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Energy efficiency of botanical systems for the remediation of indoor CO_2

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ABSTRACT

Various indoor plant systems have been proposed to have the capacity to supplement building ventilation, however, the use of artificial lighting and its energy requirements to achieve this has not previously been considered for its contribution to plant-ventilation system energy balances. To test the capacity of plant systems for ventilation system energy reduction, the light energy required per unit of photosynthetic carbon dioxide (CO_2) drawdown was recorded in sealed chambers for several ornamental and one crop plant under two light levels. All species were capable of CO_2 removal, although one ornamental species demonstrated net CO_2 emission under low light, and the crop species (*Pak choi*) substantially outperformed the ornamental species. Green walls and potted plants performed equally, dependant on the foliar area of the plants. To assess the ventilation energy savings capabilities of plant systems, their CO_2 removal capacities ('ventilation equivalence') were compared to the modelled performance of a mechanical ventilation system, with performance metrics based on various building standards. It was found that the mechanical system was far more energy efficient than any plant systems, if supplementary lighting was required by the latter. We conclude that botanical systems may play a role in reducing building ventilation energy use, but only if the plant systems are provided with natural rather than supplementary light. We propose a concept design for the integration of naturally lit, plant-based systems into the heating, ventilation and air conditioning systems (HVAC) of future buildings for the purposes of reducing the energy requirements of the built environment.

1. Introduction

Urbanisation is continuously accelerating to accommodate a predicted 87% of the human population who will live in cities by 2050 [1,2]. The expansion of cities is innately associated with the emission of a wide spectrum of air pollutants [3,4]. Increased exposure, especially indoors, leads to poorer psychological and physiological health outcomes [4–6]. With people spending around 80% of their time indoors, the need to maintain indoor air quality (IAQ) is a growing necessity [7,8].

Carbon dioxide (CO_2) serves as a surrogate indoor air pollutant, with the bulk of indoor emissions occurring through occupant respiration [9,10]. According to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards, CO_2 is one of several indicators for poor IAQ and is used in practice to estimate outdoor to indoor ventilation rates [10,11]. Average acceptable outdoor CO_2 concentrations are generally around 400 ppmv, whereas indoor CO_2 concentrations exceeding the acceptable level 700–1000 ppmv signal insufficient ventilation [10–12], which has been associated with sick-building syndrome, thermal discomfort, and reduced cognitive function [4,10,13].

In order to manage indoor environmental quality, heating, ventilation and air conditioning (HVAC) systems are integrated in most residential and commercial buildings [14,15]. HVAC manages indoor air quality by diluting indoor with outdoor air when a certain indoor CO_2 threshold is reached, typically 800–1000 ppmv [16], using CO_2 as a surrogate for all other air contaminants. This process additionally requires temperature modulation of the influent ambient air if outdoor temperature is variant from the indoor set point; which the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends at 20–26°C [17]. At present, 40–60% of total building operational energy is used in operating HVAC systems [8,18], and as global temperatures rise, heating or cooling loads will be further impacted, increasing energy draw by 5–10% for each 1°C increase in daily temperatures [19,20]. Inappropriate, old or poorly maintained HVAC systems lead to greater energy wastage. The International Energy

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Agency (IEA) states that achieving net zero emissions (NZE) by 2050 will require an 80% reduction in built environment energy use, achieved primarily by electrification and especially energy efficiency and to reduce HVAC consumption [21,22]. With a projected 650 million air conditioners installed globally, and another 2 billion to be sold by 2050 to meet the increasing cooling demand for the expanding building stock, substantial change to existing practice will be required. Integrating digitalisation and smart controls in HVAC may reduce emissions by 350 Mt CO_2 by 2050 [22,23], but these changes will be insufficient to reach NZE goals. While existing technologies such as renewable energy generation can reduce emissions associated with HVAC energy requirements, they will not affect the growing energy burden that ventilation will require. Alternative energy-efficient air management systems would thus make a major contribution to reducing the energy needed for a habitable future built environment.

The potential for indoor greening systems, particularly modular green walls, for reducing temperatures, drawing down CO_2 through plant photosynthesis and removing air pollutants has been established [24–26]. Modular green wall systems are pre-planted panels containing an organic or inorganic plant growth substrate contained within a synthetic or geotextile material [27]. Passive green walls, as tested in the current work, rely on natural circulation for air exchange, which can vary depending on a building's design and natural ventilation [28]. Along with a broad array of air quality improvements [16], modular indoor green walls have been shown to be capable of temperature regulation through insulation and evapotranspiration, facilitating improved occupant psychological health and productivity, and have been claimed to potentially reduce HVAC energy consumption by between 20 and 50% due to heat and indoor CO_2 management [28–32].

Coma et al. [28] found that external modular green walls facilitated cooling load reductions of 30 – 50% as a result of evapotranspiration and insulation, which significantly reduced the thermal stability coefficient and daily maximum wall temperatures, while increasing the thermal lag between inner and outer wall heating. Indoors, plant transpiration has been shown to reduce temperatures by 2.5–4.6°C, when green walls are provided with fans, and 1.2 – 3.6°C when ventilation is absent [29–32]. Wang and Witte [29] recorded greater energy reductions when densely planted green walls cover a greater proportion of a wall area, and are in closer proximity to windows. Regarding the potential for ventilation energy reduction, plant species selection is critical, as indoor CO_2 reductions have been found to range by an order of magnitude depending on plant leaf area and species, with the claimed potential to reduce ventilation energy consumption by as much as 20% [31,32]. Indoor potted plants and green walls typically use ornamental plant species, both for their aesthetic appeal, and their resilience in the indoor environment. However these species rarely have high photosynthetic capacities, limiting their CO_2 removal performance [33], although most systems tested to date have not been explicitly optimised for this purpose. In contrast to ornamental species, crop plants are typified by high growth rates, and thus photosynthetic performance [24]. Modifying vertical greening systems to incorporate vertical farming has the potential to provide an array of benefits to urban sustainability: increasing food production, resilience and access while simultaneously reducing the environmental footprint of urban areas [34]. Food crops have been shown to have greater potential to draw down CO_2 compared to the ornamental species usually used in green walls, with [18] demonstrating high rates of CO_2 reductions for several crop plants, with Pak choi (*Brassica rapa* subsp. *Chinensis*) providing the most efficient removal. The authors [18] estimated that occupied buildings that incorporate this crop might require 12.7–58.4% lower ventilation energy consumption [24], although the specific energy requirements to grow the crops was not empirically measured.

