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# Analysis of lighting conditions of indoor living walls: effects on CO<sub>2</sub> removal

Laura Dominici <sup>a#\*</sup>, Robert Fleck <sup>b#</sup>, Raissa L Gill <sup>b,c</sup>, Thomas J Pettit <sup>b</sup>, Peter J Irga <sup>d</sup>, Elena Comino <sup>a</sup>, Fraser R Torpy <sup>b</sup>.

<sup>a</sup> Applied Ecology Research Group, Department of Environment, Land, and Infrastructure Engineering (DIATI), Politecnico di Torino, Italy.

<sup>b</sup> Plants and Environmental Quality Research Group, School of Life Science, University of Technology Sydney, Australia

<sup>c</sup> Coastal Oceanography and Algal Research Team, Climate Change Cluster, Faculty of Science, University of Technology Sydney, Australia

<sup>d</sup> Plants and Environmental Quality Research Group, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Australia

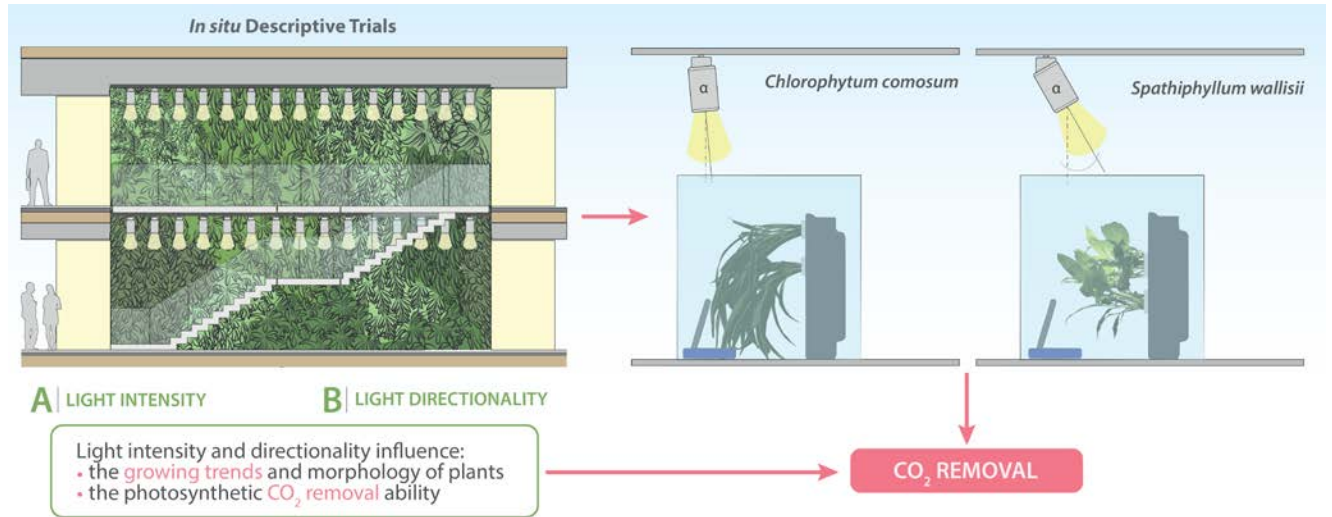
\* Corresponding Author. Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering (DIATI). Email address: [laura.dominici@polito.it](mailto:laura.dominici@polito.it)

# These authors contributed equally to this manuscript.

## Abstract

Vertical greening systems, or living walls, are becoming increasingly used indoors for improving the sustainability of buildings, including for the mitigation of excess CO<sub>2</sub> levels, derived from human respiration. However, light provision within indoor environments is often insufficient for the efficient functioning of many plant species, leading to low photosynthetic CO<sub>2</sub> removal rates, and the need for supplementary light sources. In this study, we investigated the performance of supplementary lighting employed for indoor living wall systems, and whether optimised lighting conditions could lead to improved CO<sub>2</sub> removal. *In situ* trials with several medium-large indoor living walls were performed to sample the lighting scenarios currently employed. We concluded that the majority of plants in existing systems were exposed to suboptimal lighting and will have a net-zero CO<sub>2</sub> removal efficiency. Sealed chamber experiments using two common living wall plant species were conducted to explore the effect of varying lighting conditions on CO<sub>2</sub> removal efficiency. Comparisons on optimal and “best case” *in situ* conditions were carried out, showing that CO<sub>2</sub> removal efficiency was significantly correlated with both leaf and stem angles, which suggest phototropism may influence *in situ* CO<sub>2</sub> removal. After a ten-day experimental period, the highest CO<sub>2</sub> removal efficiency for both test plant species was observed at 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> light flux density (~10500 lux) at 15° from the vertical growing surface. Our results indicate that most current lighting systems are inadequate for healthy plant photosynthesis and CO<sub>2</sub> removal, and that modified lighting systems could improve this performance. The estimation of the CO<sub>2</sub> removal ability of a 5 m<sup>2</sup> passive living wall decreases from an ACH of 0.21 h<sup>-1</sup>, achieved in an optimal light exposure condition, to only 0.03 h<sup>-1</sup> when plants are exposed to sub-optimal conditions. To reduce maintenance costs, technical guidelines for indoor living wall lighting should be established, and lighting suppliers should recognise the developing niche market for specialised indoor living wall lighting.

## Graphical Abstract



## Keywords:

Green Building, Sustainability, Green wall, Phytoremediation, Indoor air quality.

## Highlights:

- *In situ* living walls require optimized lighting conditions for high CO<sub>2</sub> removal efficiency.
- Light intensity and directionality influence the CO<sub>2</sub> removal efficiency of indoor living walls.
- Phytosystem selection and design stands to significantly improve indoor CO<sub>2</sub> removal efficiencies.

## 1. Introduction

Densification of cities has led a growing proportion of society becoming urban dwellers, spending approximately 90 % of their time indoors (Klepeis et al., 2001; Liu et al., 2019). Population exposure to many air pollutants is thus increasingly determined by their concentrations within the indoor environment (Molloy et al., 2012; Riviere, 2010), with indoor air quality increasingly recognised as a significant health concern. Carbon dioxide (CO<sub>2</sub>), derived mainly from occupant respiration, is a major determinant for the control of indoor environmental air quality. Even if CO<sub>2</sub> is considered a non-toxic compound at ambient concentrations and there is little evidence of clinical issues on human cognitive performances at high concentrations (Du et al., 2020; Fisk et al., 2019), many guidelines consider it as a metric of poor ventilation and indoor air quality. Indeed, the monitoring of indoor CO<sub>2</sub> concentration is adopted as marker for heating, ventilation and air conditioning (HVAC) systems operation in order to maintain adequate indoor air quality and thermal comfort standards in public buildings (Franco and Schito, 2020). Human respiration is considered as a significant source of CO<sub>2</sub> in non-industrial indoor environment (Azuma et al., 2018; Shen et al., 2020) and its concentration along with indoor temperature are used as parameters to operate the automatic control of HVAC systems through the regulation of ventilation rates (Li et al., 2020). However, they use considerable electrical energy, especially when the ambient air requires substantial heating or cooling prior to entering the indoor environment (Ben-David and Waring, 2016). Thus, there is a need to explore alternative, low-energy-use systems for the maintenance of CO<sub>2</sub> concentrations in indoor environments.

Vertical greening systems, also referred to as green walls or living walls, may be an effective nature-based solution to improve indoor environments and reduce the costs associated with HVAC systems (Irga et al., 2017; Pearlmutter et al., 2020). Living walls are characterised by infrastructure that enables ornamental plant species to be grown on, or within, indoor and outdoor wall spaces (Newton et al., 2007). The innate biophilic qualities of these systems are often desirable for indoor environments due to their therapeutic psychological effect of building occupants (Bringslimark et al., 2009; Montacchini et al., 2017; Tifferet and Vilnai-Yavetz, 2017; van den Berg et al., 2016). However, a commercially underappreciated aspect of living walls is their ability to remove indoor air contaminants such as volatile organic compounds, particulate matter and CO<sub>2</sub> (Aydogan and Montoya, 2011; Gubb et al., 2018; Moya et al., 2018; Oh et al., 2011; Pettit et al., 2018; Soreanu et al., 2013; Wolverton et al., 1989). Through photosynthesis, living walls are able to effectively reduce the concentrations of CO<sub>2</sub> from indoor environments, however lighting conditions have a strong influence on the efficacy of this process (Torpy et al., 2017).

Indoor living walls are often situated in areas where they have the greatest aesthetic impact on building occupants such as hallways, conference rooms or as a backdrop to building lobbies. Consequently, these locations often do not allow for adequate natural sunlight at the plant surfaces (Tan et al., 2017), and therefore, many systems are illuminated with supplementary artificial lighting. As light is a fundamental requirement for photosynthesis, the provision of sufficient lighting is essential to maintain plant health and facilitate CO<sub>2</sub> removal (Pennisi and van Iersel, 2012). Currently, there has been little research into the provision of optimal lighting for medium to large scale indoor living wall installations (Egea et al., 2014; Kaltsidi et al., 2020; Tan et al., 2017).

Various qualitative and quantitative aspects of light affect the photosynthetic activity and photomorphogenesis of indoor plants (Cope et al., 2014). Both light intensity (photon flux density) and photoperiod play a vital role in light-sensing and light-acclimatory processes, both of which regulate key physical and chemical plant mechanisms such as disease defense signaling (Karpinski et al., 2003) and photosynthesis. Within the indoor environment, light intensities and duration are often designed for human comfort during occupation periods, with light intensities of 500 to 1000 lux (equivalent to photosynthetic photon flux densities of  $\sim 10 - 50 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) being commonly used (European committee for standardization, 2011). These levels are significantly lower than the photosynthetic requirements of many plant species (Kim et al., 2012; Torpy et al., 2014), and often do not align with natural diurnal cycles.

Furthermore, the absorption of light and the resulting photosynthetic response are determined by the interaction between light directionality, and leaf orientation (Posada et al., 2012). Many plants are able to adapt to dynamic lighting conditions by changing the orientation of their leaves through phototropism, thus maximizing the light irradiance at the leaf surface (Goyal et al., 2013), however there is no existing literature describing the influence of phototropism and the effect of current commercial lighting systems on CO<sub>2</sub> removal for indoor living walls.

The current study seeks to establish a rationale for the development of technical guidelines for lighting designs for indoor living walls through manipulative laboratory experiments informed by *in situ* observations of current lighting conditions, that aimed to: (i) assess the influence of varying light intensities and light angles on CO<sub>2</sub> reduction by living walls containing two common indoor plant species, and (ii) explore the effect of living wall phototropism on CO<sub>2</sub> removal under varied lighting conditions, reflective of *in situ* conditions.

