were assessed for possible fungal bioparticle emissions. As was the case with the test office, all of the buildings were equipped with HVAC systems. Test buildings had a range of uses (Table 2) and population densities. The sizes of the installations ranged from 5 to 72 m^2, and each contained various numbers and mixtures of plant species (Table 2).

Table 2: Characteristics of plant-walls in seven Sydney city buildings.

Site usage	**Plant wall area (m^2)**	**Light level □mol m^{-2} s^{-1} (lux)**	**Plant species**
Public library	72.0	3.6 (165)	*Chlorophytum cosmosum* *Epipremnum aureum* *Philodendron bipinnatifidum* *Philodendron scandens* *Philodendron xanadu* *Neomarica* sp. *Peperomia* sp. *Spathiphyllum cochlearispathum*
Insurance offices	24.5	4.4 (200)	*Chlorophytum cosmosum* *Philodendron bipinnatifidum* *Philodendron xanadu* *Anthurium* sp. *Aglaonema* sp. Davallia sp. *Iresine* sp. *Peperomia* sp. *Phlebodium* aureum *Spathiphyllum cochlearispathum* *Syngonium podophyllum*
Courier packaging	21.0	7.7 (355)	*Chlorophytum cosmosum* *Epipremnum aureum* *Philodendron bipinnatifidum* *Philodendron xanadu* *Peperomia sp.* Davallia sp. *Phlebodium aureum* *Spathiphyllum cochlearispathum* *Syngonium podophyllum*
Cafe	12.3	6.6 (305)	*Chlorophytum cosmosum* *Epipremnum aureum* *Ctenanthe* sp. *Peperomia* spp. (2 species) *Phlebodium aureum*
University administration centre	12.0	4.6 (210)	*Epipremnum aureum* *Ctenanthe sp.* *Neomarica* sp.
Childcare centre	6.0	4.6 (210)	*Chlorophytum cosmosum* *Philodendron xanadu* *Ctenanthe* sp. *Peperomia* sp.
University conference centre	5.0	7.2 (330)	*Epipremnum aureum* *Philodendron scandens* *Philodendron xanadu* *Neomarica* sp.

For each building, sets of three replicate readings were made:

(a) Indoor 'reference' air samples were taken from an empty room without any indoor plant vegetation, that was similar to the test room containing modular plant-walls in the centre of the room-space;

(b) In the plant wall room — at a 600 mm distance from the foliage surface, and another at the centre of the room-space. In this office space, the replicates were taken at each of three heights from the floor (7.5, 130, and 180 cm respectively). It should be noted that none of the plant walls in these offices were mechanically ventilated — they were of an older type that did not contain the axial impeller aeration system.

These three sampling heights are taken to represent air quality measured at: 'floor level'; in the 'breathing zone' (head height area) when seated at a desk; and in the breathing zone at standing height (ANSI/ASHRAE Standard 62.1–2013).

(c) Simultaneous samples were taken outdoors, on the pavement adjacent to the building for comparison.

Airborne fungal bioparticles were sampled as for the office experiment. Mean values were calculated for each set of 3 replicate readings.

Results and Discussion

The results of this seven building indoor plant-wall survey are presented in Table 3. Fungal bioparticle data were recorded as colony-forming units per cubic meter (cfu.m^{-3}). With and without plant walls preset, and both indoors and outside, all samples contained significantly lower airborne fungal density compared with the WHO recommended maximum of 500 cfu.m^{-3}. Mean colony counts for rooms with plant walls was 8.8 cfu.m^{-3}, while those for reference environments was 6.9 cfu.m^{-3}; and for outdoor airborne fungi, 9.9 cfu.m^{-3}. Both the indoor sites with the Breathing Wall modules and the reference sites contained less airborne fungi than the mean colony counts of airborne fungi found outdoors.

The number of fungi found in indoor environments with green walls was generally lower than in the reference sites. However, the density of *Penicillium* spores was somewhat higher indoor sites with Breathing Wall modules at 50 ± 18.5 cfu m^{-3} than in the reference sites 21.4 ± 9.7 cfu m^{-3}.

Table. 3: Airborne fungal genera detected in indoor building sites with green walls, without green walls and outdoors with no green walls. Each sample site had its ambient air sampled for 2 minutes. Sample sites with no recorded values denotes lack of airborne fungi presence at that site. Values are means ± SEM, n = 7.

Fungal genera	Mean density of fungal colonies in samples cfu.m^{-3}		
	Indoors with green wall	Indoor without green wall ('reference')	Outdoors with no green wall
Penicillium	50 ± 18.5	21.4 ± 9.7	23.2 ± 15.8
Yeast	10.7 ± 3.7	8.9 ± 1.8	10.7 ± 8.2
Aspergillus	8.9 ± 4.5	23.2 ± 13.8	35.7 ± 20.1
Cladosporium	7.1 ± 5.4	5.4 ± 5.4	23.2 ± 12.6
Cladophialophora	5.4 ± 5.4	1.8 ± 1.8	8.9 ± 3.6
Sterile mycelia	5.4 ± 4.3	1.8 ± 4.5	12.5 ± 5.1
Scopulariopsis	5.4 ± 3.7		
Paecilomyces	3.6 ± 3.6		3.6 ± 2.3
Alternaria	3.6± 2.3	1.8 ± 1.8	1.8 ± 1.8
Acremonium	1.8 ± 1.8	10.7 ± 4.3	3.6 ± 3.6
Phoma	1.8 ± 1.8	5.4 ± 3.7	8.9 ± 5.3
Rhodotorula	1.8 ± 1.8		
Absidia			1.8 ± 1.8
Aureobasidium		5.4 ± 3.7	
Botrytis		5.4 ± 3.7	
Chaetomium		1.8 ± 1.8	5.4 ± 3.7
Cunninghamella		1.8 ± 1.8	1.8 ± 1.8
Curvularia			5.4 ± 3.7
Gliocladium			1.8 ± 1.8
Lecythophora		1.8 ± 1.8	

The number of species, and the most common types of indoor fungi found are similar to those found in our previous office experiment (Torpy et al 2013). *Penicillium,* yeasts and *Aspergillus* identified were found to be the most prevalent within the seven sample sites. The genera identified within all seven sites are generally regarded as harmless. *Penicillium* was the most prevalent airborne fungus in the seven indoor sites with the Breathing Wall modules, indoor 'reference' sites without modules and outdoor sites without modules. Overall, the fungal genera identified in the seven indoor sites are consistent in findings with other reports of indoor fungal diversity (Beguin and Nolard 1994, Górny and Dutkiewicz 2002, Choo et al 2008).

This research indicates that the Breathing Wall modules are unlikely to produce excess airborne fungal bioparticles at concentrations that could exceed WHO guidelines, or are of concern to human health when installed indoors. Although airborne fungal spores were found in the office when the modules were present, the assisted substrate aeration did not produce a greater number of fungal spores, when compared with either unventilated modules or ordinary pot plants, as previously studied by Torpy et al (2013). Nor did we find that the modules introduced potentially dangerous airborne fungal species such as *A. fumigatus* into the office that could pose a health risk to building occupants. The fungal bioparticle density associated with previously installed modules similarly produced no cause for concern, with safe numbers of non-pathogenic fungi detected in all cases.

The study shows strong supporting evidence that such plant-wall modules have no significant effect on the airborne fungal species composition or spore loads in the indoor environment. The loads were found to be very low in comparison with internationally recommended maximum indoor total concentrations. Furthermore, we found that *Legionella* spp. was of no concern when the modules are used as designed. It is recommended, however, that this research be completed with further testing for active modules after long term use.

PART II: CARBON DIOXIDE DRAW DOWN ASSESSMENT

Background

Elevated levels of carbon dioxide (CO_2) in indoor spaces generally results from human respiration. Although CO_2 is not toxic *per se*, at elevated concentrations (over ~1000 parts per million by volume; ppmv) it has strong associations with SBS through its narcotic action (Milton et al 2000; Erdmann and Apte 2004; Seppänen and Fisk 2004). High CO_2 has been associated with mucous membrane and lower respiratory tract symptoms, including dry eyes, sore throat, nose congestion, sneezing, tight chest, short breath, cough and wheezing (Erdmann and Apte 2004), all of which lead to occupant dissatisfaction with indoor environments. Poor health outcomes associated with these symptoms include lowered student academic performance and workplace productivity (Bakó-Biró et al 2004, Seppänen et al 2006, Shaughnessy et al 2006). The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) recommends a maximum CO_2 concentration of 1000 ppmv for occupant wellbeing (ASHRAE, 2011), and this maximum is also generally recognised in Australia (Environment Australia, 2001).

In most modern commercial buildings, CO_2 levels are maintained below a set point (generally 800–1000 ppmv) by the mechanical ventilation component of HVAC systems (Redlich et al 1997). Whilst these systems are effective if well designed, when there is a substantial temperature difference between outdoor and indoor air, considerable energy is required to heat or cool the incoming ventilation airstream (Schell and Inthout 2001). This leads to considerable greenhouse gas emissions if fossil fuel-derived energy is used. Research is thus needed to identify whether passive methods of decreasing ventilation requirements have potential to reduce these energy requirements (Fisk et al 2009).

Several studies have examined the potential of traditional indoor plants for mitigating excess CO_2. Oh et al (2011) detected plant CO_2 reduction potential in a laboratory test-chamber study. Pennisi and van Iersel (2012) also detected CO_2 draw down, but thought that an impractical number of indoor plants would be required to make a substantial difference to indoor CO_2 levels. Tarran et al (2007) found that offices with three or more potted plants had 10% lower CO_2 concentrations in air conditioned buildings, and 25% lower in non-air conditioned buildings. A subsequent study (Brennan, 2011) that tested the same effects in two more modern buildings, detected much lower CO_2 removal, with the reduced effect attributed to the more efficient HVAC systems in the newer buildings. The

combined findings of these two studies indicates the potential for indoor plant technology to lower building HVAC ventilation requirements. Other authors have estimated that the use of appropriate green plant design could reduce HVAC energy loads by 10–20% (Afrin 2009).

Plant selection will have a major influence on the CO_2 draw down capacity of living infrastructure. Plant species naturally vary in their light requirements and intrinsic photosynthetic rates per unit of leaf area. In addition, plant growth substrate microorganisms and non-photosynthetic plant parts respire, releasing CO_2, which also must be accounted for in CO_2 draw down testing (Somova and Pechurkin 2001).

To assist in plant selection for the design of green walls aimed at reducing indoor CO_2, we determined the break-even light levels ('compensation points') for a range of plant species used in the Breathing Wall modules. Compensation points are the light levels at which CO_2 draw down is equal to the net respiratory emission rate, and is thus the light level that is required in an indoor plant system is to reduce the CO_2 level.