Plants remove CO_2 through photosynthesis [35]. The rate of photosynthetic function is dependent on light availability (specifically photosynthetic photon flux density [PPFD]), plant species and total leaf area: all variables that can be modulated in both green walls and standard potted plants [32,36]. Regarding light photon density, a previous chamber study demonstrated that green walls containing the ornamental plant species *Chlorophytum comosum* and *Spathiphyllum wallisii* at a PPFD of 200 μmol m^{-2} s^{-1} (10,500 lx) directed at an angle of 15–45° from the vertical green wall face and at a distance of 0.8–1 m, promoted efficient CO_2 drawdown that had the potential to quantitatively influence indoor air [25]. The authors, however, used a PPFD chosen for its practicality in occupied indoor settings, rather than maximized photosynthetic performance [25]. Torpy et al [36] tested the CO_2 drawdown performance of a range of indoor plant species at PPFDs up to 350 μmol m^{-2} s^{-1}, finding significantly improved performance at higher light densities, providing evidence for greater performance if more light can be provided to plant systems. Other studies [30–32] have tested the CO_2 removal performance of a variety of ornamental plant species from starting concentrations of ~ 1200 ppm, recording sealed chamber CO_2 reductions between 5 and 50%. Taemthong and Plitsiri [30] tested a green wall in a classroom with ten students, finding a CO_2 reduction of 36%. It is thus clear that plant systems can produce CO_2 removal capabilities at useful scales, however it is not currently known whether these systems can make a realistic reduction in ventilation energy use after the energy required to power the photosynthesis is accounted for.

Lighting is important for maintaining comfortable conditions for both occupants and plants [37]. The efficiency of indoor green walls for CO_2 removal is limited in practice as they are often installed in areas with inadequate light provision (10–15 μmol m^{-2} s^{-1} is the normal indoor light range), that has been designed with the primary purpose of providing a habitable indoor environment over plant function [26,36]. It has been noted [36] that there is a practical limit to the density of light that can be provided to plants in indoor spaces shared with human occupants beyond which the spaces will become unsuited for habitation. This aspect has been retained in the current work, with the density of light in our trials limited by the maximum that can be produced by a contemporary, high performance indoor lighting system. At light levels insufficient for photosynthesis, substrate microorganisms and non-photosynthetic plant areas respire, which may result in net CO_2 generation [25,26]. Thus, it is necessary to provide specific lighting for indoor green walls if they are to provide more than just aesthetic appeal [19]. This balance between maximal PPFD and workplace habitability remains underexplored, yet is critical to the energy efficiency of indoor plant CO_2 removal. Whilst it is possible that building design could incorporate systems facilitating the capture of natural lighting for provision to green wall systems, such designs are uncommon, with supplementary lighting the currently most popular option for green wall health and functionality.

Light-Emitting Diodes (LEDs) can provide plant-optimised 400–700 nm light wavelengths with low heat output, reducing energy draw compared to incandescent or metal halide lamps [37–40] making LEDs the preferred option for sustainable and functional green walls [24,37–41]. However, there remains a knowledge gap related to the specific energy efficiency of these light systems for CO_2 drawdown. Additionally, comparisons between the energy use of indoor green wall photosynthetic CO_2 draw down and current HVAC ventilation energy draw have yet to be performed [24,25,38]. Quantitatively determining the effect size of purpose designed, indoor green wall CO_2 removal is essential knowledge to determine whether they have the potential to reduce load on HVAC systems' ventilation functions.

Hence, this study aims to determine the specific energy efficiency of high-performance LED lighting systems for CO_2 drawdown in indoor crops and ornamental green walls [24,36]. These findings will then be used to compare to the estimated energy consumption of HVAC to produce an equivalent mass CO_2 reduction. This comparison will contribute to our understanding of the potential contribution provided by green walls with optimised lighting to energy savings in the built environment [42–44].

2. Methods

To assess the energy use of botanical systems associated with CO_2 draw down, chamber tests using a variety of planted systems were performed.

2.1. Preliminary energy and light loss assessment

Experimental conditions were consistent with those described by Dominici et al. [25], unless otherwise specified. A series of control tests were conducted within the test Perspex chambers (216 L internal volumetric air capacity) fitted with 80 mm electric fans (12 V), and removable doors with new silicone rubber seals. Lights (see below) were turned on for these tests. Chamber CO_2 losses — due to either leakage through the seals or chamber walls — were assessed on the empty test chamber by generating CO_2 in the chamber through respiration to ~ 1,000 ppmv, with leakage calculated from CO_2 concentration drop over 40 min. Chamber CO_2 concentrations were monitored using a TSI Model 7525 IAQ-Calc infrared gas analyser (TSI Inc., USA; Range 0–5000 ppm, accuracy ± 50 ppm). Empty chamber controls were performed 4 independent times.

Lighting for the test plants was provided by one Parscan circular LED spotlight (12 LEDs, 30 W, 3000 K warm white; ERCO Lighting Pty. Ltd., Australia) and one Opton square LED spotlight (6 LEDs, 25 W, 35000 K warm white; ERCO Lighting Pty. Ltd., Australia), both equipped with spherulite optical polymer flood lenses (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). The luminous efficacy of radiation from the lamps was empirically determined at approximately 75%, which rates these luminaries amongst the most energy efficient LED light sources commercially available. Power requirements for the luminaries were measured using an in-circuit power usage meter (Power-Mate 10A, Cabac, Australia) at three illumination settings (Table 1). Lighting arrangement for the botanical samples within the chambers was as per Domenici et al [19,25] (Fig. 1). Both single and dual light treatments were tested in the current trials.

PPFD from the lights was quantified using a LI-250A light meter (Li-Cor Biosciences, USA) with a quantum sensor (Resolution: 0.01 μmol s^{-1} m^{-2}) at 5 cm intervals from the lens to 100 cm to evaluate the effect of increasing distance from the source on light density, so as to determine the light distance from the plant foliage to provide given PPFDs. Light absorption by the acrylic chamber door provided varying results at different light intensities, which were quantified and the energy associated with chamber light absorption accounted for in subsequent analyses. A light source distance of 75 cm from the chamber door surface provided relatively low absorption values of 7% and mean light provision of 129 μmol m^{-2} s^{-1} for one light at full intensity and 219 μmol m^{-2} s^{-1} for three lights at the foliage surface: the authors believe that these values represent reasonable levels of light provision for indoor workplaces, where specific luminaries are implemented to provide relatively high intensity plant-specific illumination without excessive spill or glare for occupant use.