## 2. Materials and Methods

### 2.1. *In situ* living wall lighting assessment

Prior to conducting manipulative laboratory experiments, the lighting conditions of four indoor living walls (LW 1 - 4) from multi-story commercial buildings in the Greater Sydney area were assessed *in situ* (Supplementary Table 1). Indoor living walls one and two (LW 1 & LW 2) each had vertical surface areas of 60 m<sup>2</sup> and were comprised of 240 individual botanical biofilter modules (0.25 m<sup>2</sup>), while living walls three and four (LW 3 & LW 4) had vertical surface areas of 27 and 16.25 m<sup>2</sup> and contained 108 and 65 individual botanical biofilter modules respectively (Fig. 2).

Botanical biofilter modules used in the commercial systems were made from recycled low-density polyethylene, containing a coconut husk-based growth substrate and designed with 16 front-facing holes into which the following plant species were grown: *Chlorophytum comosum*, *Spathiphyllum wallisii*, *Epipremnum aureum*, *Philodendron xanadu*, *Peperomia obtusifolia*, *Nephrolepis exaltata*, *Neomarica gracilis* and *Gibasis* sp.. The four living walls were selected as they were all installed in environments lacking exposure to natural light and were thus reliant wholly on artificial lighting.

At LW 1, 2 and 4, lighting was supplied by adjustable LED spotlights (COB LED spotlight, model PLD-TL-40W-F1, 130 x 200 cm, 40 W, 60° beam angle, 3000 K warm white, produced by the Huizhou Plamd Lighting Technology Co., China), installed above the living walls at a distance of 0.8 – 1 m from the planted surfaces and 0.2 m from one another. Lighting at LW 3 was supplied by in-ceiling LED downlights, 1 m from the planted surfaces, and 1 m from one another. The intensity of photosynthetically active light (photosynthetically active radiation (PAR);  $\lambda = 400 - 700$  nm) was measured with a Li-250A light meter (Li-Cor Biosciences, USA) at a distance of 0.5 m from the living wall surface (in front of plant foliage). Light intensity was measured at the wall surface either at 0.5 or 1 m vertical intervals, dependent on wall design (Fig. 2).

Lighting devices at LW 1 and 2 were photographed using a Nikon D3200 camera (ISO 100, f. 3.8, t 1/100) to establish the lighting profile and average inclination of luminaries (light angle) relative to the front surface of the walls. Images were taken from the left and right sides of the walls, at a height equal to the luminaries' position. Only LW 1 and 2 were considered for light angle evaluation as they utilised a consistent number of luminaries and represented a larger and more comprehensive lighting design than LW 3 and 4.

Image analysis was performed using Adobe Photoshop CC (Adobe Systems) and AutoCAD 2019 software (Autodesk Inc., USA) to determine the inclination angle between the vertical and the luminaire's axis for 50 luminaries (Supplementary Fig. 1). Each luminaire was isolated from photographs using Adobe Photoshop CC's (1) [Polygonal Lasso] tool to draw straight-edged segments of the selected luminaire's border, (2) the [Select > Inverse] tool was used to select the background pixels and (3) the [Crop] tool was used to delete background pixels. Luminaries were imported into the AutoCAD environment featuring a re-created layout setting of LW 1 and 2 for each lighting device. Finally, the [Measure > Angle] tool was used to calculate the luminaire's inclination angle.

## **2.2. Plant module experimental set up**

*Chlorophytum comosum* and *Spathiphyllum wallisii* were the plant species selected for manipulative examination in this study, as they are frequently used in indoor living wall applications (Egea et al., 2014; Pérez-Urrestarazu et al., 2016), were the most prevalent species in *in situ* observations, and have previously been recommended for the phytomitigation of indoor air pollution (Torpy et al., 2017; Wolverton et al., 1989). While the light requirements of individual plant species differ (Niinemets, 2006), both *C. comosum* and *S. wallisii* are capable of tolerating low light conditions (Torpy et al., 2017), making them ideal for current indoor living wall designs.

Eight individual plants of each species were housed in open-ended PVC pipes (cassettes: 90 mm external diameter and 120 mm in length) containing coco-husk substrate, similar to the substrate used *in situ*, as described previously (Pettit et al., 2018). Plant replicates were adapted to a horizontal growth position at ambient light intensities ( $\sim 6 - 7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ;  $\sim 235$  lux) within a laboratory environment for seven days (temperature  $22.0 \pm 2.3$  °C and relative humidity  $65.8 \pm 15.8$  %). Plants were watered to field capacity weekly and allowed to drain for two days prior to testing. To ensure the plant cassette arrangements were representative of a vertical wall, cassettes

were housed in a frame made of rotary molded polyethylene (500 x 500 x 130 mm;; Supplementary Fig. 2).

During experiments, the rear of the plant cassettes were covered with plastic film to limit respiratory emissions from non-green tissues and microorganisms associated with the growth substrate that would be unrepresentative of living walls with an enclosed growth substrate. (Gubb et al., 2018). Additionally, *C. comosum* plants were arranged in the upper-central module holes (Supplementary Fig. 2). As the experimental test chamber cannot facilitate wall-mounted modules, this arrangement was used to minimise leaf contact with the chamber floor to prevent unrepresentative leaf angles (“floor drag”). Living wall frames with single plant species (henceforth, plant modules) were used to perform subsequent CO<sub>2</sub> removal assessments.

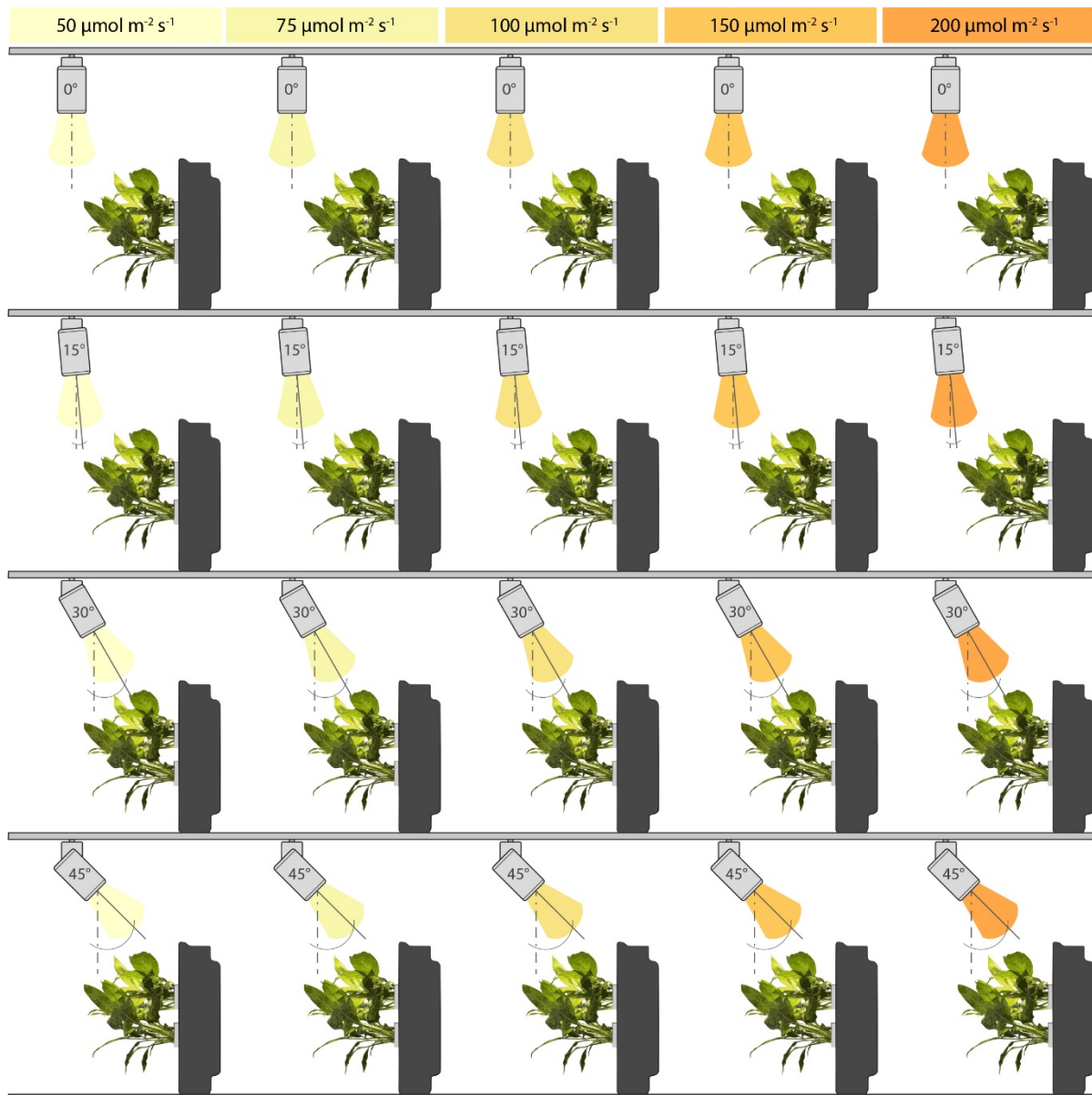
### **2.3. Sealed chamber experiments**

#### **2.3.1 Preliminary study: non-photoadapted CO<sub>2</sub> removal**

To determine the effect of lighting conditions on plant specific CO<sub>2</sub> drawdown, a preliminary study was conducted to assess the optimal lighting conditions for each plant species (Supplementary Table 1). Plants were placed in a sealed chamber and CO<sub>2</sub> drawdown was monitored under varying conditions. As the plants were given no time to adapt their physiology to the lighting conditions in each treatment, the preliminary study was termed “*non-photoadapted CO<sub>2</sub> removal*”. The results from this study were applied over a 10-day period, in which plant species could adjust their physiology to the lighting conditions (*photoadaptation*), similar to how *in situ* plants would. Prior to CO<sub>2</sub> drawdown assessments, total plant leaf area was determined using plant images in AutoCAD.

CO<sub>2</sub> drawdown assessments for both plant species were conducted in sealed Perspex chambers (216 L), fitted with an 80 mm electric fan (12 V) for air circulation. Lighting was provided by a Parscan circular LED spotlight (12 LEDs, 30 W, 3000K warm white; ERCO Lighting Pty. Ltd., Australia) and an Opton square LED spotlight (6 LEDs, 25 W, 3500K warm white; ERCO Lighting Pty. Ltd., Australia), both equipped with a spherulite optical polymer flood lens (ERCO Lighting Pty. Ltd., Australia). Both luminaries were adjustable through 0° - 90° tilt, light housings were rotatable through 360°, and the luminous flux was dimmable (Parscan luminous flux 200 – 6600 lm; Opton luminous flux 200 – 4920 lm). These light systems were selected due to their similarities to luminaries employed *in situ*, light manipulation capabilities, low energy consumption, and low radiant heat output (Morrow, 2008; Ouzounis et al., 2015; Pattison et al., 2018; Yeh and Chung, 2009). Frames were constructed to house luminaries where both spotlights were mounted on a single linear light track power supply (ERCO 3C/DALI, Jadecross, Australia) and positioned adjacent to the test chambers.