The subsequent experiments aimed to determine the light conditions required for net CO_2 removal by the Breathing Wall modules. The addition of fans to the Breathing Wall system and resulting ventilation of the substrate adds an untested variable to the experiments; thus the modules were tested both with and without fan operation.

Finally, CO_2 draw down was tested in both chamber and sealed room conditions; the latter to determine the real-world capacity of the system to ameliorate high indoor CO_2 levels, and thus to reduce HVAC energy requirements.

Part IIa: Choice of green wall plant species

Typical green wall installations use a range of plant species for aesthetic reasons. However our previous work (eg. Torpy et al 2014) shows that different indoor plants can vary in their capacity to remove some air pollutants, especially CO_2. Torpy et al (2014) tested the light levels required for net CO_2 draw down for eight common indoor plant species, finding that the compensation points ranged between 10–50 □mol.m^{-2}.s^{-1} (460–2300 lux). Thus at the light levels usually encountered in office buildings (4–10 □mol.m^{-2}.s^{-1} (180–460 lux); Safe Work Australia, 2011), plant CO_2 removal will often be zero, or in some cases, CO_2 will be released by the plants. We thus tested the light compensation points of seven plant species commonly used in the Breathing Wall modules for their relative efficacy in CO_2 removal.

Methods

Individual plants (n = 4) in 150 mm pots were supplied by Junglefy Pty Ltd. Plants were healthy, and the same size and species as individual plants that are typically planted in the Breathing Wall modules prior to installation. Seven species were supplied (Table 4). Whilst the height, leaf area and other biomass variables were inconsistent between and within species, the plants used were identical to those used in the modules, and were thus representative of the real performance that could be expected of them when used *in situ*.

Tests were performed in airtight 15 L glass chambers, fitted with 40 mm electric fans for air circulation. Chambers were kept at a 23±2°C ambient temperature by performing the experiment in an air conditioned laboratory and minimising heat generated by the lighting systems. Starting chamber CO_2 concentrations for all trials was ~1000 ppmv, which was produced by breathing into the chambers for ~10 s. CO_2 was monitored with a portable Infra-Red Gas Analyser (IRGA; TSI IAQ-CALC, TSI Inc., MN, USA) sealed inside the chambers.

Plants were watered to field capacity and drained for 1 h before testing, which was carried out between 9.00 am and 5.00 pm, when natural photosynthesis could be expected to occur. Prior to testing, the plants were maintained in a glasshouse lined with shade cloth, with maximum mid-day light level of 90 ± 10 m□^{2} .s□^{1}; average temperature 23.7 ± 3.6°C and relative humidity 68.1 ± 16.0%.

Experiments were run for 40 min, after which CO_2 losses were such that the pattern of draw down became nonlinear (see Torpy et al 2014), and chamber humidity rode to a level where it may interfere with leaf gas exchange.

Light was supplied with an unbranded 90 W / 0.4 A red blue plant-growth specific LED array, containing a ratio of 2 red: 1 blue LEDs, and 90 LEDs in total. Light level was modulated by changing the distance of the light source from the chambers. Light level was measured using an Apogee PAR light meter at a point estimated to be at the centre of the plant canopy. Plant-growth specific photon flux density (□mol.m^{-2}.s^{-1}) were converted to illuminance (lux) with calibration curves developed using a lux meter for the individual light source used.

These tests used a trial-and-error process to determine the light level at which the combined plant and substrate neither produced nor removed CO_2 for a period of 40 min, ie. the *potted-plant light compensation point* (Torpy et al 2014). This information is practically valuable as it indicates the minimum light level required for modules containing the plants to start removing CO_2. An average of four trials were required for each species to determine the compensation points. Light compensation points were conformed in triplicate with different individual plants.

Results and Discussion

Light compensation points are shown in Table 4, with species ranked in descending order of the light level required to balance respiratory CO_2 emission. Lower compensation point light intensities represent better performance, as less light energy will need to be supplied to an indoor installation before CO_2 draw down will occur.

The three species with the lowest compensation points were *Gibasis* sp., *Chlorophytum cosmosum* and *Epipremnum aureum*; thus the latter two species were selected for further testing as they are the most common of the three in green wall installations. The *Peperomia* spp. and *Philodendron xanadu* had intermediate compensation points, whilst the densely foliaged *Neomarica* sp. surprisingly required the most light to balance out substrate CO_2 emissions.

The required light levels detected were similar to those found previously by Torpy et al (2014), who tested 8 common potted indoor species under similar conditions. The lowest compensation points detected here (10 □mol.m^{-2}.s^{-1}) are the equal lowest detected for any plant species, and represent strong performance at a low light level for an indoor plant species. The current findings, along with those of Torpy et al (2014) should prove valuable for horticultural technology developers wishing to select functional indoor plants for maintaining good air quality in their client's buildings.

Apart from *Neomarica* sp., which had a fairly high compensation point light levels, all of the other species performed sufficiently to recommend their use in functional green walls, especially as part of mixed plant arrangements. *Neomarica* sp. may also be suited for use, but only in instances where sufficient light is available. The performance of all species other than *Chlorophytum* and *Epipremnum* at higher light levels is unknown, and may be high — we have previously detected that some species, such as *Dracaena deremensis*, have very high light compensation points (50 □mol.m^{-2}.s^{-1} for this species), but remove CO_2 very effectively with sufficient light (Torpy et al 2014).

Table 4: Light compensation points for the tested plant species in 150 mm pots and 15.0 L chambers. The compensation point is the light level at which the potted plant neither produces nor consumes net CO_2.

Species	**Common name**	**Compensation point light level □mol.m^{-2}.s^{-1} (lux)**
Neomarica sp.	Walking iris	25 (1150)
Philodendron xanadu	Xanadu	14 (650)
Peperomia sp.	Large Leaf Peperomia	13 (600)
Peperomia sp.	—	13 (600)
Epipremnum aureum	Golden pothos	10 (460)
Gibasis sp.	Tahitian Bridal Veil	10 (460)
Chlorophytum cosmosum	Spider plant	10 (460)

Part IIb: Chamber trials — the effect of light level and plant species choice on CO_2 removal

Methods

Having determined that *Chlorophytum cosmosum* and *Epipremnum aureum* has efficient light compensation points, these species were used for a series of efficacy trials in the Breathing Wall modules. The CO_2 draw down carbon flux performance was first assessed with a series of sealed-chamber experiments.

Eight perspex test chambers (216 L) were used, fitted with a portable Infra-Red Gas Analyser (IRGA; TSI IAQ-CALC, TSI Inc., MN, USA) to record chamber CO_2 concentrations. Fans (100mm diameter) were installed to circulate chamber air. Chamber temperature was maintained at 23–26°C by performing the experiments in an air conditioned laboratory. Plants were watered to field capacity and drained for 1 h before testing, which was carried out between 9.00 am and 5.00 pm, when natural photosynthesis could be expected to occur.

Single modules were placed in the chambers and the doors sealed after chamber CO_2 level been elevated to 1000 ± 50 ppmv by the operator exhaling into the chambers for ~ 1 min. We used this starting CO_2 concentration for all trials as this is the ASHRAE (2011) recommended maximum for air-conditioned buildings, and is the low end of the concentration range where a significant number of people experience symptoms. Previous work by our laboratory has shown that the proportional rate of CO_2 draw down by several indoor plant species is independent of the starting CO_2 concentration between 350 and 2000 ppmv; thus similar draw down rates could be expected across the range of ambient conditions *in situ*.

Chamber CO_2 concentrations were recorded by the instrument at 1 min intervals for 40 min. We did not sample beyond this time because falling chamber CO_2 levels began to affect the linearity of the CO_2 removal rate, and thus became un-representative of an *in situ* condition where constant CO_2 input would occur. Chamber humidity also rose to high levels at this time, which may have affected leaf gas exchange through altered stomate function.

Data were adjusted for variations in initial CO_2 concentrations by expressing changes in chamber air as percentages of the initial concentrations.

The modules were tested at three light intensities:

(1) 10 □mol.m□2.s□1 (460 lux), produced with Wotan 'daylight' incandescent tubes (Wotan GMBH, Munich). This level represents a common 'well-lit' office light level during our previous studies (Brennan, 2011), and has also been used in other investigations (Pennisi and van Iersel 2012, Irga et al 2013).

(2) 50 □mol.m□2.s□1 (2190 lux), using a 400 W metal arc discharge lamp (Sylvania M59R, Sylvania Lighting Australasia Pty Ltd.). This light level represents what we consider to be a modest additional light level, and is similar to what would be expected in a room brightly lit with large windows.

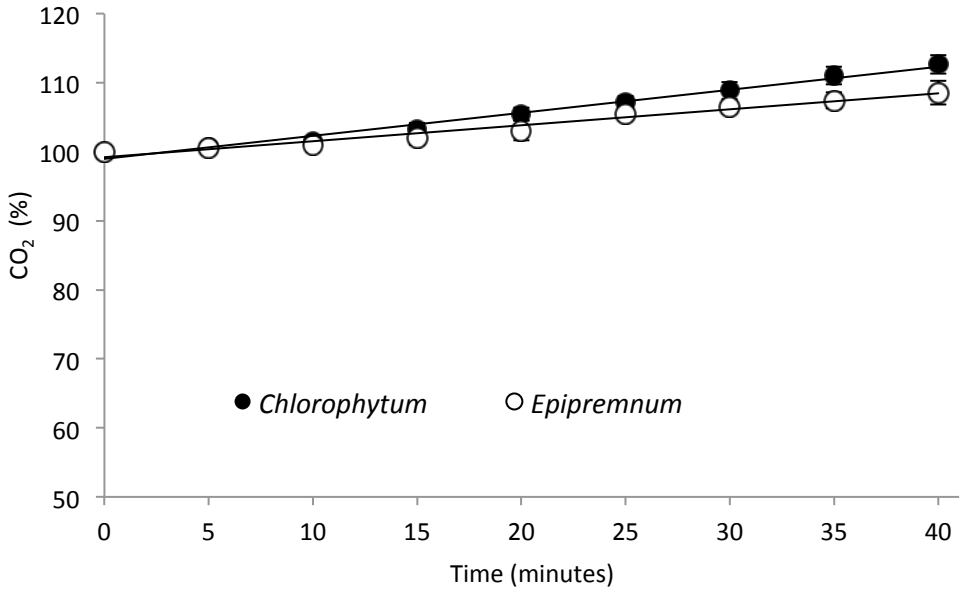
(3) 100 □mol.m□2.s□1 (4750 lux), also produced with the Sylvania M59R 400 W metal arc discharge lamp. This light level represents what we consider to be a high, but economically practical, additional light level, and is similar to what would be expected with the addition of targeted light arrays.

Modules of two species: *Chlorophytum cosmosum* and *Epipremnum aureum* were used (n = 3) in independent experiments to compare the performance of the different plant species. Modules were also tested with their ventilation fans off, running at full output (3.5 $m.s^{-1}$) and half full output (1.75 $m.s^{-1}$). Data are corrected for chamber losses ('leakage') detected in no plant control samples run between all module trials and averaged.