The lighting system tested here did not produce an even distribution of photon flux density across the green wall planted surfaces as would occur in practice, with the central area of the green walls receiving greater light than the bottom and corners under both one and three-light treatments (Fig. 2). Further, not all of the light produced by the luminaries reached the photosynthetic apparatus of the plants for any treatment: when one lamp was on, detectable light spillage (i.e. PPFD at light densities > ambient) was detected at a distance extending up to 20 cm upward, 40 cm downward, 40 cm to the left and 30 cm to the right relative to the foliage surfaces. Whilst the position and angle of the luminaries was determined to maximise light exposure to the plant surfaces, light wastage was an expected outcome for the treatments and could not be eliminated without utilising reflector systems that would be unrepresentative of and realistic *in situ* application. Electrical energy associated with wasted light is thus incorporated in our estimates, leading to slight underestimates in the CO_2 drawdown energy efficiency estimates for all plant systems, which could be expected to occur similarly *in situ*, in buildings. Ambient light was not independently eliminated from supplied light for these trials, and varied between 2–4 μmol s^{-1} m^{-2} at the foliage surface throughout the trials: the energy used to generate this light was not included in the calculations, as it was trivial relative to the energy use of the experimental lighting systems.

Table 1
Power usage of different LED lights and intensities.

Power	One light (W)	Light at 5 cm (μmol m^{-2} s^{-1})	Two lights (W)	Light at 5 cm (μmol m^{-2} s^{-1})
Full intensity	25.29	4440	79.88	11,291
Medium intensity	3.65	528	–	–
Low intensity	1.33	73.99	–	–

2.2. Sealed chamber experiments

The modular green walls used in this study (Junglefy Breathing Wall[TM]; FoliaNetwork Pty Ltd, Australia) have been the subject of significant previous research [25,26,36,45–49]. The modules had a 0.25 m^2 front face and a depth of 0.125 m, were made from recycled polyethylene and had 16 holes in the front face from where the plants grew in a vertical alignment (Fig. 1). A coconut husk-based plant growth substrate was used in the modules. An additional treatment with 4 potted specimens of *Spathiphyllum wallisii* in 200 mm, 6.2 L pots containing 4 L of soil and plant root volume was included to represent the most commonly-used indoor plant arrangement for comparison, as green walls are less commonly found in office space. Four pots were chosen, as their footprint was approximately equivalent to the planted area of the green wall modules.

Plant selection consisted of 4 ornamental species which are commonly used in indoor greening systems, are tolerant of low light [45] and have been previously tested for air pollutant and CO_2 phytoremediation [45–51]. Additionally, we tested the crop species *B. rapa*, which has previously been shown to have a highly efficient CO_2 draw down rate [24]. For comparison, traditional potted *S. wallisii* plants in four 180 mm x 210 mm pots with pine bark substrate (Greenlife, Australia) were tested.

Photosynthetic function is improved when plants are watered adequately [52]. Thus, green wall modules were grown horizontally and watered to field capacity two times a week until developed, before being allowed to adapt to vertical alignment for several weeks. Potted specimens were watered at an equivalent frequency. Prior to testing, all plant treatments were watered to field capacity and allowed to drain until water drainage ceased.

As determined in the preliminary tests, plant treatments were located 75–80 cm from the luminaries, angled at ~ 45° to the vertical planted surfaces of the green walls or the upper horizontal plane of the foliage for the potted plant trial.

Average starting CO_2 concentrations of ~ 1,000 ppmv (982 ± 54 ppmv) were generated in the chambers through human respiration into the chamber, as has been done previously [36]. This concentration is representative of poor indoor air quality and is a common set-point for the initiation of ventilation system operation [10,13]. Previous trials using our chamber set up [36] determined that the effects of accumulating humidity on photosynthetic CO_2 draw down for a very broad range of plant treatments begin to occur well after 40 min: thus, this period was conservatively selected for the current tests to ensure that humidity build up did not confound species comparisons. Whilst this

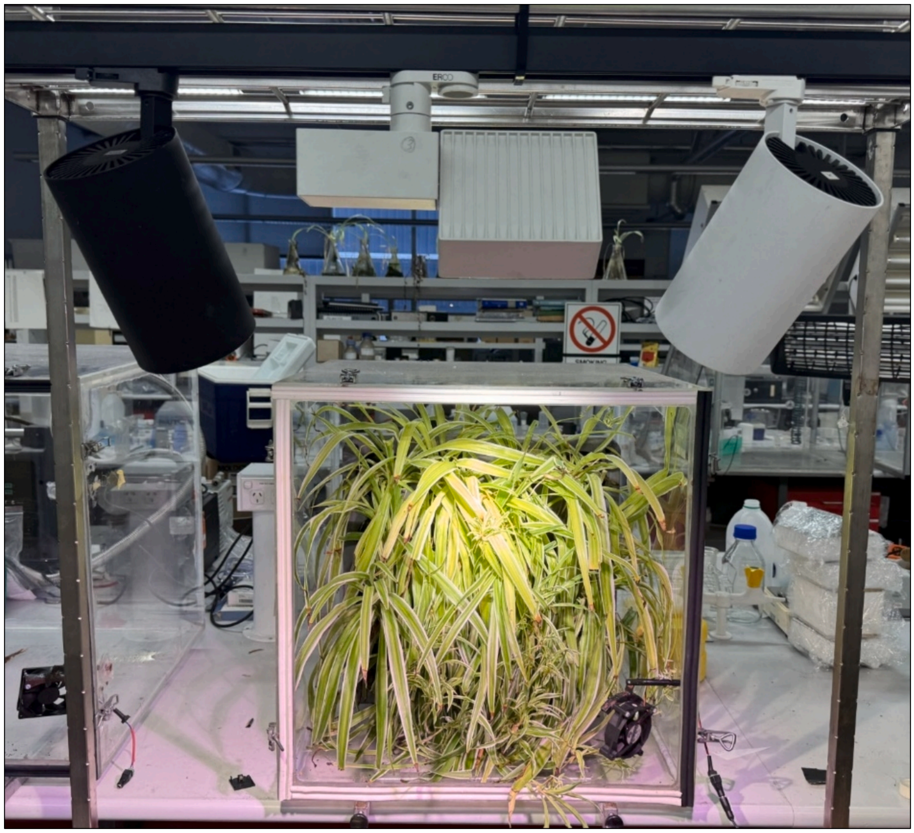

Fig. 1. Lighting arrangement with angle relative to front face of chamber.