Single-species plant modules containing eight plants (Supplementary Fig. 2) were placed within the chamber where light angles and intensities were set vertically (Fig. 1). Four light inclinations (0°, 15°, 30° and 45° from solar apex) were tested in combination with five light intensities (50, 75, 100, 150, and 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ; ~ 1946, 2919, 3893, 5839, and 7785 lux), providing assessments of CO<sub>2</sub> removal for both plant species under 20 lighting scenarios.



**Fig. 1.** Lighting design for angle and intensity used in Experiment 1 for *Spathiphyllum wallisii* and *Chlorophytum comosum*. Species depicted in Fig. is *S. wallisii*.

As indoor CO<sub>2</sub> concentrations trigger many heating, ventilation and air conditioning (HVAC) systems to increase ventilation rates when indoor CO<sub>2</sub> concentrations reach ~1000 ppm (Lawrence et al., 2018), we assessed CO<sub>2</sub> drawdown from a starting concentration of ~1000ppm, generated by respiration until chamber concentrations reached this threshold (mean starting concentrations of CO<sub>2</sub> were 985ppm ± 90ppm). CO<sub>2</sub> drawdown was measured using an infrared gas analyzer (IAQ-CALC 7525, Tsi Inc., USA; Range 0 – 5000ppm, Accuracy ± 3% or 50ppm, Resolution 1ppm, Response Time 20 seconds) which was sealed within the chamber to monitor the concentration of CO<sub>2</sub> at one-minute intervals over a period of 40-minutes. This instrument was brand new with factory calibration at the time of these trials. Instrument specifications were: CO<sub>2</sub> Range 0 – 5000 ppm, Accuracy ± 3% or 50 ppm, Resolution 1 ppm, Response Time 20 seconds. These experiments were performed in triplicate with ~5-minute intervals between testing to return chamber CO<sub>2</sub> concentrations to ambient laboratory conditions (baseline global CO<sub>2</sub> concentration of ~410 ppm).

Sampling was repeated three times (sample triplicate), with lighting conditions maintained between measurements by measuring the light intensity across plantlet canopies, averaged across four points. Light measurements were taken 150 mm from the module using a LI-250A light meter (Li-Cor Biosciences, USA). Light intensity adjustments between treatments were achieved through modulation of the light dimmers and repositioning of the frame, as necessary.

CO<sub>2</sub> removal efficiency was calculated as percentage removal over the 40-minute period from the 1000 ppm starting concentration after stabilisation. This method accounted for variations in starting CO<sub>2</sub> concentrations among replicates (n = 3). All CO<sub>2</sub> removal data was corrected *post hoc* for chamber leakage (ie. CO<sub>2</sub> decay from the empty chamber without plants), calculated to be  $1.24 \pm 0.387$  % (mean  $\pm$  SEM) over the 40-minute testing period. Chamber design did not allow for manipulation of temperature and humidity, however these factors did not vary significantly throughout the 40 min experiments.

The results from this experiment informed the optimal lighting angles and intensities required for heightened photosynthetic performance to be assessed in comparison with the conditions observed *in situ*.

### **2.3.2 CO<sub>2</sub> removal efficiency and phototropic adaptation study**

To determine how prolonged exposure at the optimal light angles and intensities identified during the *in situ* field assessments and laboratory experiments influences CO<sub>2</sub> removal efficiency and plant morphology (phototropism), single-species plant modules were exposed to the following treatments continuously for ten days (Supplementary Table 1):

1. 100  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (~5250 lux) at 15°; this was the highest light intensity detected in the *in situ* field assessments, and the most common light angle observed in *in situ* systems,
2. 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (~10500 lux) at 15°; this was the optimum lighting combination detected in the laboratory study for non-photoadapted *C. comosum*,
3. 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (~10500 lux) at 45°; this was the optimum lighting combination detected in the laboratory study for non-photoadapted *S. wallisii*.

Single-species plant modules containing four plants were assessed in triplicate with a photoperiod of ten hours per day, using the above experimental set up. CO<sub>2</sub> removal was measured daily, and daily movements in leaf and stem angles were measured by taking photographs of four leaves per plant, which were then isolated from the photobank and adjusted to a reference axial system (xy) using Adobe Photoshop (Adobe Inc., USA) (Supplementary Fig. 3). Variation in leaf and stem angle relative to the axis was measured using AutoCAD 2019 (Autodesk Inc., USA; Fig. 5).

A pilot study conducted by the authors indicated that phototropism would be complete after ten days, with negligible leaf/stem angle movement observed after this time thus this trial was performed for 10 days.

## **2.4. Statistical analysis**

Non-photoadapted CO<sub>2</sub> removal was assessed using multiple linear regression to quantify linear associations with plant species, light intensity, and light angle.

To assess whether the observed, linear changes in photoadapted CO<sub>2</sub> removal efficiency through time were significant, a series of linear regression models were generated separately for each plant species and the three, light angle-intensity combination treatments (six in total). Similar models for species and light treatment were conducted to assess whether leaf and stem angle position changed linearly through time (nine total: 6 x leaf angle, 3 x stem angle).

To determine whether photoadapted CO<sub>2</sub> removal efficiency, leaf or stem position on the final day differed significantly between plant species and amongst light treatments, analyses of variance (ANOVA) with Tukey HSD *post hoc* tests were employed independently (three in total). A rank transformation was applied *a priori* to leaf/stem angle data for the ANOVAs only as the data violated parametric data analysis assumptions. As such, these analyses compare differences in median leaf/stem angles.

To investigate whether CO<sub>2</sub> removal efficiency was associated with phototropism, multiple Pearson's correlations were computed between both absolute leaf and stem angle positions, and the net daily movements in these parameters, across the ten-day period. These were performed separately by plant species, both across and within the three light treatments (fifteen in total).

All analyses and graphs were generated using R Project v3.6.2 (Team, 2019) and using the following packages; "car" (Fox and Weisberg, 2019), "dplyr" (Wickham et al., 2019), "ggplot2" (Wickham, 2016), "ggpubr" (Kassambara, 2019), "multcomp" (Hothorn et al., 2008), and "xlsx" (Dragulescu et al., n.d.).

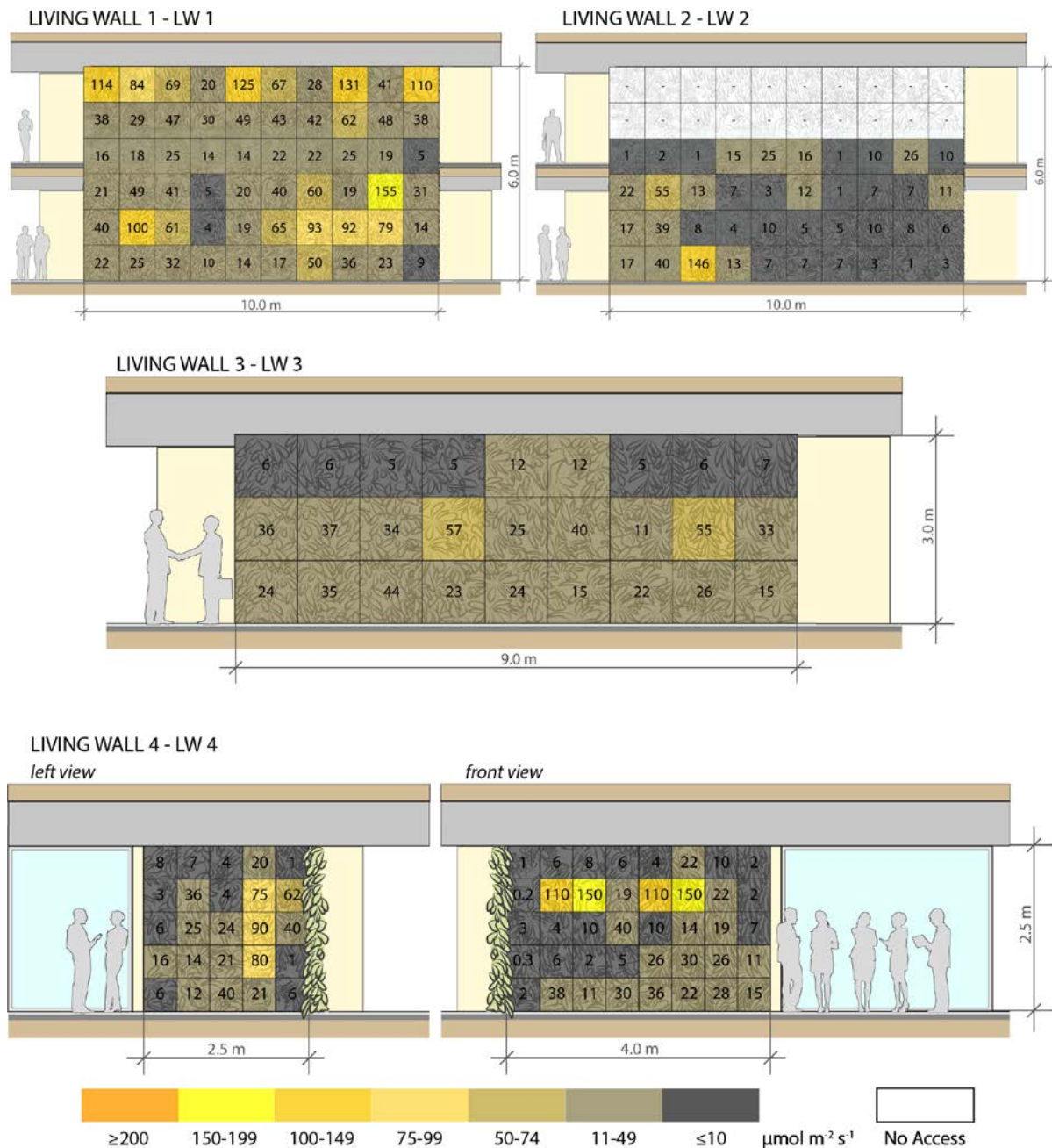
## **3. Results**

### **3.1 In situ living wall lighting conditions**

Field measurements of light intensity for *in situ* commercial living walls from the Greater Sydney area are presented in Fig. 2. All *in situ* living walls demonstrated non-uniform light distributions across their plant foliage, due to insufficient light provision in both intensity and direction. Additionally, sub-optimal lighting conditions due to inefficient plantscape design and infrastructure was observed (Fig. 2). Luminaries were observed to create shade zones, and larger branching plant species (such as *Philodendron xanadu* and *Neprolepis exaltata*) were observed blocking light to smaller, non-branching species below (such as *Epipremnum aureum*, *Spathiphyllum wallisii* and *Peperomia obtusifolia*).

Luminary angles of 11–50° were observed *in situ* at LW 1 and LW 2 no luminaries produced light at angles of between 0–10°, and only 16 % of luminaries were positioned at angles greater than 50° (Supplementary Fig. 1).

Of the four living walls measured, no lighting infrastructure was able to achieve light intensities at the plant foliage of  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (Supplementary Table 2). In all cases, most plants were exposed to light levels similar to ambient indoor lighting ( $\leq 10 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and  $11\text{--}49 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  for 35.6 % and 51.8 %, respectively).