Results and Discussion

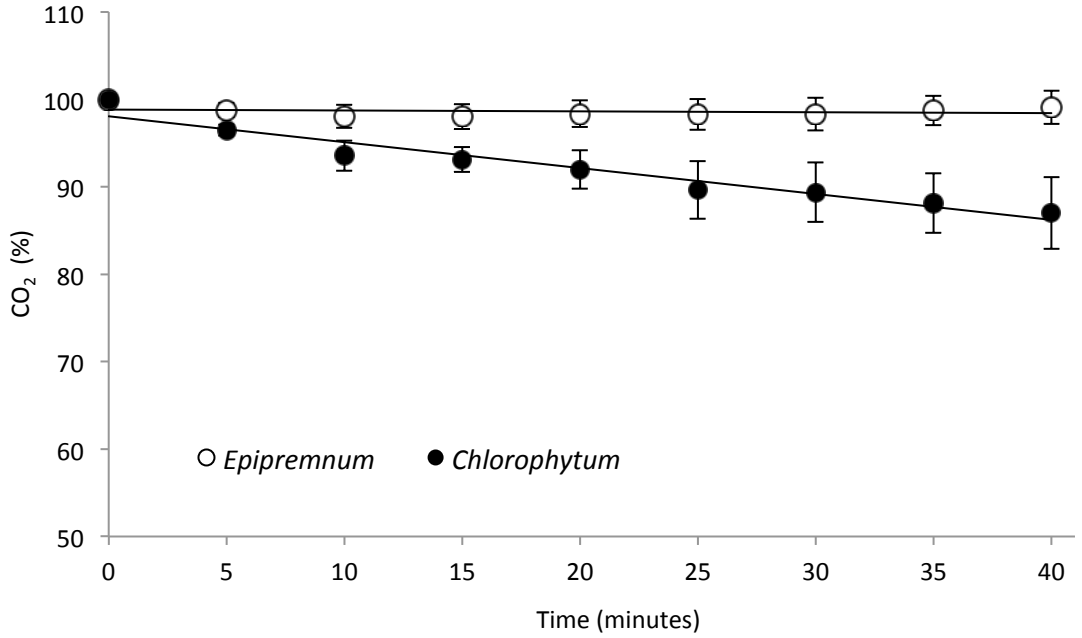
At 10 □mol.m^{-2}.s^{-1} with the module fans off, modules containing both plant species released CO_2 (Figure 2). This was as expected, and similar to our previous findings using potted plants (Torpy et al 2014). We have found that this low light level is generally insufficient for indoor plants to photosynthesise at an adequate rate to balance net CO_2 emissions from the substrate, and thus should not be used if green wall systems are to be used for CO_2 removal purposes indoors.

Figure 2: Chamber trials of CO_2 evolution (as a % of a starting concentration of ~1000 ppmv) for *Chlorophytum* and *Epipremnum* at 10 □mol m^{-2} s^{-1}. Module fans were not running. Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



With a modest increase in light to 50 □mol.m^{-2}.s^{-1}, modules containing *Chlorophytum* removed an average of 13% of the CO_2 from the chamber air over the 40 min testing period, whilst *Epipremnum* removed less than 1% (Figure 3). These findings emphasise the importance of plant species selection for functional green wall systems: if this light levels was selected for an installation, *Chlorophytum* is clearly a far more effective species at CO_2 reduction than *Epipremnum*.

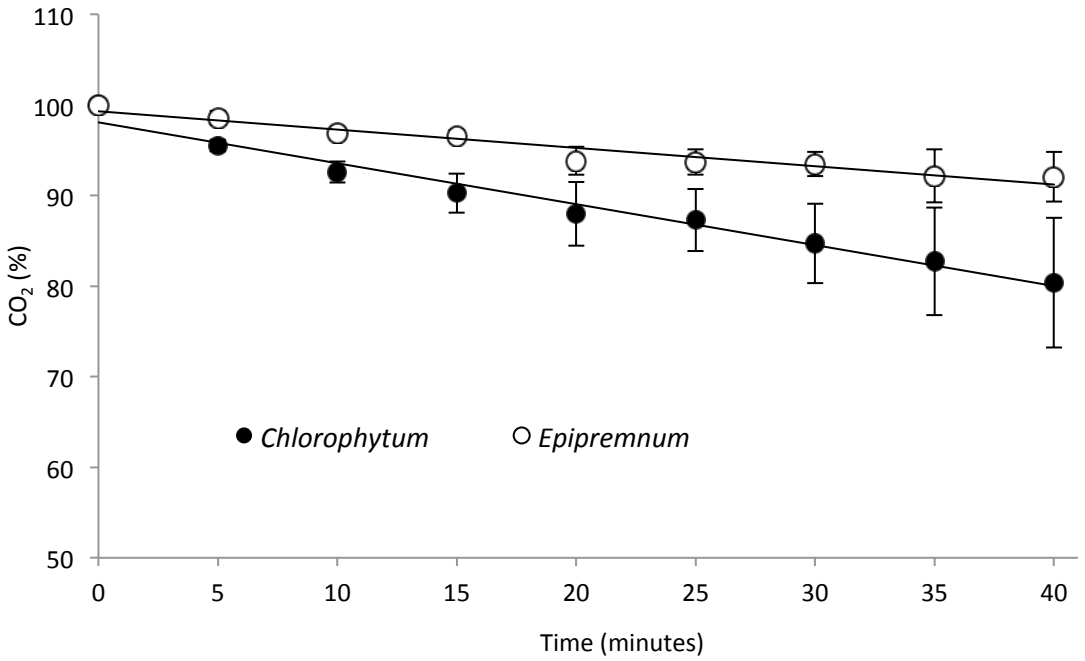
Figure 3: Chamber trials of CO_2 draw down (as a % of a starting concentration of ~1000 ppmv) for *Chlorophytum* and *Epipremnum* at 50 □mol.m^{-2}.s^{-1}. Module fans were not running. Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



Further increasing the light level to 100 □mol.m^{-2}.s^{-1} allowed *Chlorophytum*-containing modules to remove ~20% of the chamber CO_2 over 40 min, whilst *Epipremnum* modules removed an average of ~8% (Figure 4). Thus doubling the light level lead to an increase of ~54% in the rate of CO_2 removal for *Chlorophytum*, but an 8-fold increase in the CO_2 removal rate for *Epipremnum*. These increases are both high, and would dramatically increase the effectiveness of the modules as air cleaners *in situ*.

We have previously performed tests on other plant species at higher light levels — up to 350 □mol.m^{-2}.s^{-1}, and detected continuing increases in the rate of CO_2 removal for most indoor species (Torpy et al 2014). We thus recommend that functional green walls be supplied with sufficient light levels to ensure effective CO_2 removal. We explore this further in the sealed room trials described later in this report.

Figure 4: Chamber trials of CO_2 draw down (as % of a starting concentration of ~1000 ppmv) for *Chlorophytum* and *Epipremnum* at 100 □mol.m^{-2}.s^{-1}. Module fans were not running. Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



Part IIc: Chamber trials — the effect of module fan operation on CO_2 removal

Whilst it would be expected that the addition of mechanical ventilation to the modules might increase the ability of the modules to reduce some air contaminants such as particulate matter and volatile organic materials due to the substrate acting as a filter, their effect on CO_2 removal was unknown before these trials. Thus the effect of varying the fan speed on chamber CO_2 draw down was compared. The light levels used for these trials was 100 □mol.m^{-2}.s^{-1} (4750 lux), as this was the intensity that lead to the greatest removal of CO_2 in the previous experiment. Modules were tested with the fans off, with velocity at 50% of maximum (with the use of a potentiometer), and at maximum speed. Fans speed at full power was 3.5 m.s^{-1}, measured with a Davis anemometer with the fans detached from the modules (<1 m.s^{-1} airflow was detected flowing through the modules).

Figure 5 shows the results of the trial of *Chlorophytum*-containing modules. With the fans off, the modules removed 80% of the chamber CO_2 as was the case in the previous experiment. However with the fans on either half or full speed, a further 10% of chamber CO_2 was removed. These findings are surprising, and the reasons for these effects are not known, although is probable that increased gas exchange at the leaf surfaces had some influence. Fan operation also increased the rate of CO_2 removal for *Epipremnum* (Figure 6), although for this species the higher fan speed had a greater effect. These observations are surprising, and are worthy of further experimentation.

Based on these results, combined with those from the bioparticle emission experiment, fan operation thus appears to be a positive addition to a functional green wall, and can safely be recommended for continued use. The choice of fan speed is less clear, with a lower speed performing well for *Chlorophytum*, but less so for *Epipremnum*. Fan speed will be discussed further on the following section on particulate matter draw down.

Figure 5: Chamber trials of CO_2 draw down (as % of a starting concentration of ~1000 ppmv) for *Chlorophytum* at 100 □mol.m^{-2}.s^{-1}, with module fans off, running at full output (3.5 m.s^{-1}) and half full output (1.75 m.s^{-1}). Data are corrected for chamber losses ('leakage). Data are means ± SE, n = 3.