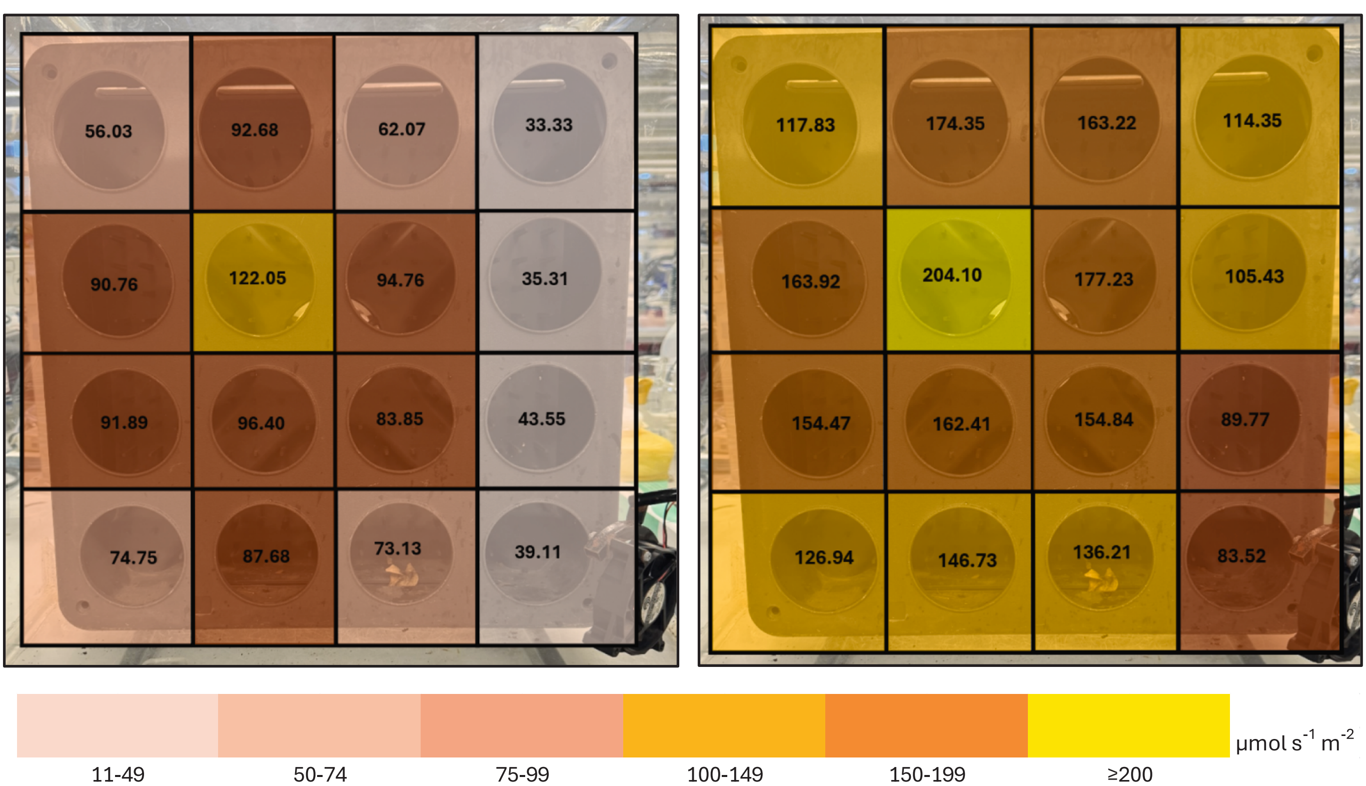

Fig. 2. Light map of the PPFD values (μmol s^{-1} m^{-2}) overlayed on an unplanted green wall module using one (left) and three (right) lights. PPFD measurements for each rectangle were obtained from the centre point of each plant orifice. One light: Average PPFD of 73.6μmol m^{-2} s^{-1}; 3 lights: Average PPFD of 142.2μmol m^{-2} s^{-1} (Image by the authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

method introduced minor variability in chamber starting CO_2 concentration, humidity, and possibly trace gases, these effects were reduced by using a single operator, with any residual variation randomised amongst treatments. This method has been shown previously to be sufficient to compare plant treatments for photosynthetic CO_2 removal [36]. Experiments were performed with four replicates ($n = 4$) with > 15 min intervals between testing to allow chamber CO_2 to return to baseline outdoor concentrations (~415 ppm). This level of replication was empirically determined to be sufficient to provide statistical power of $\beta = 0.8$, reducing uncertainty between each trial. Chamber CO_2 concentration was sampled at 10 min intervals.

As net photosynthesis is proportional at the area of a plant's foliage that is exposed to light, the leaf area index (LAI) of all treatments was calculated (Table 2). LAI was calculated as the one-sided leaf area per module front face area (green walls) or pot surface area (potted plant treatments).

The energy draw per unit of CO_2 removal (mg CO_2/kWh) was calculated by first determining the average leakage-corrected net CO_2 concentration removal per hour for each treatment, and conversion to mass (mg CO_2/ h). Energy use by the lights was corrected for light absorption by the chamber door. The specific CO_2 removal rate per unit lighting energy used (mg CO_2/kWh) was thus determined as follows:

$$CO_2\ mass\ removed = \frac{(0.0409\ *\ (Gross\ CO_2 removed - CO_2\ leaked)\ *\ Molecular\ weight\ )\ *\ Chamber\ volume}{(Power - Absorption)\ \div 1000}$$

2.3. Statistical analysis

Data was collated in Microsoft Excel. To statistically compare treatments, the average rate of CO_2 removal for the treatments over the test duration was determined with ordinary least squares linear regression, with the gradients of the decay curves used as the response variables for comparisons. Both rate of removal and light energy use were compared amongst treatments with one-way PERMANOVA using a Euclidean similarity index in PAST 4.14 [53]. Tukey's *post hoc* test was used for pairwise comparisons.

2.4. Comparison of ventilation rate methodology

As no previously published baseline model data for the energy draw specifically associated with ventilation could be located, we developed a model for comparison with our empirical data.