**Fig. 2.** Lightmap of the four Living Walls (LW 1 – 4). Light measurements were taken at 1 m intervals for LW 1-3, and at 0.5 m intervals for LW 4 due to the relative complexity in both design and plant composition. The number within each square represents the average light intensity ( $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) available at the plant canopy for each  $1 \text{ m}^2$  area of living wall ( $0.5 \text{ m}^2$  for LW 4). No access was available for light measurements at LW 2 for the upper  $20 \text{ m}^2$  due to infrastructure limitations.

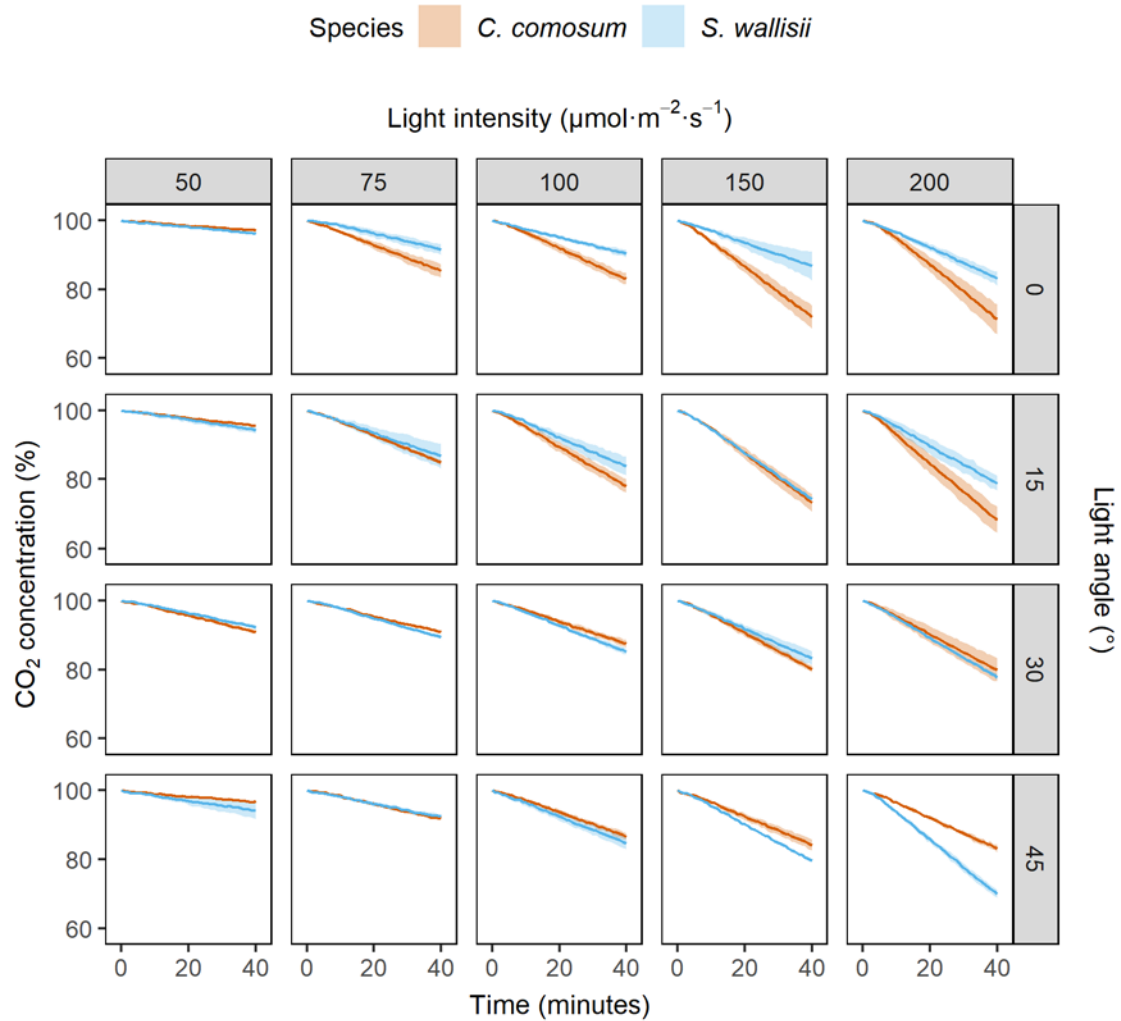
### **3.2 Non-photoadapted plant CO<sub>2</sub> removal**

The relationship between non-photoadapted net CO<sub>2</sub> removal over the 40-minute time period, and the combined effects light intensity and angle, was significant in multiple linear regression for both *C. comosum* ( $F(7,52) = 46.390$ ,  $p < 0.001$ ,  $R^2 = 0.86$ ) and *S. wallisii* ( $F(7,52) = 37.420$ ,  $p < 0.001$ ,  $R^2 = 0.83$ ).

As expected, higher light intensities displayed significant, positive effects on net CO<sub>2</sub> removal for both plant species ( $p < 0.01$  in all cases; Supplementary Table 3). For *C. comosum*, light intensities of 75, 100, 150 and 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  were associated with a mean increase in net CO<sub>2</sub> removal of 6.8, 11.2, 17.7, and 19.4 % relative to 50  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , respectively. *S. wallisii* featured similar associations with intensity, where 75, 100, 150 and 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  of light were associated with a relative mean increase in CO<sub>2</sub> removal of 4.1, 8.2, 13.1, and 16.7 %, respectively.

For *C. comosum*, there was no difference in net CO<sub>2</sub> removal between light angles of 0 and 15° from the vertical ( $p = 0.144$ ; Supplementary Table 3). Greater angles of 30 and 45° both lead to lower mean net CO<sub>2</sub> removal efficiencies of 4.1 and 6.8 %, relative to 0°, respectively ( $p = 0.002$  and  $p < 0.001$ , respectively). Contrastingly, *S. wallisii* displayed significantly higher net CO<sub>2</sub> removal for all light angles, where inclinations of 15, 30 and 45° from the vertical were associated with a mean increase in net CO<sub>2</sub> removal of 6.1, 4.0, and 5.4 %, relative to 0°, respectively ( $p < 0.001$  in all cases; Supplementary Table 3).

Overall, the greatest mean CO<sub>2</sub> removal was observed under the maximum tested light intensity of 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  for both *C. comosum* and *S. wallisii* at  $31.72 \pm 3.74$  and  $30.00 \pm 1.14$  % (mean  $\pm$  SD) respectively, and at light angles of 15° and 45° respectively (Fig. 3, Supplementary Fig. 4).



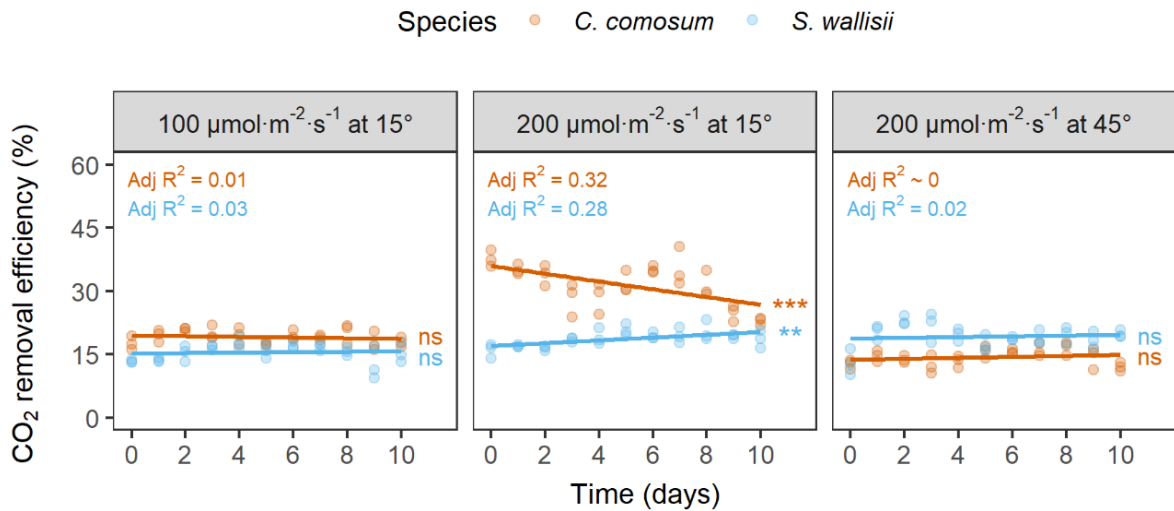
**Fig. 3.** Mean CO<sub>2</sub> removal concentration (%) from input concentration (~1000 ppm) over 40-minute period for *C. comosum* (orange) and *S. wallisii* (blue) plant species under various intensities and angles of light. Shaded areas represent SDs (n = 3). CO<sub>2</sub> concentration (%) is expressed as a proportion of the inlet CO<sub>2</sub> at the end of the 40-minute test period.

### 3.3 Photoadapted CO<sub>2</sub> removal and phototropism

#### 3.3.1 CO<sub>2</sub> draw down performance

Linear regression models of CO<sub>2</sub> removal efficiency across the ten day adaptation periods revealed non-significant relationships for all light treatments except for the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at 15° treatment (Fig. 4), where both models for *C. comosum* and *S. wallisii* were significant ( $F(1,31) = 15.890$ ,  $p < 0.001$ ,  $R^2 = 0.34$  and  $F(1,31) = 13.500$ ,  $p = 0.001$ ,  $R^2 = 0.28$  respectively). These models show contrasting directional influence of time on CO<sub>2</sub> removal efficiency, where for each additional day, CO<sub>2</sub> removal efficiency decreased on average by 0.92 % for *C. comosum*, whilst it increased by 0.33 % for *S. wallisii* (Supplementary Table 4).

The interaction between species and light treatment had a significant effect on final (day ten) photo-adapted CO<sub>2</sub> removal efficiencies ( $F(2,12) = 29.120$ ,  $p < 0.001$ ), indicating that treatment effects were not equivalent for the two species (Fig. 4).



**Fig. 4.** Linear regression models of CO<sub>2</sub> removal efficiency time series in *C. comosum* (orange) and *S. wallisii* (blue) species under the three-light angle-intensity treatments. Replicates depict experiments performed in triplicate on single plant modules. Lines of best fit represent fitted models of daily CO<sub>2</sub> removal efficiency through time, where asterisks denote significant relationships (\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ ).