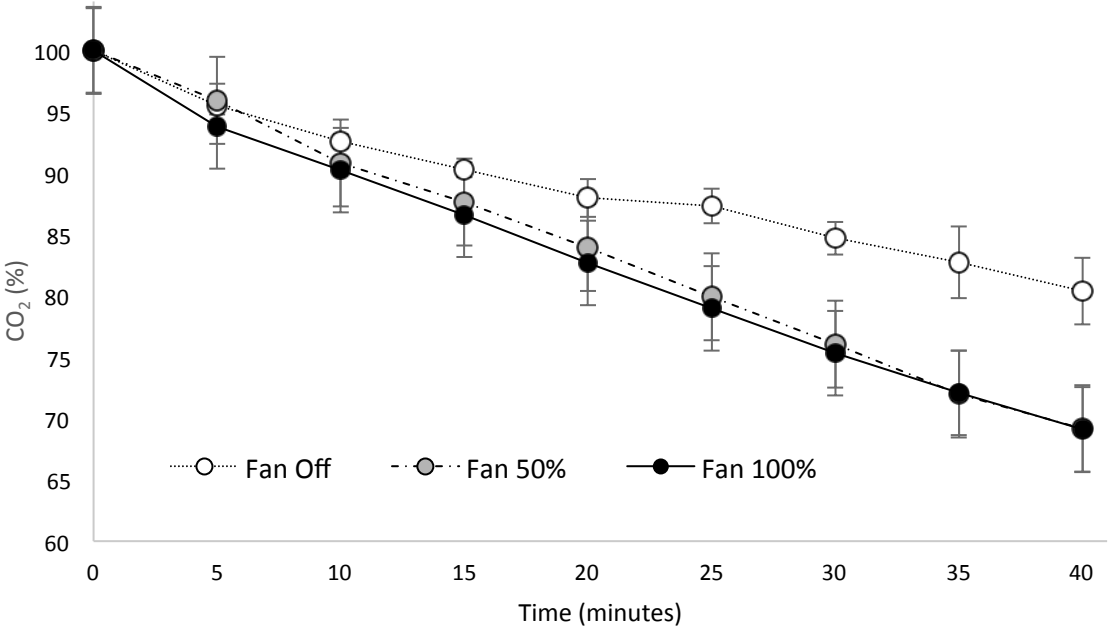
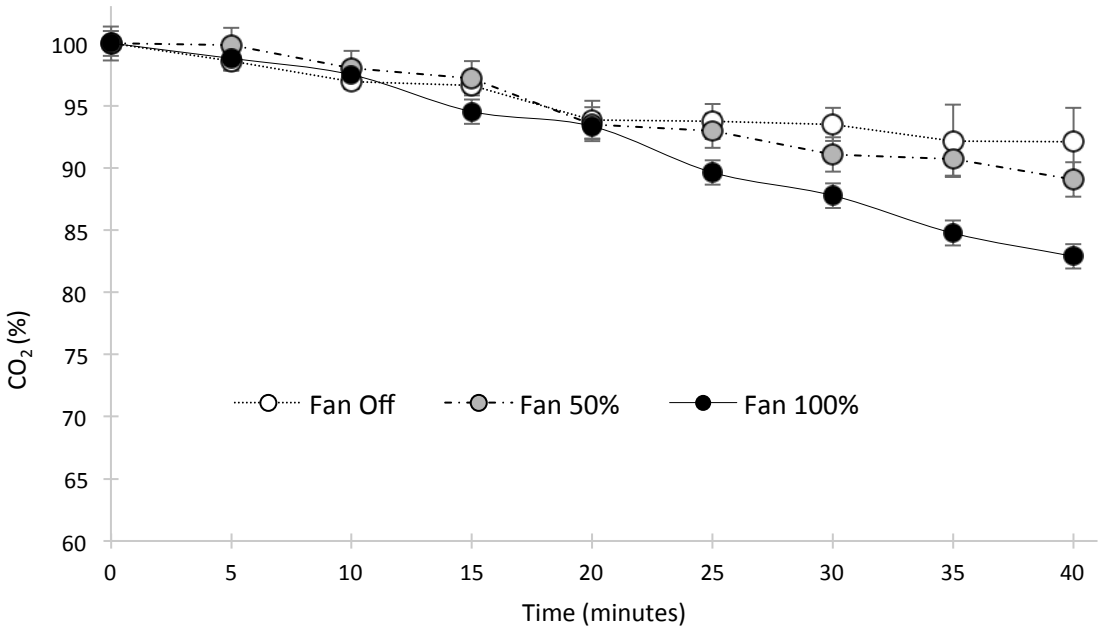


Figure 6: Chamber trials of CO_2 draw down (as % of a starting concentration of ~1000 ppmv) for *Epipremnum* at 100 □mol.m^{-2}.s^{-1}, with module fans off, running at full output (3.5 m.s^{-1}) and half full output (1.75 m.s^{-1}). Data are corrected for chamber losses ('leakage). Data are means ± SE, n = 3.



Part IId: Sealed room trials — The combined effects of light level and module fans on module CO_2 removal

Whilst chamber experiments provide a good indication of the performance of plant systems for air quality bioremediation, and have dominated experimentation in this field of research, some authors (eg. Llewellyn and Dixon 2011) have challenged the validity of this work, claiming that generalizations made from small chamber experiments to real buildings have been insufficiently tested. Thus to ensure the reliability of our chamber experiments and to test the claims of Llewellyn and Dixon (2011), we replicated the chamber experiments in a fully-sealed, room sized chamber.

Methods

The test room was a decommissioned freezer, which was carefully sealed to be as gas-tight as possible with silicone sealant, and tested with CO_2 leak down trials until the rate of gas loss was minimised (~20% per hour). Leakage was again tested between plant wall runs, and all subsequent measurements using the modules were corrected for this leakage rate.

The volume of the test room was 15.650 m^3, and its floor area dimensions are shown in Figure 6. The size of the room was slightly smaller than an average university staff office. The void carried building services, and was sealed from the interior of the test room. The floor in the room was sealed concrete, and the walls and ceiling powder coated and riveted aluminium sheet. The door was sliding aluminium, with rubber flap seals on all sides. Most gas leakage appeared to be through the door seals, thus significant attention was paid to arranging them carefully during tests. All seams, rivets and the air equalization vent were sealed with silicone, and all surfaces were cleaned thoroughly before the tests. Duct tape was used to seal the edges of the door.

Four modules containing single plant species were tested for each sample, as a conservative estimate of the size of green wall that would be installed in a space of this size. The four modules were stacked in a 2 x 2 square on steel shelving. Light was supplied with a custom plant-growth specific LED array constructed of 4 strips of 27, 1 W LEDs, with a ratio of 2 red per 1 blue LED, along with two of the 90 W LED arrays previously described.

We tested green wall performance at both a conservative 50 □mol.m^{-2}.s^{-1} (2837 lux) and a higher 250 □mol.m^{-2}.s^{-1} (9781 lux), which was the maximum we could attain with the LED lights without causing temperatures within the foliage to become excessively hot (>30°C). The first light level was used to test the performance of a highly energy efficient installation, and the second as a test of

the 'maximum practical' performance that could be achieved. Once again, data is supplied for a 40 min testing period to avoid data artefacts due to the changing CO_2 concentration and heat build-up in the sealed room. CO_2 was generated with the release of 16 g CO_2 cylinders designed for tyre inflation, and monitored with a portable Infra-Red Gas Analyser (IRGA; TSI IAQ-CALC, TSI Inc., MN, USA). A domestic floor fan was used to circulate air within the room during the trials. temperature inside the sealed room increased from 23–28°C during each trial, and the room was cooled and fully ventilated between trials. Modules of *Chlorophytum* and *Epipremnum* were tested independently, and with fans both off and running at 3.5 m s^{-1}.

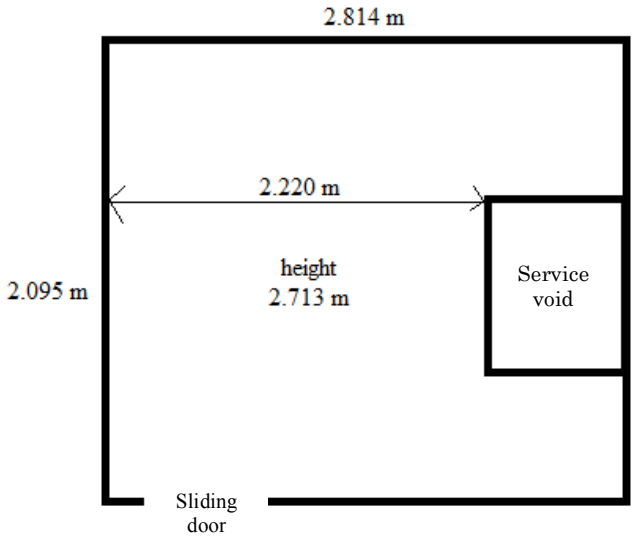


Figure 6: Dimensions of the sealed test room

Results and Discussion

Results for sealed room trials are displayed as the absolute amount of CO_2 draw down (ppmv) rather than as percentages to allow generalization to rooms of different sizes.

Results for *Chlorophytum* green walls at 50 □mol.m^{-2}.s^{-1} are shown in Figure 7. Unlike the chamber trials, the fans relatively minor effect on CO_2 draw down in the sealed room, giving credence to Llewellyn and Dixon's (2011) claims that chamber trials may be unrepresentative of real-world circumstances (see Modelling Calculations section for a quantitative estimate of the fan effects). In any case, the modules removed considerable quantities of CO_2. For easier interpretation, CO_2 draw down has been recalculated on a ppmv-lost basis, the models for which are shown in Figure 8. The linear models from this pattern

have been used to calculate the net CO_2 removal of the modules (see following section).

Figure 7: Sealed room trials of CO_2 draw down (as ppmv) for four modules containing *Chlorophytum* at 50 □mol.m^{-2}.s^{-1}, with module fans off (dotted line) and running at full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.

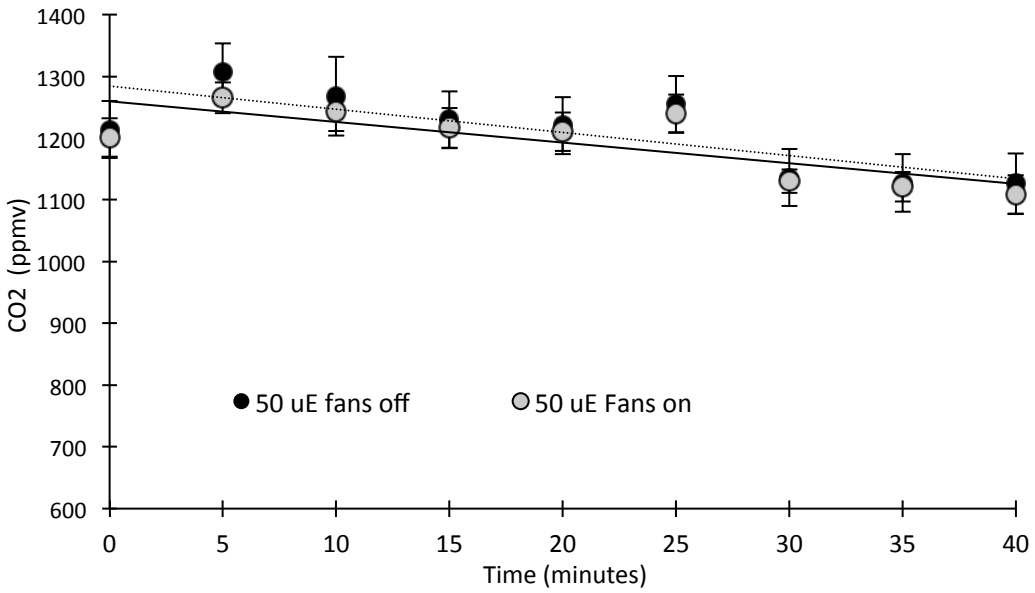
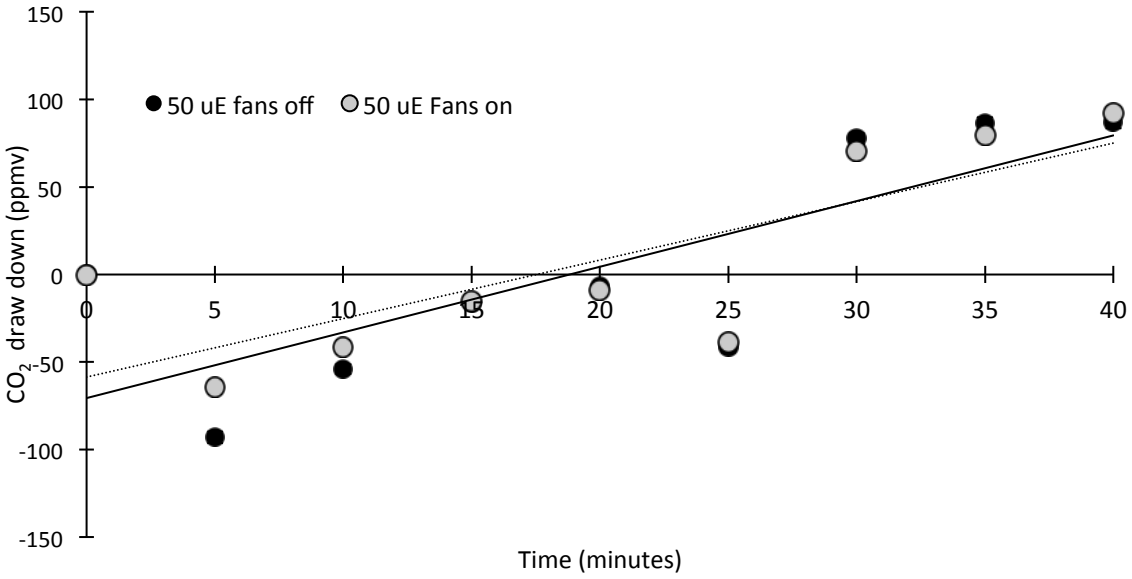