We considered a single occupant, 'normal office space' with 10 m^2 floor area and a volume of 24 m^3, based on the Australian National Construction Code (NCC; Australia) and the relevant Australian standard (AS1668) [54]. Whilst our quantitative comparisons, being solely based on this model, are likely to differ if modelled on other building typologies such as classrooms, residential spaces, etc. [55], the magnitude of the effect sizes recorded here, in particular the difference in energy performance between plant and mechanical ventilation equivalence, indicates that our conclusions are very unlikely to reverse under alternative conditions. We modelled a single, constant operation purge of this room, to reduce a starting concentration of 1000 ppmv CO_2 down to an acceptable 600 ppmv [10], with HVAC operation on an outdoor air exchange rate of 12.5 L/s as defined by ASHRAE 62.2 for a single occupant, with gas modelling based on 25°C, 1 atm pressure, and an outdoor air CO_2 concentration of 422.7 ppmv (global average 2024, [56]). The outdoor air exchange rate (ACH) in this model is equivalent to < 1.9 air changes per hour (ACH), and a mixing time of 119 min. This is low compared to recommended built environment ACHs, which range from 4 to 6 [57], and much lower than the rates found in building surveys, which may be > 15 ACH [58]. The practical consequences of this metric in our study would thus be to reduce the relative performance of the HVAC model compared to the plant model, thus creating a best-case estimate for the plant systems tested, which is what attempted to achieve in the current work. For the purposes of our model, we assumed the room was a perfectly mixed zone, with CO_2 dilution (HVAC) or removal (plants) following exponential decay as follows:

$$C(t) = C_{out} + (C_0 - C_{out})e^{-Qt/V}.$$

Where: C(t) is the concentration of CO_2 in the room and the end of the purge = 600 ppmv, C_0 is the initial concentration = 1000 ppmv, C_{out} is the concentration of CO_2 in the inlet = 422.7 ppmv, Q is the ventilation rate = 12.5 L/s and V is the room volume = 24 m^3. This gives a ventilation purge time of 37.78 min using 28.33 m^3 of outdoor air.

For HVAC capacity, we used the commercial building 'rule of thumb' of 1 T of cooling power per 500–600 sq ft of floor space, giving 0.631–0.757 kW for the 10 m^2 room [59,60]. It is recognised by the authors that this estimate is primarily used in North America and can lead to incorrect comparisons for other regions or oversizing of cooling systems [59,60]. However it nevertheless makes a useful basis for comparison, and, in this instance, any overestimate of cooling potential would have no effect on the direction, and little effect on the magnitude of our conclusions (see Section 3.3). The coefficient of performance (COP) of the cooling component of an HVAC system is the refrigeration capacity at full load per unit electrical input power. Whilst chillers in HVAC systems do not operate at full load in all conditions, for the purposes of our model we have made comparisons under full capacity output. We have calculated chiller energy COP for the extreme values of the current Australian Government minimum energy performance standards (MEPS) [61], ranging from 2.7 for an air cooled, 350 kW chiller to 6 for a > 1500 kW water-cooled unit, giving a chiller energy estimate for the model 10 m^2 space of 0.1052–0.2804 kW.

Ventilation fan energy was determined using the Australian National Construction Code (2016) Volume 1, Specification J5.2a [62], giving a supply and return fan energy for a space < 100 m^2 of 5.3 W/m^2, adding 53 W to the HVAC energy use in our current model. We have not included fan power consumption for cooling towers, closed circuit coolers or evaporative condensers in our calculations, as this usage would be comparatively small for a single occupant office space in an otherwise large building containing many such offices.

Table 2
Leaf area index for plant species used in chamber study.

Species	Common Name	Leaf Area Index (m^2 / m^2)
Spathiphyllum wallisii[a]	Peace Lily	1.54
Chlorophytum comosum	Spider Plant	6.61
Nematanthus wettsteinii	Goldfish Plant	1.43
Peperomia obtusifolia	Baby Rubber Plant	2.37
Brassica rapa. var *Chinensis*	Bok Choy	4.27

[a] Potted plant treatment, using 4 pots.

3. Results

3.1. Botanical CO_2 removal efficiency

Statistically significant differences in CO_2 removal rates amongst most treatments under both one and three light conditions were found. Under three lights, *B. rapa* exhibited significantly greater CO_2

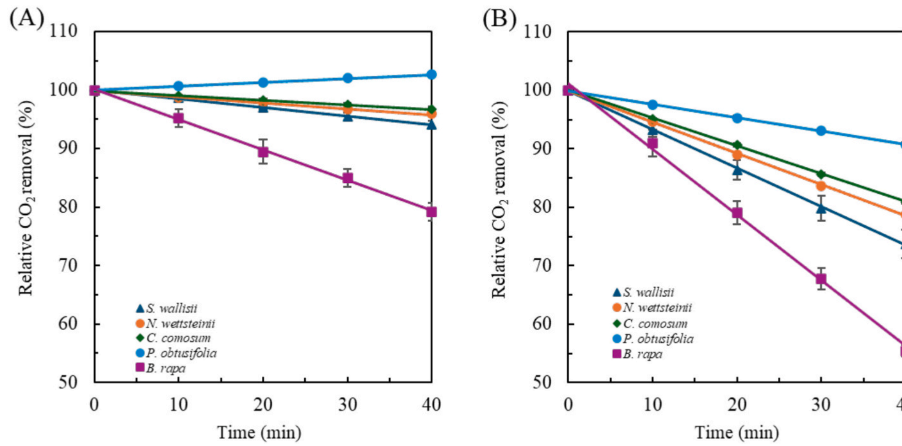

Fig. 3. Average percentage CO_2 removed from initial concentrations (~ 1,000 ppm) over 40 min for all plant treatments under one (A) and three (B) light conditions. Error bars represent the SEM for all treatments (n = 4). Due to small SEM values, the error bars cannot be seen for several data points.

drawdown rates compared to all other plant treatments (One-Way PERMANOVA: $p = 0.000$), as predicted. The greater photosynthetic performance of *B. rapa* was further demonstrated by its higher CO_2 removal rate under one light being statistically equivalent to potted *S. wallisii* ($p = 0.114$), *N. wettsteinii*, ($p = 1.00$), and *C. comosum* ($p = 0.968$) under three lights.

Amongst the ornamental plant species tested, the most efficient CO_2 remover was surprisingly potted *S. wallisii,* followed by *N. wettsteinii*, *C. comosum*, and *P. obtusifolia* (Fig. 3). The rates of CO_2 removal for *S. wallisii, N. wettsteinii* and *C. comosum* under either one or three lights were not significantly different (all $p > 0.05$), indicating consistent photosynthetic rates amongst ornamental species. As expected, all treatments removed CO_2 at greater rates when more light was provided, with significantly faster CO_2 removal rates for the three-light treatment for all of these species (all $p < 0.05$).