### 3.3.2 Physiological phototropism

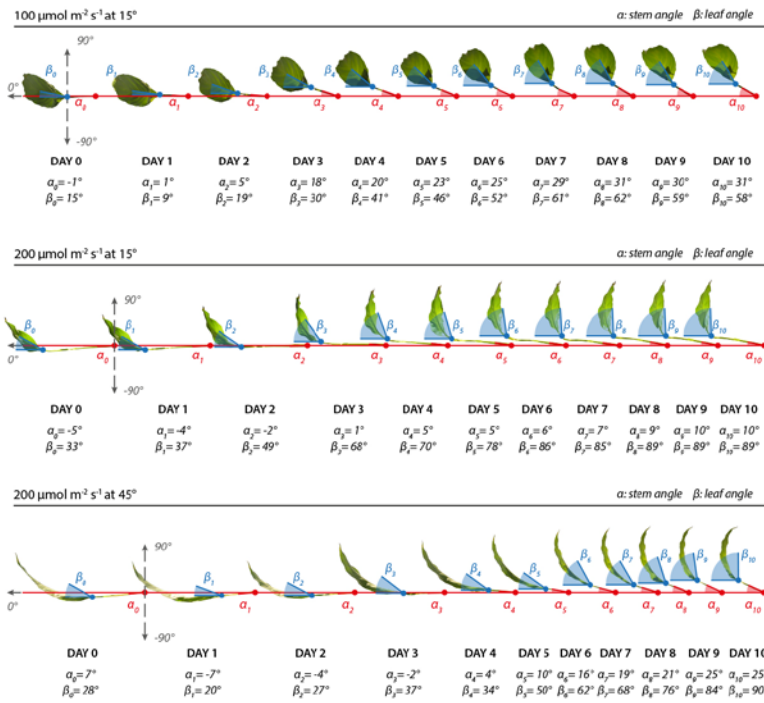
Linear regression models of leaf angle changes with time revealed significant relationships for all light treatments for both plant species ( $F(1,130) = 4.623-42.860$ ,  $p < 0.05$  in all cases,  $R^2 = 0.03-0.25$ ), although with contrasting directional trends. *C. comosum* demonstrated an average daily 0.88 to 1.12° decrease in leaf angle from the vertical across treatments, whereas *S. wallisii* demonstrated a 4.2 to 5.2° increase (Figs. 5 and 6, Supplementary Table 5). Additionally, linear regression models of *S. wallisii* stem angle changes over time were also significant across all treatments ( $F(1,130) = 56.770-144.900$ ,  $p < 0.001$  in all cases,  $R^2 = 0.30-0.53$ ), where stem angle increased on average by 1.5–2.4° per day (Figs. 5 and 6, Supplementary Table 5).

The final leaf position at day ten differed significantly amongst the three light treatments ( $F(2,63) = 8.564$ ,  $p < 0.001$ ), which was driven by a single comparison between the 100  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at 15° and 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at 15° treatments ( $p_{\text{adj}} = 0.048$ ). Here, higher leaf angle positions were observed under the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at 15° treatment for both species (Fig. 6). The final leaf position of *S. wallisii* was significantly greater than that of *C. comosum* across treatments ( $F(2,63) = 148.308$ ,  $p < 0.001$ ), ranging on average between 29 to 71° and -17.8 to -30.5°, respectively (Fig. 6). There was no significant interaction between treatment and species ( $F(2,63) = 0.276$ ,  $p = 0.760$ ).

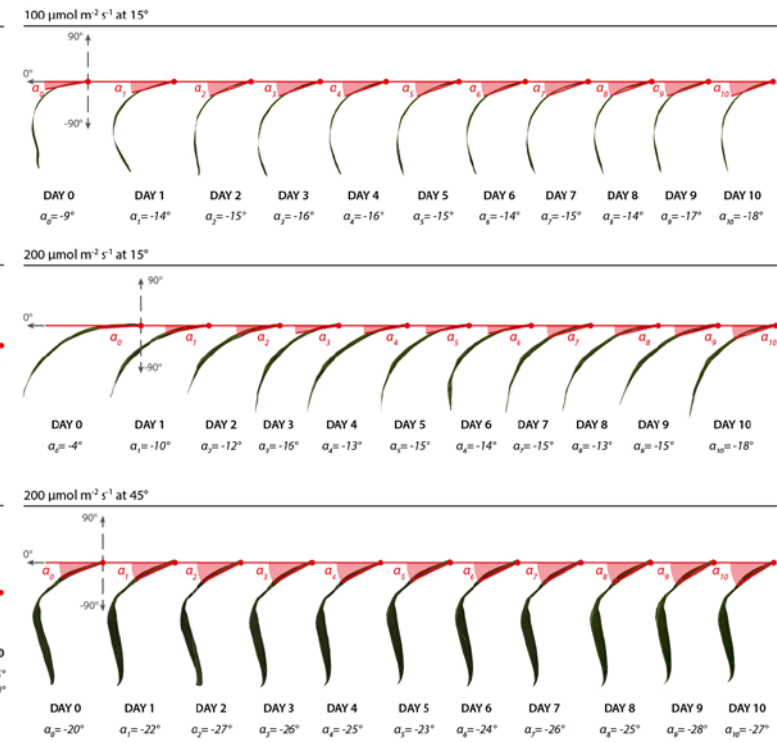
The final stem angle position in *S. wallisii* differed significantly across treatments ( $F(2,30) = 24.416$ ,  $p < 0.001$ ), where all treatment comparisons were significant ( $p_{\text{adj}} < 0.05$  in all cases). The final stem angle for the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at 15° treatment was closest to the vertical at  $8.25 \pm 7.41^\circ$  (mean  $\pm$

SD), followed by the  $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  and  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $45^\circ$  treatments at  $14.00 \pm 12.99^\circ$  and  $23.50 \pm 3.87^\circ$  respectively.

Phototropic adaptation analysis - *Spathiphyllum wallisii*

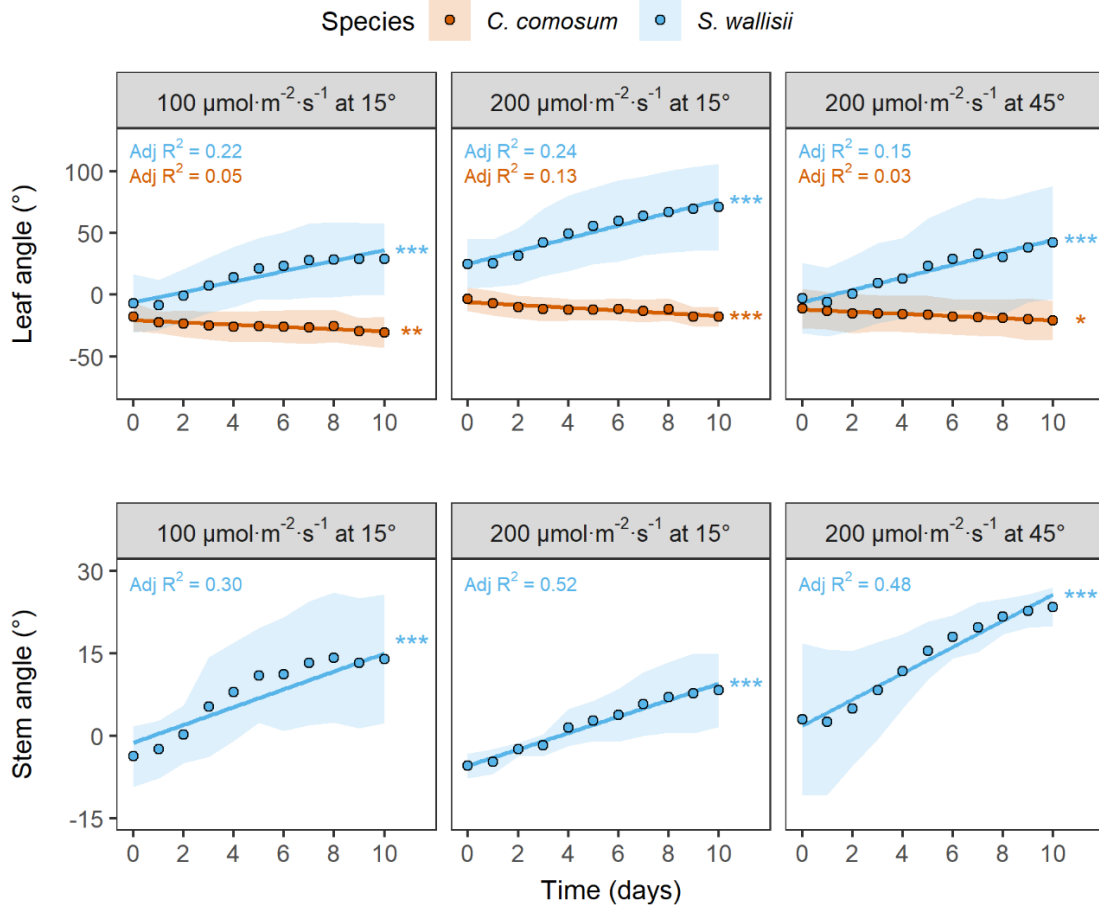


Phototropic adaptation analysis - *Chlorophytum comosum*



1  
2  
3  
4  
5

**Fig. 5.** Leaf movement analysis of *S. wallisii* (left) and *C. comosum* (right) through time under the three light angle-intensity treatments. Single representative replicates are shown here (n = 4 were used in the trial), where  $\alpha$  denotes average leaf angle and  $\beta$  denotes average stem and leaf angle, respectively.



6

7

**Fig. 6.** Linear regression models of leaf positions for both *C. comosum* (orange) and *S. wallisii* (blue) (top subplots) and stem positions for *S. wallisii* (bottom subplots) across a 10-day trial under the three light angle-intensity treatments. Points represent the mean leaf/stem angles from the vertical for each day, where the shaded areas depict the SDs ( $n = 4$ ). Lines of best fit depict fitted models where asterisks denote significant regressions (\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ ).

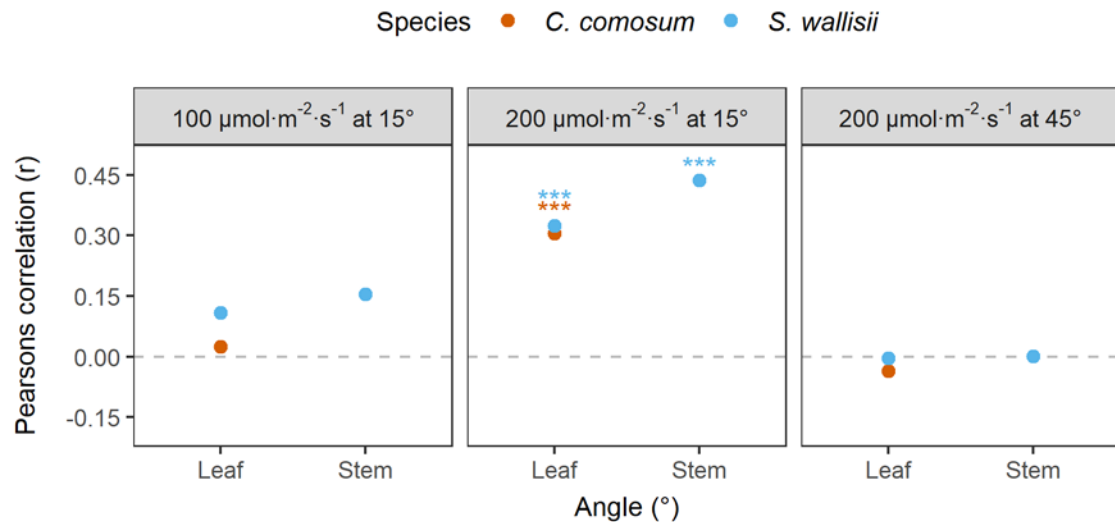
12

Leaf position and net daily phototrophic movement had a small effect on  $\text{CO}_2$  removal efficiency, with fairly weak correlations observed for both plant species (*C. comosum* leaf position:  $r = 0.258$ ,  $p < 0.001$ ; *C. comosum* leaf movement:  $r = -0.027$ ,  $p = 0.594$ ; *S. wallisii* leaf position:  $r = 0.198$ ,  $p < 0.001$ ; *S. wallisii* leaf movement:  $r = 0.168$ ,  $p = 0.001$ ). *S. wallisii* stem position and movement was also weakly correlated with  $\text{CO}_2$  removal efficiency (*S. wallisii* stem position:  $r = 0.137$ ,  $p = 0.006$ ; *S. wallisii* stem movement:  $r = 0.158$ ,  $p = 0.002$ ).