Figure 8: Sealed room trials of CO_2 draw down (as ppmv CO_2 removed) for four modules containing *Chlorophytum* at 50 □mol.m^{-2}.s^{-1}, with module fans off (solid line) and running at full output (3.5 m.s^{-1}; dotted line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



CO_2 removal was more efficient with the 5-fold increase in light level, as predicted (Figures 9 and 10), and once again the fans had a reduced effect on CO_2 removal effectiveness. Overall, *Chlorophytum cosmosum* removed CO_2 very effectively, and would be a sound choice for green walls specifically targeted at improving the CO_2 balance of an indoor space.

Figure 9: Sealed room trials of CO_2 draw down (as % of a starting concentration of ~1000 ppmv) for four modules containing *Chlorophytum* at 250 □mol.m^{-2}.s^{-1} (11500 lux), with module fans off (solid line) and running at full output (3.5 m.s^{-1}; dotted line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.

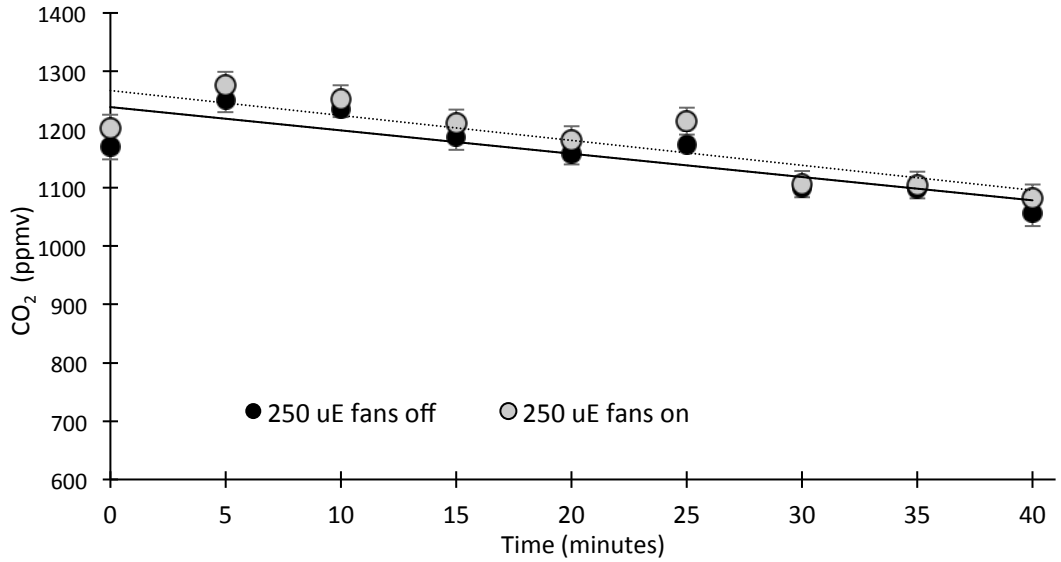
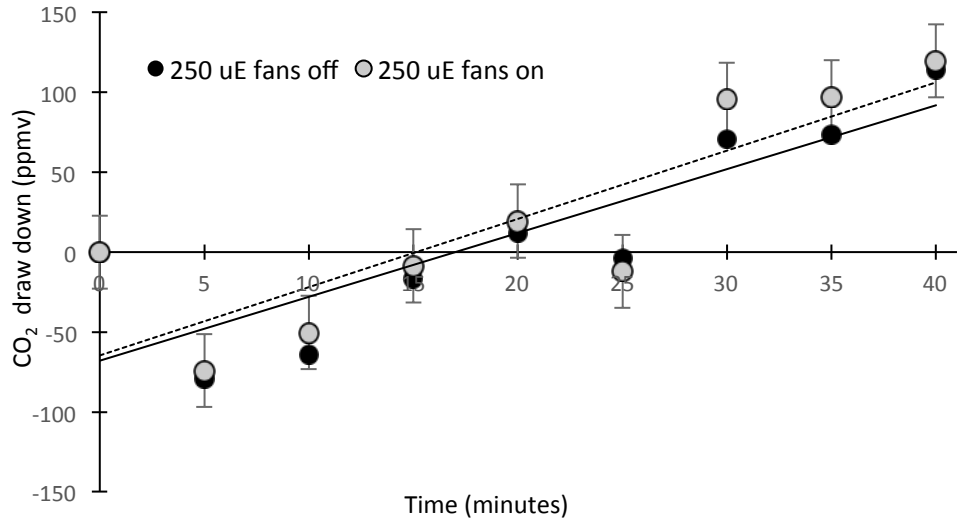


Figure 10: Sealed room trials of CO_2 draw down (as ppmv CO_2 removed) for four modules containing *Chlorophytum* at 250 □mol.m^{-2}.s^{-1}, with module fans off (solid line) and running at full output (3.5 m.s^{-1}; dotted line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



In contrast with modules containing *Chlorophytum cosmosum*, *Epipremnum aureum* had a minor effect on the CO_2 concentration of the sealed room, whether at moderate light (50 □mol.m^{-2}.s^{-1}; Figure 11 and 12) or high light (250 □mol.m^{-2}.s^{-1}; Figure 13 and 14). At the low levels of CO_2 removed, the linear modelling exercise to estimate the net CO_2 removal efficiency of these modules may have lower accuracy. In any case, *Epipremnum* was far less effective at CO_2 removal on a room scale than *Chlorophytum*, and would be an lesser choice for CO_2 amelioration in indoor spaces.

Figure 11: Sealed room trials of CO_2 draw down (as ppmv) for four modules containing *Epipremnum* at 50 □mol.m^{-2}.s^{-1}, with module fans off (dotted line) and running at full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.

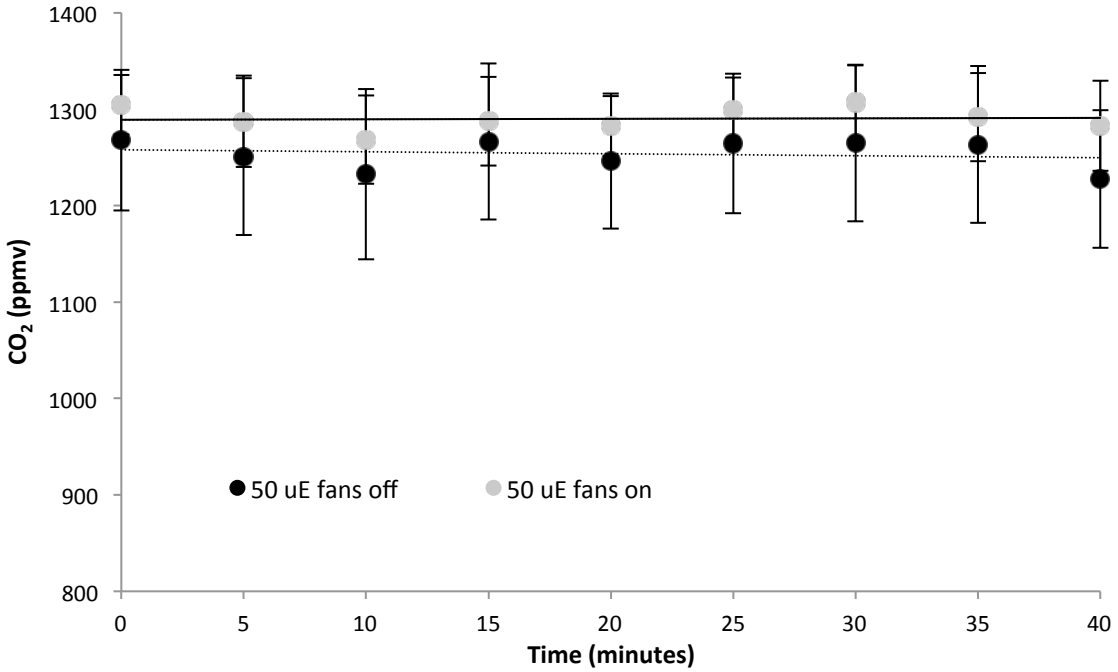


Figure 12: Sealed room trials of CO_2 draw down (as ppmv CO_2 removed) for four modules containing *Epipremnum* at 50 □mol.m^{-2}.s^{-1}, with module fans off (dotted line) and running at full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.