P. obtusifolia was the lowest performing species, producing a net increase in CO_2 of 2% over the 40 min testing period under one light, as a result of respiratory emissions from the plant and substrate subsuming any photosynthetic draw down [36]. It has been shown previously [25] that achieving even lighting across a green wall is impractical *in situ*. Thus, in any installation, areas of a green wall containing *P. obtusifolia* would inevitably receive light levels below the minimum required for carbon drawdown, resulting in poor performance. Under 3 lights, *P. obtusifolia* only exhibited a 9% reduction in chamber CO_2 over the 40 min trial, which was significantly less efficient than the other tested species (all $p < 0.05$). It is therefore unlikely that a green wall system with this species could provide net carbon reductions, and this species is thus not recommended for use in indoor CO_2 management.

Table 3
Comparison of annual energy use for CO_2 drawdown (mg/kWh) between observed plant species and HVAC systems under one and three lights.

Species	Energy usage (mg/kWh)
S. wallisii	1229 – 1838
N. wettsteinii	732 – 1431
C. comosum	487 – 1282
P. obtusifolia	−811 – 630
B. rapa	3052 – 4745

3.2. Botanical energy efficiency for CO_2 drawdown

The lighting energy usage per unit mass of CO_2 removed was significantly different amongst plant treatments ($p = 0.000$). All species exhibited greater energy efficiency under three lights than under one, as predicted (Fig. 4, Table 3), with the only exception, surprisingly, *B. rapa*, which removed roughly 1.5-fold more CO_2 under one light ($p = 0.0275$; Fig. 3). *B. rapa* displayed the greatest mean energy efficiency for CO_2 drawdown amongst the plant treatments under both one ($p = 0.000$) and

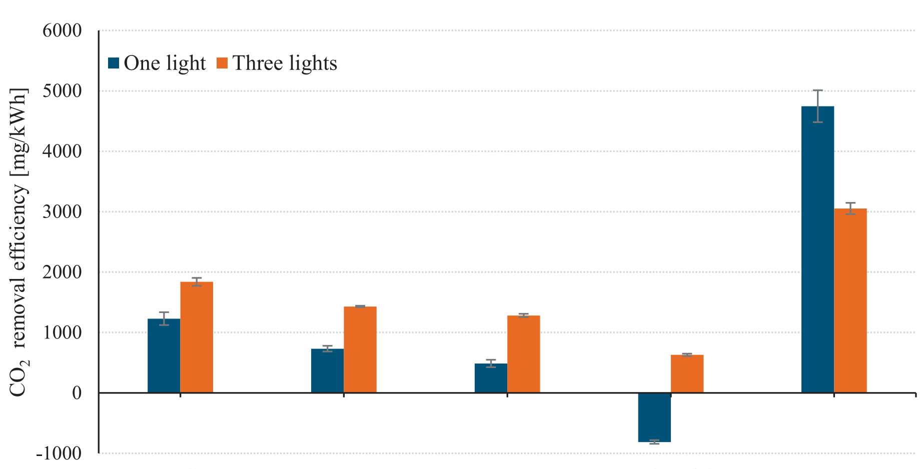

Fig. 4. CO_2 removal lighting energy usage for five plant species under one and three light conditions (mg/kWh), with starting CO_2 concentrations of ~ 1000 ppm. Error bars are the SEM (n = 4).

three lights ($p = 0.000$).

The potted *S. wallisii* treatment was the second most efficient, with a higher average removal efficiency of under three lights compared to one ($p = 0.0285$). Compared to *B. rapa*, this is 2.5-fold lower CO_2 draw down under one light ($p = 0.0308$) and a 1.5-fold reduction under three lights ($p = 0.0296$). *S. wallisii*, *N. wettsteinii*, and *C. comosum* displayed similar drawdown efficiencies ($p > 0.05$; Fig. 3).

3.3. Comparison of photosynthetic and HVAC ventilation rates

To reduce the CO_2 concentration in the model room from 1000 to 600 ppmv, a total of 17,279 mg CO_2 must be removed. Across the plant treatments that produced positive carbon removal in the current work, the energy efficiency required to perform this task was 487–4,746 mg CO_2/kWh. In comparison, the modelled HVAC ventilation energy efficiency was a considerably higher 81,813–172,445 mg CO_2/kWh.

Independent of energy efficiency, to be capable of providing an adequate net CO_2 removal rate to match the ventilation requirements of the model room (i.e. drawing down 17,279 mg CO_2 within 37.78 min), significant plant densities would be required: 17.75 m^2 of the most efficient *B. rapa* green wall, or 89 m^2 of the less efficient *C. comosum* green wall. The findings of the current study therefore do not support the use of artificially illuminated plant systems for ventilation equivalence.

4. Discussion

4.1. General trends

These findings reinforce the need for provision of ample light energy to green walls if they are to provide useful services, as has been the case with other studies [25,26,30,32,50,52]. Thus, as expected, the three light treatments led to greater net CO_2 reductions for most plant treatments, and further increases in CO_2 drawdown could be expected with further increases in light density up to the photoinhibition level of the plants, which is 500–1000 μmol s^{-1} m^{-2} for most ornamental species [36]. Plant metabolism type was expected *a priori* to be associated with a difference in CO_2 drawdown efficiency, with the three C3 test species (*S. wallisii*, *C. comosum* and *B. rapa*) outperforming the Crassulacean acid metabolism (CAM) species *P. obtusifolia* and *N. wettsteinii* [32,50,52,63,64]. Whilst C3 plants perform photosynthesis in the light, CAM plants typically perform this function at night to reduce stomatal opening during the hotter daylight hours: an adaptation to their natural habitats [64,65]. However, no consistent pattern of this type was detected, potentially due to metabolism shifts to C3 in our CAM species: a phenomenon previously described for the closely related species Mesembryanthemum crystallinum [48]. Similarly, raised atmospheric carbon has been shown to increase metabolic rate in CAM species [65], also potentially contributing to the observed patterns in the current work, where testing was performed under CO_2 levels substantially elevated over ambient.

Whilst increased light intensity improved photosynthetic CO_2 draw down for *P. obtusifolia* as has been shown in previous work [50], we recorded a net increase in CO_2 at the lower light intensity level tested. It is likely that this was a result of soil microbiota respiration and CAM-like behaviour [36,52]. Whilst these effects would also have occurred in the previous study [42], which used a similar substrate and light levels to the current work, Smith et al. [50] tested an active version of the green wall system, with mechanical air circulation through the substrate and foliage. It is likely that this contributed to the differences in CO_2 removal by *P. obtusifolia* between [42] and the current work: active green walls usually display improved CO_2 draw down over equivalent passive systems [26]. However, whilst active systems may draw down CO_2 more efficiently than their passive analogs, fan energy consumption by the former is likely to result in a lower net energy efficiency for active systems, although further work will be necessary to test this hypothesis.