19

Interestingly, light treatment specific correlations between leaf position and  $\text{CO}_2$  removal efficiency yielded comparatively higher correlations for both plant species under the  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  treatment compared to the other two treatments ( $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  leaf position:  $r = 0.304$ - $0.323$ ,  $p < 0.001$ ;  $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  and  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $45^\circ$  leaf positions:  $r = -0.036$ - $0.109$ ,  $p = 0.214$ - $0.679$ ; Fig. 7). This same trend was also observed for stem position in *S. wallisii* ( $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  leaf position:  $r = 0.437$ ,  $p < 0.001$ ;  $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  and  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $45^\circ$  leaf positions:  $r = 0.001$ - $0.155$ ,  $p = 0.076$ - $0.991$ ; Fig. 7).

27



28 **Fig. 7.** Pearson correlations between CO<sub>2</sub> removal efficiency, and the leaf/stem angle positions  
 29 throughout the ten-day testing period for each light angle-intensity treatment and plant species.  
 30 Note, no stem measurements exist for *C. comosum* due to the physiological nature of the species.  
 31

#### 32 33 4. Discussion

34  
 35 The angle of incident light, light intensity and photoperiod all influence the photosynthesis and  
 36 photomorphogenesis of plants, affecting plant metabolism and developmental morphology (Folta  
 37 and Childers, 2008; Morrow, 2008). The indoor environment often provides light that is  
 38 considerably different to the lighting requirements of most species of plants. Currently, the  
 39 scientific literature pertaining to optimal lighting for indoor greenery is sparse (Gunawardena and  
 40 Steemers, 2019; Kaltsidi et al., 2020; Moya et al., 2018). Consequently, commercial suppliers of  
 41 living wall systems often follow the recommendations provided by lighting suppliers and indoor  
 42 horticultural practices, which may be based on conditions for human habitability rather than plant  
 43 health.

44  
 45 In this study, we highlight the reduced efficiency for indoor CO<sub>2</sub> removal under current lighting  
 46 conditions and demonstrate the practical and ideal lighting conditions for heightened CO<sub>2</sub> removal.  
 47 By extension, our work also provides direction that may assist in determining the suitability of a  
 48 given light treatment for plant health, using CO<sub>2</sub> drawdown as a surrogate for photosynthesis and  
 49 plant metabolic activity.

50  
 51 The lighting conditions observed for the *in situ* living walls in this study featured relatively low light  
 52 intensities at a range of inclinations, where ~87 % of all sampled living walls received > 49  
 53 μmol·m<sup>-2</sup>·s<sup>-1</sup> (Fig. 2) at angles of between 11 and 50° (Supplementary Fig. and Table 1).  
 54 Experimentally, these conditions were associated with a mean chamber CO<sub>2</sub> removal efficiency of  
 55 between 1.68 and 7.95 % of ~1000 ppm over 40-minutes (Fig. 3). Non-photoadapted removal  
 56 efficiencies for *C. comosum* and *S. wallisii* were greatest at a light intensity of 200 μmol·m<sup>-2</sup>·s<sup>-1</sup>  
 57 and inclinations of 15 and 45° from the vertical respectively, reaching ~30 % CO<sub>2</sub> removal over  
 58 40-minutes (Fig. 3, Supplementary Fig. 4). For comparability with existing practices used for indoor  
 59 environmental quality maintenance in buildings, we have used the CO<sub>2</sub> draw down rates calculated

60 in the current work to estimate the ventilation equivalence that might be possible with the use of  
61 indoor living walls using optimised lighting systems *in situ*. The best performing treatment we found  
62 was *C. comosum* at the 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light flux density at 15° from the vertical growing surface.  
63 Assuming this CO<sub>2</sub> removal was constant per plant, the extrapolated effects from a reasonably-sized,  
64 5 m<sup>2</sup> passive living wall containing 400 plants in a typical 40 m<sup>3</sup> office can be estimated. Such a  
65 system could reduce a 1000 ppm CO<sub>2</sub> concentration to roughly 872 ppm, which has a ventilation  
66 equivalence based solely on CO<sub>2</sub> removal to an ACH of 0.21 h<sup>-1</sup>, assuming an ambient CO<sub>2</sub>  
67 concentration of 410 ppm. As stated previously, this light level will be difficult to achieve in practice:  
68 an equivalent sized living wall receiving up to 50  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  light flux density will achieve an  
69 estimated ACH of only 0.03 h<sup>-1</sup>.

70

71 While no *in situ* living walls received a light intensity of 200  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , ~5 % of the sampled walls  
72 achieved intensities between 100 and 199  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (Fig. 2 and Supplementary Table 2). If  
73 changes to plantscape design or lighting infrastructure could support an average light intensity  
74 greater than 100  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , it may be plausible to increase the rate of elevated indoor CO<sub>2</sub>  
75 removal by 1.5–7-fold (Fig. 3), and thus reduce building reliance on HVAC ventilation by some  
76 degree, if adequately sized living walls can be used. Our findings confirm the positive correlation  
77 between light intensity and CO<sub>2</sub> assimilation rates by ornamental plants observed in previous  
78 studies (Cetin and Sevik, 2016; Gubb et al., 2018; Oh et al., 2011) and highlight the need for  
79 technical guidelines to be established for the lighting of indoor living walls.

80

81 Previous studies highlight the strong influence of the angular distribution of light incident at the leaf  
82 surface on the internal absorption profiles and photosynthetic capacity of a plant (Brodersen and  
83 Vogelmann, 2010; Smith et al., 1997). In low-light environments such as those optimised for human  
84 occupation, light intensity and directionality affect the penetration of light through leaf tissues,  
85 limiting the effective rate of photosynthesis (Brodersen et al., 2007). Plants respond to this through  
86 phototropic and spectral signaling, where leaves will respond to light stimuli by changing their  
87 structural features to more efficiently perform their function (Smith et al., 1997). Further,  
88 phototropism can act synergistically or antagonistically with gravitropic effects to enhance or  
89 reduce plant growth behaviours such as light or gravitational sensing, transduction of signals, and  
90 differential growth of organs and tissues (Correll and Kiss, 2002). Previous studies have  
91 demonstrated that leaf orientation is critical to leaf-level light and that some plant species modify  
92 their morphology to increase the light quantity received [9]. In living wall systems, plants are  
93 orientated with their apical stems parallel to the ground as opposed to a natural vertical orientation,  
94 and thus plant morphology must respond in accordance with gravitropic and spectral signals. During  
95 laboratory testing, *S. wallisii* leaves and stems sought to be closer to the light source in all three  
96 treatments, while *C. comosum* displayed a downwards trend in response to the light sources over  
97 the ten-day testing periods (Fig. 5). Differences in plant physiology are likely the key factor in this  
98 finding, where *C. comosum* lacks the stem structural integrity to facilitate an increase in inclination  
99 over time, leading to a response dominated by gravitropism. However, despite the variance in  
100 phototropism between species, both plant species displayed effective CO<sub>2</sub> removal efficiencies over  
101 the ten-day test period.

102

103 Contrary to our hypothesis, the absolute position of plant leaves and stems and net morphological  
104 changes appeared to have weak associations with CO<sub>2</sub> removal efficiency. However, morphological

105 movement did appear to induce some sort of photosynthetic response in specific treatments (Fig. 7).  
106 Under  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $15^\circ$  lighting conditions, *S. wallisii* exhibited significant leaf/stem  
107 movement in a vertical plane, seeking the light source, of  $+15^\circ$  and  $+56^\circ$  (leaf and stem respectively;  
108 Figs. 4 and 5), which exhibited comparatively strong correlations ( $r = 0.323$  and  $0.437$ , respectively;  
109 Fig. 7) with a  $\text{CO}_2$  removal efficiency increase of  $0.33\%$  per day (Fig. 4). Similarly, *C. comosum*, under  
110 the same conditions, exhibited significant downwards leaf movement (away from the light source)  
111 of  $-14^\circ$  (Figs 4 and 5), which was also significantly correlated ( $r = 0.304$ ), compared to the other  
112 treatments (Fig. 7), with a daily  $\text{CO}_2$  removal efficiency reduction of  $0.92\%$  (Fig. 4). While there  
113 were significant differences observed between species under this treatment, both completed the  
114 ten-day period with a  $\text{CO}_2$  removal efficiency of  $\sim 18\%$ , which was higher than  $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  
115  $15^\circ$  and  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $45^\circ$ . These findings indicate phototropism should be considered in the  
116 decision making process of plantscape design, and could be utilised to optimise light capture,  
117 prevent light stress, or to balance the effects of other abiotic factors (Goyal et al., 2013; Ouzounis et  
118 al., 2015), although decisions will inevitably be species specific.

119

120 Neither species displayed significant changes in  $\text{CO}_2$  removal efficiency under the  $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  
121  $15^\circ$  and  $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  at  $45^\circ$  lighting conditions over the ten-day period (Fig. 4). These findings  
122 indicate these treatments had a generally equivalent effect on final  $\text{CO}_2$  removal efficiency,  
123 independent of plant species. Variations in plant species performance (Fig. 4) could again be  
124 attributed to various physiological characteristics, however it is likely that these results speak to the  
125 robust nature of these species and further validates their popularity for species selection in living  
126 walls.

127 Brodensen and Vogelmann (2010) notes that at the leaf surface, only illuminated tissues are  
128 capable of photosynthesis. As light intensity measurements were taken only across the top of the  
129 plant foliage, variations in single leaf light exposure attributed to inclination and orientation may  
130 have been overlooked in the current work. nevertheless, from the work conducted, it is evident that  
131 light inclination is an important factor in living wall performance and should be considered in future  
132 designs or retrofits, such as optimisation of individual species placement to suit the available light.