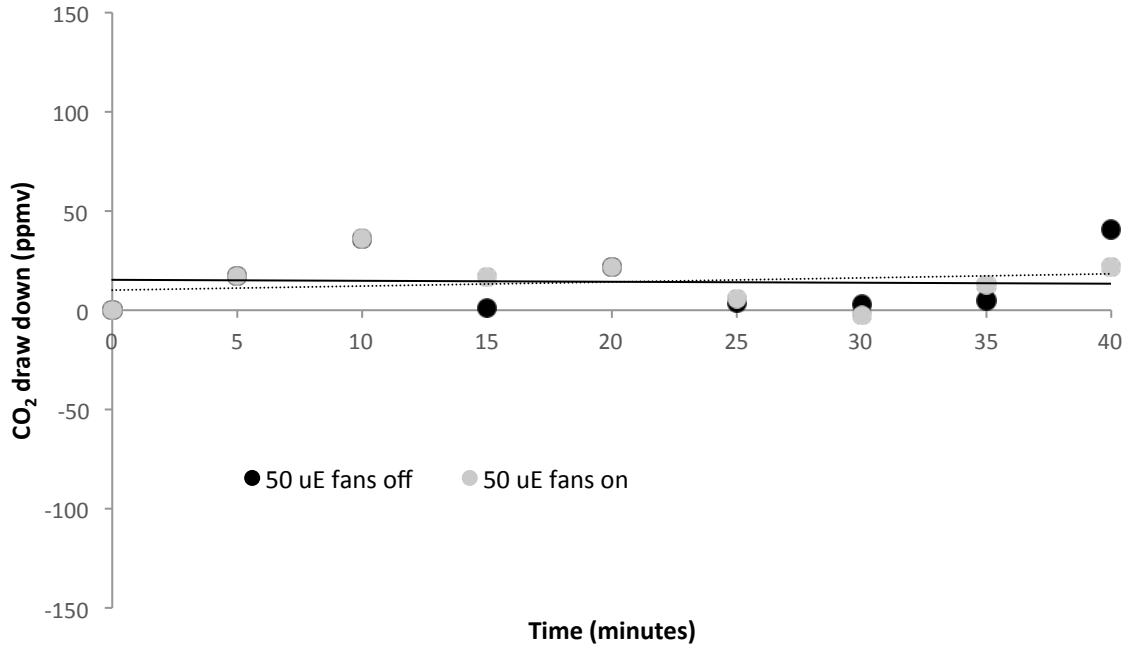


Figure 13: Sealed room trials of CO_2 draw down (as % of a starting concentration of ~1000 ppmv) for four modules containing *Epipremnum* at 250 □mol.m^{-2}.s^{-1} (11500 lux), with module fans off (solid line) and running at full output (3.5 m.s^{-1}; dotted line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.

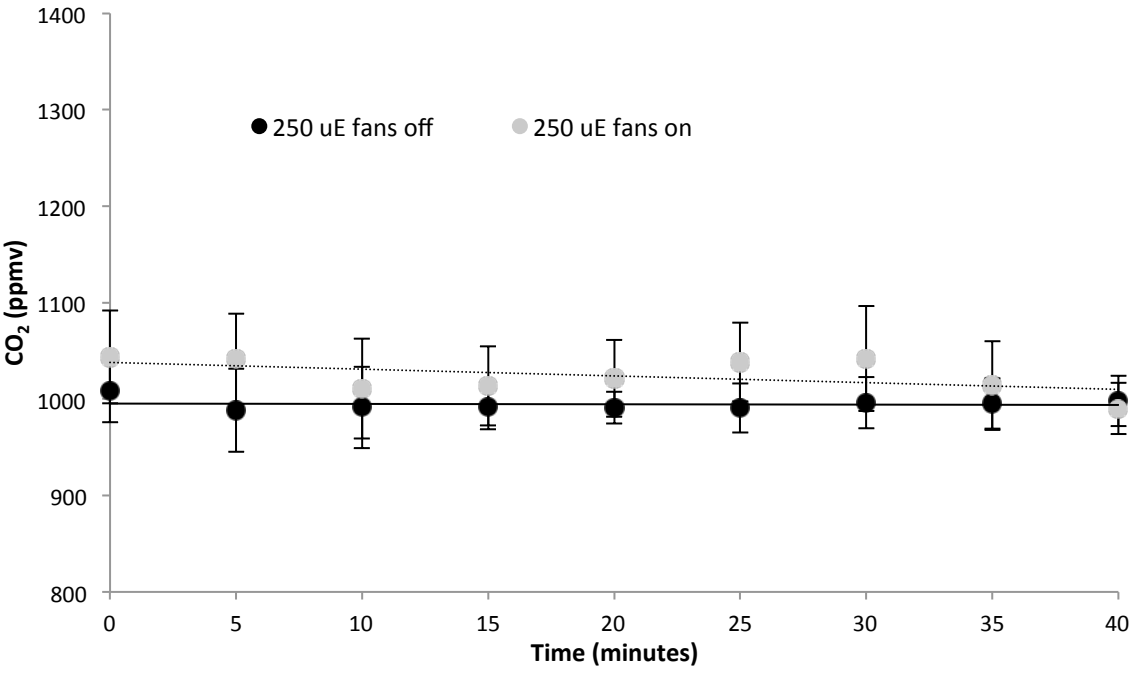
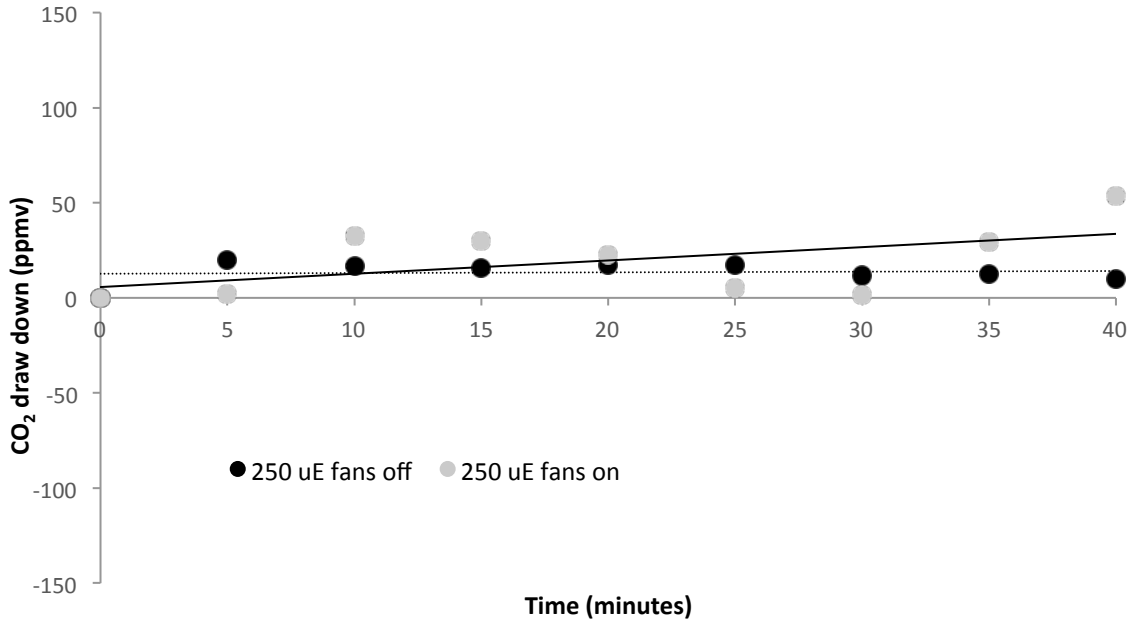


Figure 14: Sealed room trials of CO_2 draw down (as ppmv CO_2 removed) for four modules containing *Epipremnum* at 250 □mol.m^{-2}.s^{-1}, with module fans off (dotted line) and running at full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses ('leakage'). Data are means ± SE, n = 3.



Modelling calculations

The linear models representing ppmv CO_2 draw down were used to calculate the net effective CO_2 removal performance of the modules. After determining the CO_2 concentration reduction in the sealed room by the 4 modules by ~90 ppmv over 40 min, the mass of CO_2 removed was calculated based on 1 kg CO_2 at RTP having a mass of 0.5458 m^3 (airproducts.com). Findings are shown in Table 5.

Table 5: Net effective CO_2 removal by 4 modules containing 2 different plant species, at two different light intensities and with module fans off and running at full output (3.5 $m.s^{-1}$). All data are corrected for chamber losses ('leakage').

Plant species	**Light level** □**mol.m^{-2}.s^{-1}**	**Fan speed** **m.s^{-1}**	**Volume of CO_2 removed** **mL.h^{-1}**	**Mass CO_2 removed** **g.h^{-1}**
Chlorophytum	50	0	2418	4.43
	50	3.5	2221	4.07
	250	0	2688	4.92
	250	3.5	2999	5.49
Epipremnum	50	0	194	0.35
	50	3.5	351	0.64
	250	0	232	0.43
	250	3.5	745	1.36

Chlorophytum clearly outperformed *Epipremnum* in these trials as was the case in the chamber experiments, indicating that it should be considered a 'preferred' species for functional use in the Breathing Wall. It should be noted that the plant hybrid used had variegated foliage — thus a proportion of the leaves were not photosynthetically functional. It is likely that selecting non-variegated *Chlorophytum* hybrids could be expected to further improve the CO_2 draw down performance of the green wall, potentially by a substantial margin given that an estimated 50% of the leaf areas of the tested plants was non-photosynthetic.

Epipremnum also removed CO_2 at both moderate and high light levels, and so would also contribute to functionality in a mixed plant arrangement.

On average, fan operation increased CO_2 removal, as was the case in the chamber experiments. *Chlorophytum* at a moderate light level was the singular exception to this, although in this case there was very little difference in CO_2

draw down with fans on or off. Overall, these findings once again indicate that running the modules with fan operation will, in most cases, result in an increase in CO_2 removal, and can be recommended for use.

Increasing the light available to the modules predictably increased CO_2 removal. On average, increasing the light levels between 50 and 250 □mol.m^{-2}.s^{-1} increased CO_2 draw down rates by 45.3%, but with a high degree of variability between treatments groups (between 11.1% for *Chlorophytum* with fans off to 112.5% for *Epipremnum* with fans on). The difference between CO_2 removal rates might not justify the additional energy requirements for this substantial increase in lighting, depending on the efficiency of the light source.

Plant efficiency at ameliorating respiratory CO_2 emissions has been modelled previously (Irga et al 2013, Torpy et al 2014). Irga et al (2013) estimated that an average human exhales 34.5 g CO_2.h^{-1}. Based on this estimate, 4 modules containing *Chlorophytum* at 250 □mol.m^{-2}.s^{-1} with the fans running would be capable of balancing out ~16% of the respiratory CO_2 from a single occupant. Twenty modules would thus balance out one person's respiratory emissions. Given that offices are generally occupied for 6–8 h.d^{-1}, with an unoccupied period in the middle of the day, 8–12 modules would be a logical starting estimate for a single occupant office if a self-sustaining system was desired.

The air conditioning power required for a room similar to the test space is ~1.77 –3.2 kW (range determined from a large number of commercial online calculators). Whilst running, the plant wall arrangement tested used a maximum of only 0.352 kW (108 W for the strip LED arrays, 180 W for the 90 LED arrays, and 64 W for the fans). Thus for a single occupant, 0.227–0.456 kWh could be saved by using four modules in a room.