The potted plant treatment was more effective at CO_2 removal than all green wall treatments except *B. rapa* (Table 3). However, in many applications, the smaller ground footprint and flexible installation characteristics of green walls may still make them the preferred option for service provision.

The *B. rapa* green wall, which had the third highest LAI amongst our plant treatments (Table 2), removed 243 mg of CO_2 from the 216 L test chamber in the 40 min trial period under three lights. The greater comparative photosynthetic performance of *B. rapa* is consistent with Shao et al. [24], where it also outperformed several trial ornamental species. It is thus possible that other crop species might provide efficient CO_2 removal, and further research may be warranted to identify the highest performing species in this regard, especially if functional use is to be made of photosynthetic CO_2 draw down for indoor air service provision.

The high net photosynthetic rate observed by *B. rapa* could be attributed to its relatively short life-cycle and fast growth rate, leading to rapid CO_2 uptake [24,66]. When growing under high light conditions, rapid biomass development allows chlorophyll to be distributed deeper into leaf tissue to allow greater photosynthetic capacity [66,67]. However, the lifecycle of *B. rapa* is far shorter than ornamental plants, in the current work we recorded flowering and subsequent leaf senescence in our test plants, only two months after planting. Thus crop species used in the proposed application tested here will not perform well over the long term, but rather will involve regular harvest and replanting, with the ancillary benefits of food production, economic value and longer term, improved urban food security [34].

4.2. Botanical biofiltration ventilation provision comparison to HVAC

Building energy reductions by green walls have been claimed in many studies, with ranges of 5–50% depending on the basis for comparison (ventilation, cooling, humidification) method of calculation, size of the planted area relative to indoor space volume, light provision, plant species, density and diversity [24,32,52]. The current study is the first to quantify the mass of CO_2 removed per unit of energy usage by green walls using high performance supplementary LED lighting. The energy efficiency of each ornamental plant was consistent with their increased CO_2 drawdown rates under higher light densities; with three lights facilitating a greater mass of CO_2 removed per kWh. Conversely, *B. rapa* removed CO_2 at a greater energy efficient under one light, which was unexpected given the inherently fast growth rate of *B. rapa*. The biological reason for this effect was not tested here, but is likely a result of photoinhibition, which is a phenomenon known to occur in several Brassicaceae species [68], although to date has not been tested in *B. rapa*. In any case, the lower light requirements and high photosynthetic rate of this species produced efficient CO_2 drawdown, and thus was useful as a comparison with mechanical ventilation energy efficiency.

In order to make this comparison, we made estimates using generic standards for a model 10 m^3 'office'. While HVAC types differ amongst building types and country guidelines [42–44,69], we used the most common general guidelines for HVAC size available. Our findings indicate that when supplementary lighting is considered, botanical systems do not remove CO_2 in an energy efficient manner, with specific CO_2 removal rates 1–2 orders of magnitude less energy efficient than ventilation. This is unsurprising, as it has been shown that office space often uses greater energy for lighting than ventilation [37,40,44]. These findings contrast with those of Taemthong and Plitsiri [30], who compared an HVAC with a separate exhaust fan with 2 green walls containing *Epipremnum aureum* in a classroom in Thailand, finding that while both systems removed CO_2 at roughly similar rates, the green wall's energy efficiency far surpassed that of the exhaust fan: consuming 26% less energy, despite including small fans for air circulation attached to the green wall. Differences between [30] and the current work were significant, including HVAC size, the additional exhaust fan and different room volumes, however the major difference between the experimental conditions was light provision, with [30] using a ~ 98 μmol s^{-1} m^{-2} LED array supplemented with ~ 170 μmol s^{-1} m^{-2} of natural light: leading to far greater light densities at lowered energy draw than the current work. This is evidence that botanical CO_2 removal can play an effective role in ventilation energy use reductions, but only when reliant on natural light. Naturally lit, plant-based systems would use little electrical energy, but as has been shown in the current study, can remove CO_2 with high efficiency.

Even using natural light as the energy source for photosynthesis, considerable volumes of green plant material would be required to make major impacts on building energy use. Incorporating an adequate density of ornamental and crop green walls in office buildings can be architecturally and operationally feasible; although such buildings would vary significantly from existing building stock and would introduce multiple novel cost factors to ensure favourable lifecycle performance [70–72]. Manufacturing and installing green walls requires considerable resources, mainly for water and irrigation, and support. [27,71] in locations where the green walls are exposed to direct sunlight at appropriate levels at different periods of the diurnal and annual solar cycles [73].

Maintenance for plant systems will also impact their net energy balance as water provision and crop maintenance related to harvesting and replacement will add additional energy costs which have not been considered in the current work [72,73]. Whilst *B. rapa* and other fast-growing leafy crops have a comparatively high market value and low space requirements which may improve energy and economic performance compared to lower-value crops [71–73], the work required to manage and maintain any crop is non-trivial. Additionally, systems that minimise physical maintenance and harvesting with automated irrigation would reduce labour, but will likely increase energy consumption [71]. Consequently, future assessments of the complete net energy balance and economic viability of plant systems will be required to determine the viability of such systems, and to establish guidelines for future installations.

In response to these considerations, we propose an alternative future application of plant systems for office building energy reduction by combining urban farming with a system of recirculating indoor air treatment. Such a system is proposed in the following section. We hypothesise that if well designed and integrated with the building, such systems would provide contributions to food security along with indoor air pollutant removal, cooling, humidification and ventilation energy reduction through CO_2 removal.

4.3. Proposed integration of naturally lit phytosystem into building ventilation

Here we propose a conceptual integration pathway that incorporates green wall technology into HVAC systems. We have used active green wall (AGW) systems in these designs as they facilitate both air pollutant removal [47–49] and more efficient CO_2 removal [26], maximizing the services provided by green systems. These concepts aim to implement nature-based solutions to help reduce the energy consumption of HVAC while being able to be integrated/adapted into systems of varying sizes and functionality.