133

134 In many current photosystems used for indoor living walls, static lighting at fixed light inclinations is  
135 employed, typically placed  $\sim 0.8 - 1$  m from the foliage. This 'one size fits all' approach has proven to  
136 be suitable for maintaining plant survival between maintenance periods, however it provides little  
137 in the way of optimised, plant specific lighting, especially if photosynthetic activity is to be  
138 harnessed for indoor environmental quality improvement. Our observations indicate that some  
139 living walls are constructed with little forethought for the morphology of specific plant species,  
140 giving the impression of a 'set and forget' installation with a reliance on plant cycling and  
141 maintenance. In some instances, this approach creates shaded areas across the wall surface, where  
142 scrambling plant species such as *Philodendron xanadu* and *Neprolepis exaltata* block plants below  
143 from adequate lighting (Fig. 2). This can be overcome only if regular and costly maintenance is  
144 performed.

145

146 From the *in situ* measurements performed, up to  $\sim 63\%$  of plant foliage was exposed to light levels  
147 less than  $10 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  (Supplementary Table 2). Previous literature has demonstrated that light  
148 intensities below  $10-15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  may lead to increased ambient  $\text{CO}_2$  concentrations through

149 plant respiration (Torpy et al., 2014; Treesubstorn and Thiravetyan, 2018), and that light levels of  
150  $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  are optimal for highly efficient living walls (Torpy et al., 2014). It is entirely possible  
151 that at the low light levels recorded, the overall effectiveness of living walls could be  $\text{CO}_2$  neutral,  
152 with plant species exposed to insufficient lighting contributing to indoor  $\text{CO}_2$  concentrations.

153

154 Insufficient lighting (i.e. below the light compensation point, where plant photosynthetic  $\text{CO}_2$   
155 drawdown is greater than respiratory  $\text{CO}_2$  emission) provided to living walls may indeed contribute  
156 to elevated  $\text{CO}_2$  concentrations of an indoor space. Although there is little literature to suggest that  
157 this occurs *in situ*, it might be prudent to assess the costs associated with this inefficiency.  
158 Maintenance costs are thought to be the bottleneck in the widespread implementation of air  
159 phytoremediation technology worldwide (Perini and Rosasco, 2013), where it is common for  
160 maintenance to be conducted purely for 'plant health management'. With insufficient lighting,  
161 ornamental plants are able to sustain biomass, but are unable to properly utilise certain biological  
162 functions such as disease defenses (Karpinski et al., 2003), which in turn leads to the deterioration  
163 of plant health, and subsequent increases in the maintenance required. For improved economic  
164 management and implementation, designs with sufficient lighting systems for living walls are  
165 required. While current systems can provide adequate lighting to limited regions of living walls (Fig.  
166 2), there are opportunities in the interior plantscape industry for the development of lighting to  
167 provide a more adequate range of illumination.

168

169 Recently, light emitting diodes (LEDs) have increased in popularity amongst indoor horticulture  
170 applications due to their reduced pricing, operational costs, longevity and energy consumption (Yeh  
171 and Chung, 2009). LEDs demonstrate remarkable promise as supplementary lighting in terms of  
172 luminous flux control due to their low radiant heat output and wavelength specificity (Kaltsidi et al.,  
173 2020). While some capital costs of LEDs may be high, they are characterised by long lifetimes  
174 (Pattison et al., 2018) and are more versatile than current indoor lighting systems (Rehman et al.,  
175 2017). They can be easily adjusted to increase photosynthetic photon flux density (PPFD: the  
176 proportion of the light spectrum usable by photosynthetic tissues) at the leaf surface, without  
177 creating an undesirable glare to building occupants. Additionally, plantscape design is a currently  
178 underutilised aspect of indoor living walls, with many suppliers basing plant species placement  
179 solely on aesthetics, as opposed to optimal lighting. For example, of the walls observed in this paper,  
180 branching species such as *Philodendron Xanadu* and *Nephrolepis exaltata* should be placed towards  
181 the base of the LW, to reduce plant-shading. Moreover, plant species with relatively low light  
182 compensation points such as *Peperomia obtusifolia* ( $13 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ; Torpy et al., 2014), may be  
183 situated where light intensities are sufficient to ensure photosynthesis. To this extent, future  
184 studies that incorporate any form of *in situ* living wall analysis should take note of the plantscape  
185 design employed and monitor the light distribution across the wall.

186

## 187 **5. Conclusion**

188 As living walls have become more common for indoor air quality improvement, technical guidelines  
189 for lighting design should be developed to promote plant health, enhance phytoremediation  
190 potential, and reduce maintenance costs. A systemic design approach that considers plant species  
191 responses to supplementary lighting variations would facilitate an understanding of how and where

192 plants should be placed across vertical greening infrastructure to receive optimal lighting  
193 conditions.

194

195 The current study demonstrates that living wall lighting systems are a crucial yet often neglected  
196 consideration to enhance the removal of CO<sub>2</sub> from indoor air. This study simulates the current  
197 removal efficiencies of living wall systems to remove CO<sub>2</sub> under commonly used *in situ* conditions  
198 (50 μmol·m<sup>-2</sup>·s<sup>-1</sup>) to be low. Due to the lack of homogenously distributed light observed at the four  
199 living walls tested, the shortcomings of the lighting systems employed are clear. To address these  
200 shortcomings, commercial suppliers should invest in better lighting systems to increase  
201 photosynthesis and reduce maintenance costs associated with plant care and replacement.

202

203 This study found the highest CO<sub>2</sub> removal efficiency for both plant species to be in the 200  
204 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 15° treatment. This, coupled with the enhanced phototropic movements observed,  
205 suggests that phototropism at specific light angles may play a significant role in increasing the CO<sub>2</sub>  
206 removal efficiency for some plant species. However, achieving these light intensities requires  
207 retrofitting lighting systems with a lower impact light such as LEDs. If commercial suppliers can  
208 deliver consistent light intensities of 100 μmol·m<sup>-2</sup>·s<sup>-1</sup>, the final challenge for optimised CO<sub>2</sub> removal  
209 will be morphological considerations for plantscape design. The intensity and directionality of light  
210 will influence the growing trends and morphology of branching species, leading to increased  
211 maintenance work when excessive shading occurs (as observed in this study). For this reason,  
212 further analysis on plant species growth under *in situ* conditions, and extended light exposure, may  
213 facilitate the design of an appropriate vegetation framework for indoor living walls.

214

215 The authors recommend that living wall providers undertake research and development to  
216 incorporate not only comprehensive lighting systems, but also a plant-scape design optimised for  
217 lighting. This will facilitate the development of more efficient living walls for indoor air pollution  
218 removal, rather than those that prioritise aesthetics or ease of access.

219

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223

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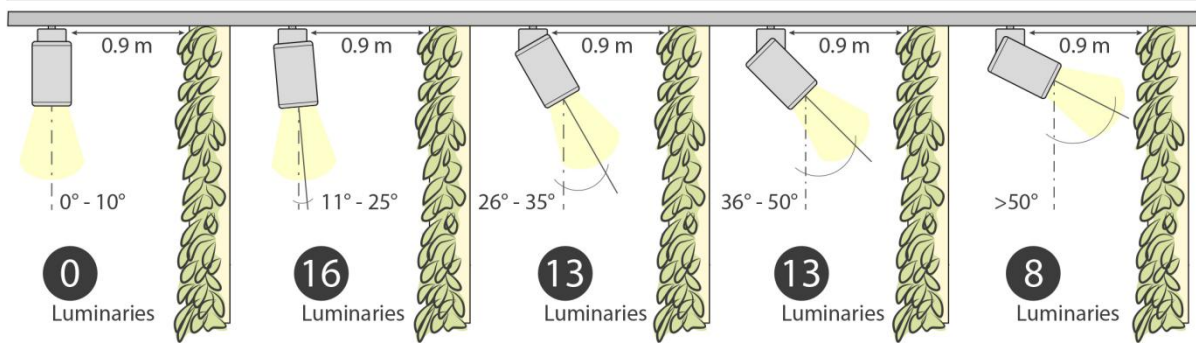
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385 **Supplementary materials**

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Number of luminaries per range of light angle

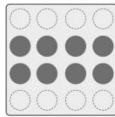


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388 **Supplementary Fig. 1.** Range of luminary angles as observed for the 50 units isolated from on-site  
389 image assessment of LW 1 and LW2.

Plant module layout




**PLANT RESPONSE TO LIGHT ANGLE/INTENSITY**  
**8** plant of *Chlorophytum comosum*




**PLANT PHOTOADAPTATION TO LIGHT ANGLE/INTENSITY**  
**4** plant of *Chlorophytum comosum*




**PLANT RESPONSE TO LIGHT ANGLE/INTENSITY**  
**8** plant of *Spathiphyllum wallisii*




**PLANT PHOTOADAPTATION TO LIGHT ANGLE/INTENSITY**  
**4** plant of *Spathiphyllum wallisii*

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391 **Supplementary Fig. 2.** Design layout of *Chlorophytum comosum* and *Spathiphyllum wallisii* modules  
 392 used during Experiment 2.2 (Plant response to light angle/intensity) and 2.3 (Phototropism and  
 393 plant response).

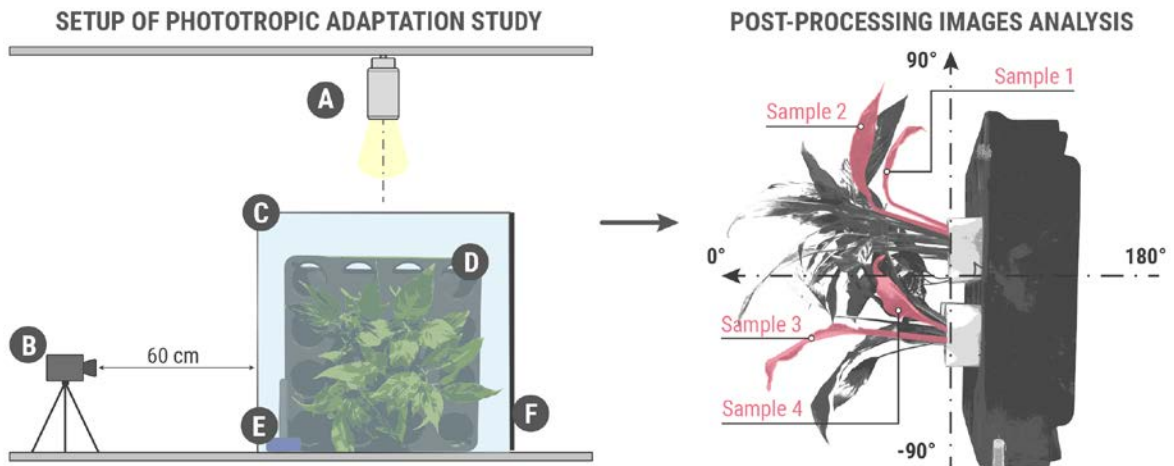
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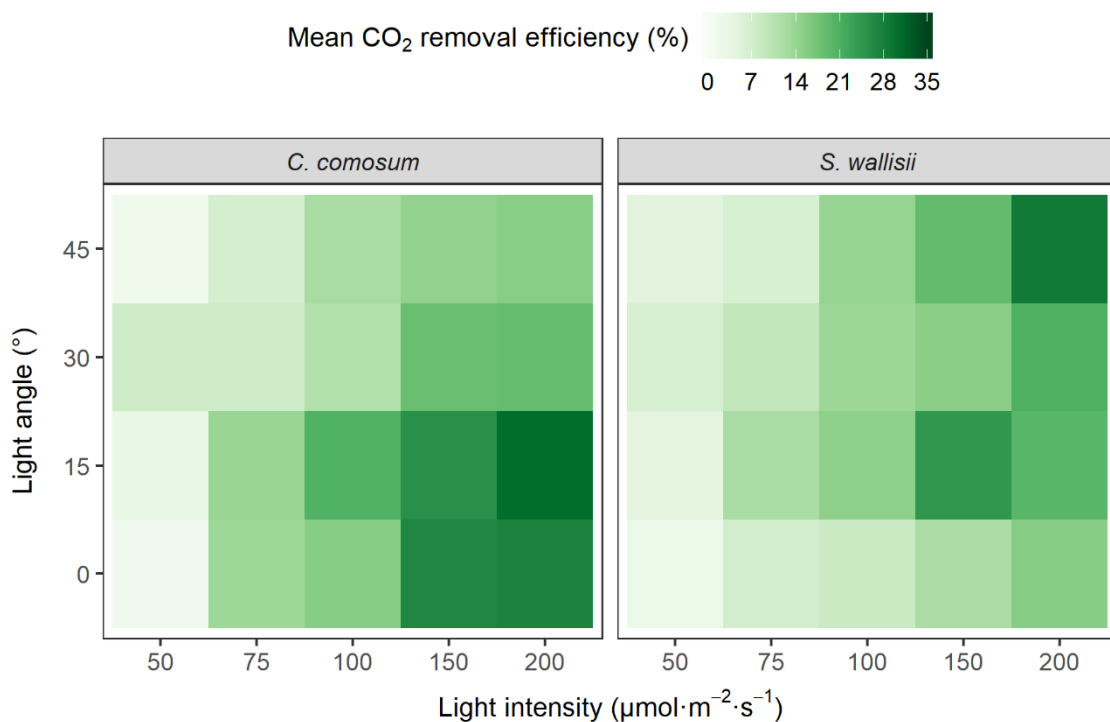