Guo et al (2014) performed an experiment along similar lines to the current one. These authors tested the capacity of indoor salad gardens to balance the respiratory emissions of humans, in the context of sustainable space travel. The study tested CO_2 removal at 450– 550 □mol.m^{-2}.s^{-1} from red and blue LEDs, with a 24 h photoperiod, inside a 246.4 m^3 sealed facility. The authors found that increasing the light level from 450–550 □mol.m^{-2}.s^{-1} had a large effect on CO_2 removal rate. The area of the plant-growing beds in Guo et al's (2013) study were 23.2 m^2, and was capable of balancing the respiration of 2 humans, removing 2380 g CO_2 d^{-1}. This is equivalent to 4.7 g CO_2 m^{-2}.h^{-1}, which is somewhat lower than the performance we detected for *Chlorophytum* at a light level less than 50% of Guo et al's (2013) study. It thus appears that the performance of the Breathing Wall modules is high — salad vegetables would be expected to remove CO_2 at a very high relative rate due to their rapid growth habit.

In conclusion, the current study indicates that the Breathing Wall modular green wall system has the potential to efficiently remove substantial CO_2 from indoor air, and in a well-designed installation to potentially balance out the respiratory emissions of a modest number of inhabitants. For this to occur, several factors should be considered:

1. Plant choice takes into account their ability to remove CO_2: smaller installations may need more efficient plants, whilst larger systems proportional to the number of occupants may perform well with less efficient species

2. Sufficient light is supplied. Our findings indicate that 250 □mol.m^{-2}.s^{-1} is a suitable light level for a highly efficient green wall, whilst some CO_2 will still be removed at 50 □mol.m^{-2}.s^{-1}. Below 10–25 □mol.m^{-2}.s^{-1} the modules will increase indoor CO_2 levels.

3. Plants be maintained with regard to substrate moisture, and plant coverage over the exposed front of the modules

PART III: PARTICULATE MATTER DRAW DOWN ASSESSMENT

Background

The effects of airborne particulate matter (PM) on human health include well-established links to asthma, lung cancer and cardiovascular disease (Perrino 2010), with tested associations between the PM concentration in ambient air and the rate of morbidity due to respiratory and cardiovascular diseases. It has also been suggested that there may be a link between PM exposure and autism (Volk et al 2013). The specific health effect of PM depends on the size, shape and chemical composition of the particles (Dockery and Stone, 2007; Perez et al 2009; Perrino 2010).

Compared to other air pollutants, there is comparatively little literature on the capacity of indoor plants to reduce ambient PM levels. Lohr and Pearson-Mims (1996) compared PM deposition on surfaces in rooms with and without plants, and found that the rooms with plants accumulated lower deposited PM. Gawro□ska and Bakera (2014) showed that the leaves of *Chlorophytum cosmosum* has a high affinity for trapping PM through deposition on the leaf surfaces. Thus there may be some potential for indoor plant systems to control PM levels indoors, but clearly substantial further research is required. Moreover, the addition of ventilation to the Breathing Wall modules, along with their dense vegetation, could be expected to improve their capacity to remove PMs over traditional passive potted-plants.

This experiment aimed to provide proof-of-concept that the Breathing Wall modules have PM-reducing capabilities. For this trial we used sealed chambers and the emission from burning diesel fuel as a model PM source. The *in situ* effectiveness of the modules to control PM will be tested in a later stage of this research.

Methods

These tests followed a similar procedure to the CO_2 chamber trials, and used the same 216 L sealed perspex chambers with 100 mm fans for air circulation.

PM was generated by burning a small quantity of diesel fuel in a spirit burner and collecting the smoke in a large glass vessel. After allowing larger particles to precipitate for 5 min, ~50 mL of the gas containing suspended PMs was admitted to the chambers via a syringe, producing approximately 1000 $\mu g.m^{-3}$ of total suspended particulate matter (TSP). Time-course chamber PM analysis was performed using a Dust track II laser densitometer, sealed in the chambers.

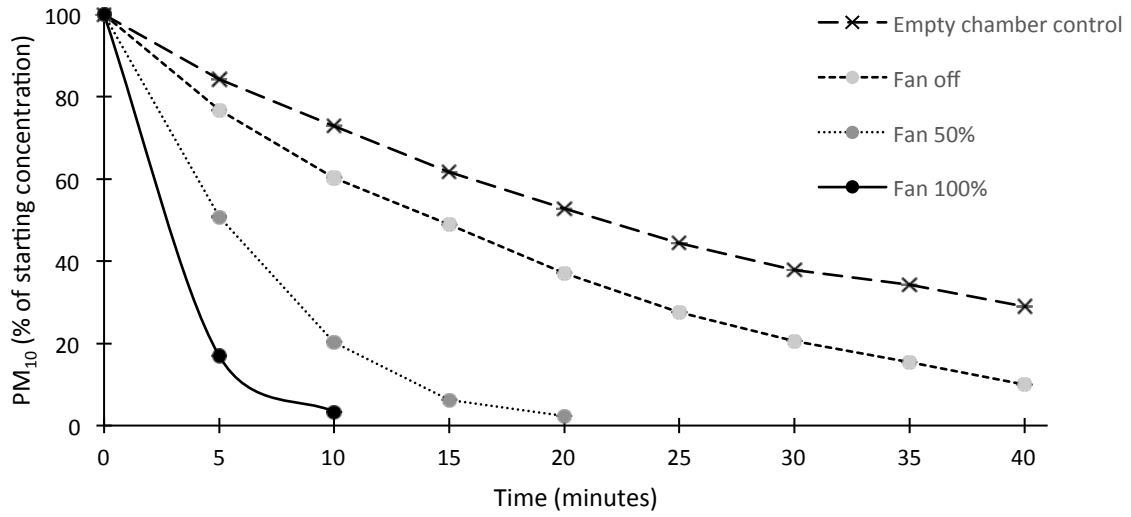
Single modules were tested at three fan operation modes (fans off, half full output (1.75 $m.s^{-1}$) and full output (3.5 $m.s^{-1}$). Modules containing both *Chlorophytum* and *Epipremnum* were tested separately, with 100 □$mol.m^{-2}.s^{-1}$ light level supplied by Wotan fluorescent tubes. As different sizes of PM have different health consequences, trials were performed for both particles under 10 □m diameter (PM_{10}) and particles under 2.5 □m diameter ($PM_{2.5}$). Separate modules were used for all trials.

Data was collected until chamber air reached ambient PM levels (~25 $\mu g.m^{-3}$). However, despite the air circulation fans in the chambers, substantial precipitation of the particulate matter was detected in empty chamber control trials — approximately 80% per hour of both PM_{10} and $PM_{2.5}$ was precipitated out or adhered to the chamber walls. To deal with this, empty chamber-corrected data only for the first 15 min of operation has been shown. This data is sufficient to demonstrate both the speed of PM draw down when the modules were present, and the effect of the fans.

Results and Discussion

PM removal from the chambers followed a general pattern demonstrated in Figure 15. However as noted, the large empty-chamber PM precipitation rates made use of the full data sets invalid (modelling empty-chamber corrected PM removal rates for the modules would extend below zero after ~20 min). It should be noted that with the fan of full speed, the initial concentration of PM was removed in ~10 min.

Figure 15: Pattern observed for PM removal trials.: example data for *Chlorophytum cosmosum*, PM_{10}. Data are means ± SEM, n = 3.



Fan operation had a major effect on PM removal. Whilst the modules with fans off removed PM considerably faster than the empty chamber precipitation rate, fan operation, whether on half or full speed, dramatically increased the effect. Patterns of removal were very similar for both species, and for PM_{10} and $PM_{2.5}$ (Figures 16–19). With the fans at full speed, 62–66% of the PM was reduced within 5 min, and ambient levels (empty chamber losses corrected) were achieved between 10 and 15 min in all cases. With fans on half speed, between 34 and 47% of chamber PM was removed within 5 min, and chamber PM reached ambient levels after 60–100 min (data not shown).

Figure 16: Chamber trials of particulate matter <10 □m (PM_{10}; % of an initial starting concentration of ~1 mg/m^{-3}) removal by modules containing *Chlorophytum* with module fans off (dashed line), half full output (1.75 m.s^{-1}; dotted line) and full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses. Data are means ± SE, n = 3. Note that due to chamber losses, the PM_{10} concentration in the chambers containing modules cannot decrease below ~25 %.

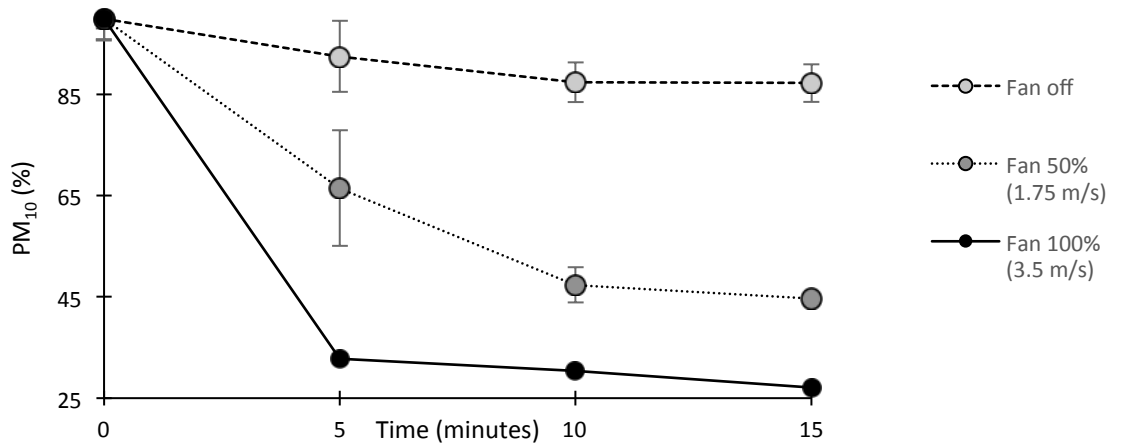


Figure 17: Chamber trials of particulate matter <10 □m (PM_{10}; % of an initial starting concentration of ~1 mg/m^{-3}) removal by modules containing *Epipremnum* with module fans off (dashed line), half full output (1.75 m.s^{-1}; dotted line) and full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses. Data are means ± SE, n = 3. Note that due to chamber losses, the PM_{10} concentration in the chambers containing modules cannot decrease below ~25 %.