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400 **Supplementary Fig. 3.** Experimental setup adopted for the “CO<sub>2</sub> removal efficiency and phototropic  
 401 adaptation study”, composed by: A) a luminary disposed to recreate the three artificial lighting  
 402 treatments; B) the Nikon D3200 camera adjusted to take photographs from the left and the right  
 403 side of the sealed chamber; C) the sealed glass chamber; D) the single-species plant module; E) the  
 404 IAQ-CALC 7525 infrared gas analyzer; F) a black screen used to increase the image’s contrast in  
 405 photographs. Each photograph was post-processed and analysed as shown.

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409 **Supplementary Fig. 4.** Mean CO<sub>2</sub> removal efficiency (%) from input concentration (~1000 ppm) over  
 410 40-minute period for *C. comosum* and *S. wallisii* species under various intensities and angles of light  
 411 (n = 3).

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413

414 **Supplementary Table 1.** Summary of methodology adopted in the study with details about  
 415 experiments' motivation, measurements assessed, methods and instruments used.

	Experiment	Measurements	Method & Instruments
<i>in situ</i>	<i>In situ</i> living wall lighting assessment	Light intensity along living wall surface	Data collection using the Li-250A light meter
	<i>Description of artificial lighting features observed in the in situ applications</i>	Luminary angles	Images post processing and analysis using a Nikon D3200 camera, Adobe Photoshop CC and AutoCAD 2019 software
Manipulative laboratory experiments	Preliminary study: non-photoadapted CO <sub>2</sub> removal of <i>Chlorophytum comosum</i> and <i>Spathiphyllum wallisii</i>	CO <sub>2</sub> drawdown assessment	Data collection using IAQ-CALC 7525 infrared gas analyzer
	<i>Description of plants response to varied lighting conditions</i>		<i>Additional instrument: Li-250A light meter</i>
	CO <sub>2</sub> removal efficiency and phototropic adaptation study on <i>Chlorophytum comosum</i> and <i>Spathiphyllum wallisii</i>	CO <sub>2</sub> drawdown assessment	Data collection using IAQ-CALC 7525 infrared gas analyzer
	<i>Description of plants response to the 10-days exposure to varied lighting conditions determined from results obtained in the in situ assessment and in the preliminary study</i>	Leaf and stem angles	<i>Additional instrument: Li-250A light meter</i> Images post processing and analysis using a Nikon D3200 camera, Adobe Photoshop CC and AutoCAD 2019 software

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419 **Supplementary Table 2.** Average light availability at the proportion of the total plant foliage area at  
 420 the four *in situ* living walls.

Light intensity ( $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ )	LW 1	LW 2	LW 3	LW 4	Average
≤ 10	6.7 %	62.5 %	26 %	44.6 %	35 %
11–49	65 %	32.5 %	66.6 %	43.1 %	51.8 %
50–74	11.6 %	2.5 %	7.4 %	1.5 %	5.8 %
75–99	6.7 %	0 %	0 %	4.6 %	2.8 %
100–149	8.3 %	2.5 %	0 %	3.1 %	3.4 %
150–199	1.7 %	0 %	0 %	3.1 %	1.2 %

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423 **Supplementary Table 3.** Statistical output of multiple linear regression models for net  
 424 non-photoadapted CO<sub>2</sub> removal over 40-minutes across levels of light intensity and light angle, for  
 425 both *Chlorophytum comosum* ("C.com") and *Spathiphyllum wallisii* ("S.wal") models. Variable levels  
 426 listed are in reference to 50 μmol·m<sup>-2</sup>·s<sup>-1</sup> for light intensity effects, and 0° for light angle effects.

Variable	Coefficient	SE	t-value	p-value
<b>C.com:</b>			$F(7,52) = 46.390, p < 0.001, R^2 = 0.86, \text{Adj } R^2 = 0.84$	
<b>Intercept</b>	7.189	1.237	5.812	< 0.001
<b>Intensity</b>				
75 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	6.816	1.383	4.929	< 0.001
100 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	11.228	1.383	8.119	< 0.001
150 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	17.702	1.383	12.801	< 0.001
200 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	19.375	1.383	14.010	< 0.001
<b>Angle</b>				
15°	1.836	1.237	1.484	0.144
30°	-4.115	1.237	-3.327	0.002
45°	-6.755	1.237	-5.461	< 0.001
<b>S.wal:</b>			$F(7,52) = 37.420, p < 0.001, R^2 = 0.83, \text{Adj } R^2 = 0.81$	
<b>Intercept</b>	1.993	1.127	1.769	0.083
<b>Intensity</b>				
75 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	4.137	1.260	3.284	0.002
100 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	8.153	1.260	6.472	< 0.001
150 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	13.119	1.260	10.413	< 0.001
200 μmol·m <sup>-2</sup> ·s <sup>-1</sup>	16.712	1.260	13.265	< 0.001
<b>Angle</b>				
15°	6.068	1.127	5.385	< 0.001
30°	4.013	1.127	3.561	0.001
45°	5.408	1.127	4.799	< 0.001

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440 **Supplementary Table 4.** Statistical output of linear regression models for photoadapted CO<sub>2</sub>  
 441 removal efficiency time series in *Chlorophytum comosum* (“C.com”) and *Spathiphyllum wallisii*  
 442 (“S.wal”).

Variable	Coefficient	SE	t-value	p-value
<b>C.com: 100 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 15°</b>				
Intercept	19.455	0.549	35.468	< 0.001
Days	-0.082	0.093	-0.882	0.384
<b>C.com: 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 15°</b>				
Intercept	35.980	1.368	26.303	< 0.001
Days	-0.922	0.231	-3.987	< 0.001
<b>C.com: 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 45°</b>				
Intercept	13.699	0.632	21.680	< 0.001
Days	0.114	0.107	1.069	0.293
<b>S.wal: 100 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 15°</b>				
Intercept	15.173	0.704	21.547	< 0.001
Days	0.053	0.119	0.442	0.662
<b>S.wal: 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 15°</b>				
Intercept	16.967	0.537	31.622	< 0.001
Days	0.333	0.091	3.674	0.001
<b>S.wal: 200 μmol·m<sup>-2</sup>·s<sup>-1</sup> at 45°</b>				
Intercept	18.739	0.979	19.133	0.024
Days	0.085	0.166	0.514	0.611

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444 **Supplementary Table 5.** Statistical output of linear regression models for photoadapted leaf and  
 445 stem position time series in *Chlorophytum comosum* (“C.com”) and *Spathiphyllum wallisii* (“S.wal”).

Variable	Coefficient	SE	t-value	p-value
<b>Leaf angle in C.com: 100 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 8.083, p = 0.005, R^2 = 0.06, \text{Adj } R^2 = 0.05$				
Intercept	-20.682	1.892	-10.933	< 0.001
Days	-0.909	0.320	-2.842	0.005
<b>Leaf angle in C.com: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 21.200, p < 0.001, R^2 = 0.14, \text{Adj } R^2 = 0.13$				
Intercept	-6.068	1.443	-4.207	< 0.001
Days	-1.123	0.244	-4.604	< 0.001
<b>Leaf angle in C.com: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 45°</b>				
$F(1,130) = 4.623, p = 0.033, R^2 = 0.03, \text{Adj } R^2 = 0.03$				
Intercept	-12.080	2.408	-5.018	< 0.001
Days	-0.875	0.407	-2.150	0.033
<b>Leaf angle in S.wal: 100 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 36.770, p < 0.001, R^2 = 0.22, \text{Adj } R^2 = 0.22$				
Intercept	-6.136	4.125	-1.488	0.139
Days	4.227	0.697	6.064	< 0.001
<b>Leaf angle in S.wal: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 42.860, p < 0.001, R^2 = 0.25, \text{Adj } R^2 = 0.24$				
Intercept	25.239	4.656	5.421	< 0.001
Days	5.152	0.787	6.547	< 0.001
<b>Leaf angle in S.wal: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 45°</b>				
$F(1,130) = 24.420, p < 0.001, R^2 = 0.16, \text{Adj } R^2 = 0.15$				
Intercept	-6.034	6.054	-0.997	0.321
Days	5.057	1.023	4.942	< 0.001
<b>Stem angle in S.wal: 100 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 56.770, p < 0.001, R^2 = 0.30, \text{Adj } R^2 = 0.30$				
Intercept	-2.023	1.520	-1.330	0.186
Days	1.936	0.257	7.534	< 0.001
<b>Stem angle in S.wal: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 15°</b>				
$F(1,130) = 144.900, p < 0.001, R^2 = 0.53, \text{Adj } R^2 = 0.52$				
Intercept	-5.455	0.735	-7.421	< 0.001
Days	1.496	0.124	12.036	< 0.001
<b>Stem angle in S.wal: 200 <math>\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}</math> at 45°</b>				
$F(1,130) = 124.000, p < 0.001, R^2 = 0.49, \text{Adj } R^2 = 0.48$				
Intercept	1.841	1.271	1.449	0.150
Days	2.391	0.215	11.133	< 0.001

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