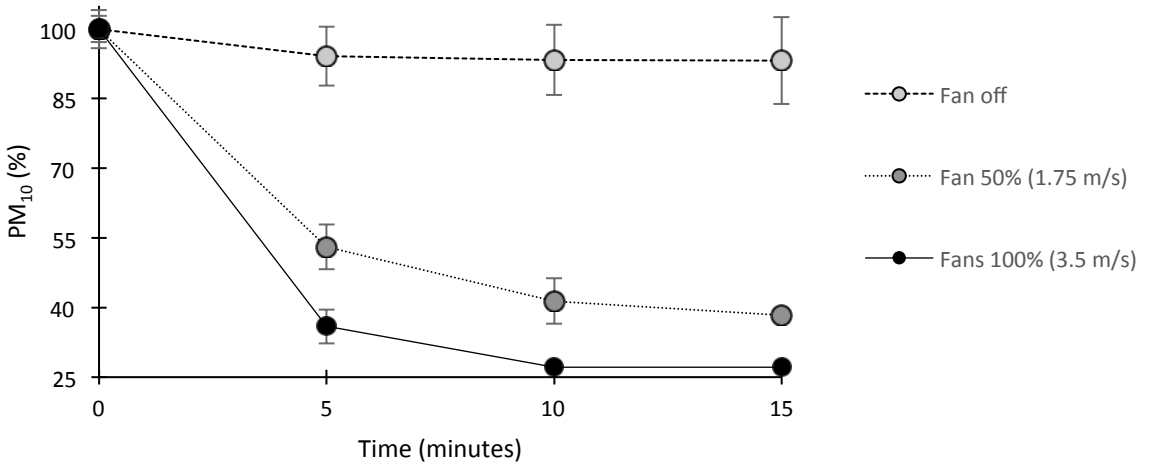


Figure 18: Chamber trials of particulate matter <2.5 □m ($PM_{2.5}$; % of an initial starting concentration of ~1 mg/m^{-3}) removal by modules containing *Chlorophytum* with module fans off (dashed line), half full output (1.75 m.s^{-1}; dotted line) and full output (3.5 m.s^{-1}; solid line). Data are corrected for chamber losses. Data are means ± SE, n = 3. Note that due to chamber losses, the $PM_{2.5}$ concentration in the chambers containing modules cannot decrease below ~25 %.

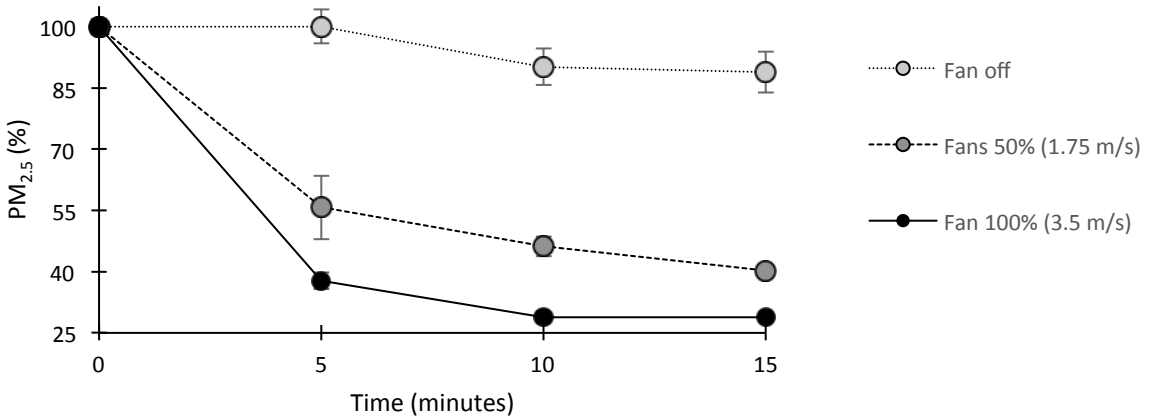
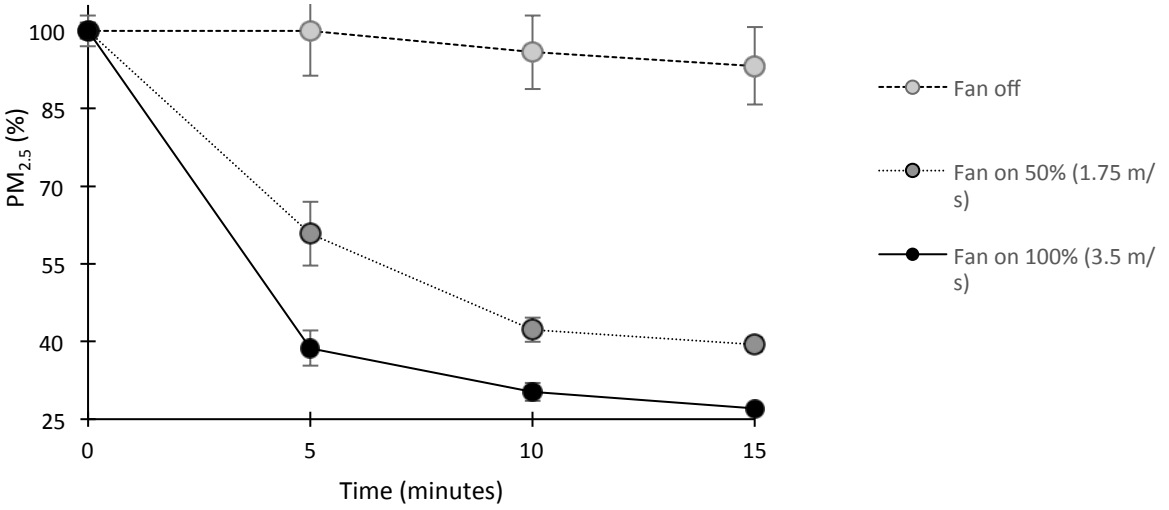


Figure 19: Chamber trials of particulate matter <2.5 □m ($PM_{2.5}$; % of an initial starting concentration of ~1 mg/m^{-3}) removal by modules containing *Epipremnum* with module fans off (dashed line), half full output (1.75 $m.s^{-1}$; dotted line) and full output (3.5 $m.s^{-1}$; solid line). Data are corrected for chamber losses. Data are means ± SE, n = 3. Note that due to chamber losses, the $PM_{2.5}$ concentration in the chambers containing modules cannot decrease below ~25 %.



Thus the Breathing Wall modules are extremely efficient at PM removal when the fans are in operation, especially at the higher tested input velocity of 3.5 $m.s^{-1}$.

In buildings, the mechanical ventilation component of HVAC systems prevents the intrusion of a large fraction of particulate matter through simple filtration (Park et al 2014). In an unrelated experiment (Irga et al — manuscript submitted to *Building and Environment*) recently assessed the difference between ambient and indoor PM concentrations for a number of Sydney buildings and found that whilst there was a consistently lower level of PM in buildings with HVAC than naturally ventilated ones, the difference was not statistically significant (ANOVA; n = 12; P = 0.142), with on average only ~3 □$g.m^{-3}$ greater concentration in naturally ventilated buildings. It is thus plausible that a building using a fan-ventilated green wall could experience lower PM levels one using than a mechanically ventilated system. Expansion of the current work to an *in situ* study will be required to fully test this hypothesis.

Comparing the efficiency of PM filtration by the modules to HVAC filtration is difficult. Whilst ASHRAE Standard 52.2 describes a range of minimum efficiency reporting values (MERV), ASHRAE 52.2 (2015) does not explicitly state values for PM_{10} or $PM_{2.5}$ removal efficiency (Azimi et al 2014), as a number of different

PM size classes are used. This Standard also defines single-pass filtration efficiency, whilst the air containing PM in the current experiment could circulate through the module many times during the testing period. Future research will be directed at determining the single-pass efficiency of the modules so as to better align with ASHRAE standards and allow comparison with HVAC filtration media, and also to determine the filtration efficiency of the modules with a broader particle size distribution.

PART IV: SOUND ATTENUATION CAPACITY OF JUNGLEFY BREATHING WALL MODULES — PRELIMINARY TRAIL

Whilst there has been limited research into the capabilities of green walls to reduce indoor noise levels, there have been a range of studies on roadside vegetation that have demonstrated strong noise reduction potential (eg. Van Renterghem et al 2012). Azkorra et al (2015) performed a study explicitly quantifying green wall sound reduction. These authors found a sound reduction of 15 dB for a modular system, assessed in a soundproof room. Wong et al (2010) tested the sound absorption characteristics of a range of vertical green wall systems, detecting low to middle frequency sound reductions of 5–10 dB and high frequency reductions generally between 2–3.9 dB. As a component of the development of the Breathing Wall system for the management of the maximum aspects of the indoor environment, we thus performed a basic laboratory trial to determine whether the Breathing Wall modules had the capacity to reduce reflected sound levels.

Methods

The 'control' treatment for this test was a flat laminated MDF board ('reflecting screen') of the same dimensions as the front surface of the modules (500 mm^2). The surrounding conditions in the laboratory were not altered in any way between samples (although we tested the effect of moving proximal items outside of the sound channel, and detected no effects).

Sound was recorded with a Digitech environment meter. The data variable recorded with this meter is dBc, which measures relative signal power ratios. This variable is sufficient to determine whether there are differences between the sound level reflected from the modules and reflecting screen, within the frequency range produced by our device. Standard sound attenuation experiments use ISO 10534–2 and sound absorption coefficient spectra, which required testing with an impedance tube. All sound levels recorded include background ambient noise at 70.8 dBc. Readings were taken once the sound level stabilised (approximately 60 seconds), after which we estimated the midpoint of the fluctuating values produced. Fluctuations were approximately 0.3 dBc.

Measurements were taken with the sound recording device and reflecting screen and modules in precise locations (± 5 mm). Sound generation was from a noisy laboratory instrument (Griffin flask shaker) set to produce a reflected sound level of 89.1 dBc at 500 mm, and 90.2 dBc at 1000 mm from the reflecting screen. This machine produces a mechanical noise which will contain a mixture of a large range of frequencies.

The sound generating device was positioned ~1250 mm from the testing plane, and fixed to the laboratory floor. The initial test measured reflected noise with the reflecting screen in place at 500 and 1000 mm distances from the screen, with the noise meter facing the reflecting screen.

We then replaced the reflecting screen with a single module containing healthy *Chlorophytum cosmosum* in all cells. We then recorded reflected sound in two permutations: 1. The surface of the outermost leaves at the level of the testing plane ('Leaf surface'); 2. The front surface of the modules at the level of the testing plane ('Module front surface').

Results and Discussion

The findings from this trial are shown in Table 6:

Table 6: Noise attenuation trial results

Reflector	Reflected sound at 500 mm (dBc)	Reflected sound at 1000 mm (dBc)
Laminated MDF	89.1	90.2
Leaf surface	86.5	88.2
Module front surface	85.0	88.7

The modules thus absorbed substantial noise levels. It should be noted that dBc is measured on a logarithmic scale, thus the 4.1 dBc maximum reduction recorded is 41% lower than that reflected from the flat screen, which is substantial, and within the range of values detected by Wong et al (2010), despite our basic apparatus. The greatest reduction was recorded with the sound meter at 500 mm from the module front surface. We repeated these measurements several times to ensure their accuracy.

Without further testing, we cannot determine the effect of the modules on sound of different frequencies, or whether multiple modules have a greater effect than a single module. Sound attenuation at greater differences from the plant surface also cannot be determined from this trial, nor how these findings can be applied in real-world circumstances. Nonetheless, it is apparent that the modules have considerable noise dampening potential, and further research is warranted into the magnitude of this effect.

PART V: REFERENCES

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