By positioning an AGW array on the outside of the building, the return air in the HVAC system can still be efficiently filtered without the need for supplementary artificial lighting (Fig. 5). To ensure the filtered air remains within the closed HVAC system and not released into the surrounding environment, the green walls could be enclosed within a glasshouse. In doing so, the botanically filtered air can then be transported back into the standard ducting system to then be processed and treated by the air handling unit. The main consideration of this concept would be the initial construction costs and the need for *de novo* construction: it would be difficult to retrofit this design.

Closed-loop plant systems has been analysed previously, as self-sustaining O_2 generation / CO_2 removal systems for extended space-flight [74,75]. Whilst the primary purpose of these systems were realised and significant benefits to air quality were recorded, particularly VOC removal [16,47], several limitations of these systems must be considered. In particular, it was previously established that a significant amount of plant biomass would be required to provide adequate effects for living spaces of useful volume [74]. As such, future modelling of closed-loop plant systems must determine an optimal balance where plant biomass is sufficient to provide useful CO_2 removal. Secondly, the sustainability of incorporating large-scale plant systems into a closed-loop system is affected by crop lifecycle [71], and the associated

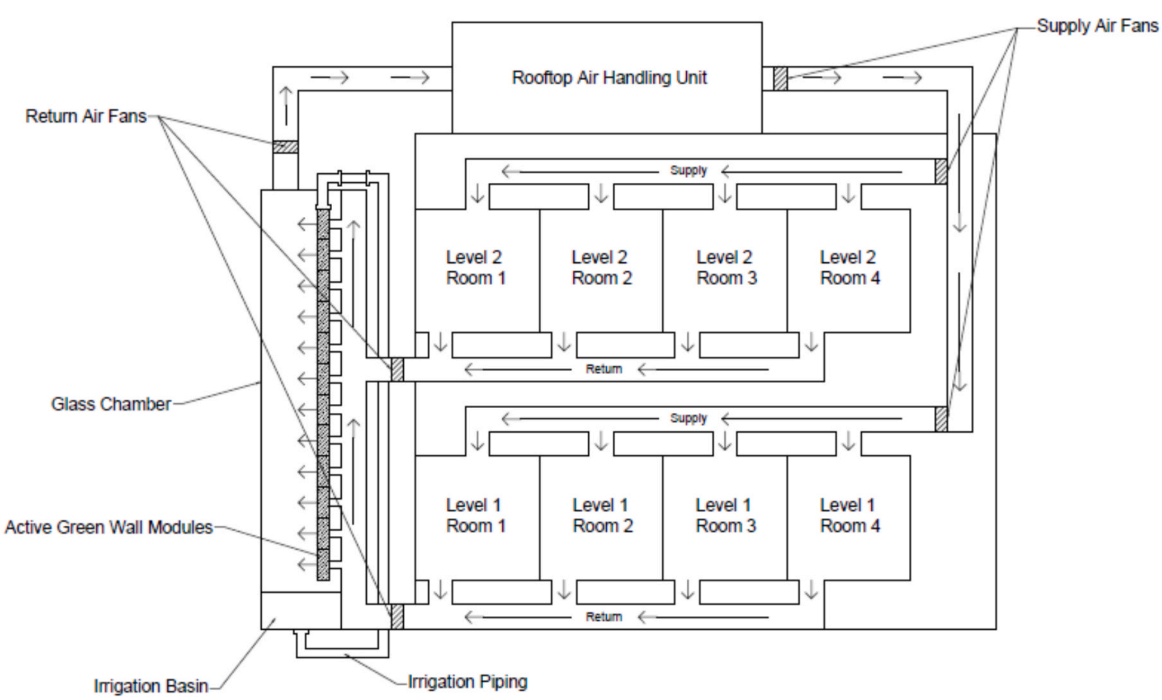

Fig. 5. Proposed schematic illustration design for a large scale naturally lit AGW / HVAC system.

labour and system design required to achieve consistent performance [27,72] (feasibility of large-scale plant systems has been addressed in Section 4.2). Furthermore, whilst the use of solely natural lighting would offset the high artificial light energy demands experienced in previous systems [74,75]; under low-light or night-time conditions, CO_2 generated through plant respiration would be released into the ventilation system [74] unless a night-time control sensor within the closed-loop system to disconnect the AGW from the HVAC airflow was incorporated to release these emissions to atmosphere: an additional design consideration. Similarly, plant systems have a relatively slow response to fluctuations in CO_2 concentrations, humidity, temperature, and light [41], which may introduce response delays that may complicate HVAC control and subsequently increase energy consumption required to maintain comfortable indoor environments [76,77].

4.4. Limitations and future research

Whilst our findings clearly show that green walls with supplementary lighting will not reduce the ventilation energy use of buildings, they could make considerable reductions in energy use if used to treat high-CO_2 indoor air in a recirculating system, with reliance on natural lighting for plant growth. Other studies have proposed the use of plant systems in tandem with HVAC systems to improve indoor air quality, while reducing the energy consumption and subsequent greenhouse gas emissions [13,24,30–32]: to which the current study has emphasised the necessity of natural lighting to achieve energy-efficient performance.

The quantification of photosynthetic carbon drawdown in this study was limited by the non-uniform provision of light to all plant surface areas, likely due to absorption through chamber doors or obstruction from the edge of the chamber. Conversely, in real buildings, light spill may add to general building illumination, reducing reliance on occupant-specific lighting systems. To ensure carbon drawdown is maximised by green walls with the most efficient usage of solar energy, further research into green wall design and building integration are warranted. A diverse range of plants may be most effective, with species exhibiting good photosynthetic rates under low light conditions mixed with high light adapted crop species providing maximal CO_2 removal at all phases of the sun.

Our energy modelling was also subject to limitations. Most importantly, our study was limited to CO_2 ventilation equivalence, and as such, we did not include cooling and humidifying performance by the green walls which would have improved the overall energy use balance of our green walls against mechanical systems, but not by a magnitude adequate to redress the higher efficiency of HVAC. Similarly, our estimates of HVAC ventilation energy use did not include the energy required to move air against temperature gradients, as these values would be trivial compared to fan, cooling and lighting power draw. It should also be noted that the ventilation equivalence measured in this study specifically refers to the CO_2 mass balance, and does not account for the equivalence in overall IAQ control – including the removal of other indoor air pollutants and pathogens [78]. Whilst it has been shown previously that indoor plant systems can remove pollutants with high efficiency [16,47–49], it will be essential in future trials expanding on the current work to quantify the total ventilation equivalence of green walls.

As this study was limited to chamber experiments and a generic HVAC energy use model, our estimates do not account for building type, size, and occupancy behaviour [13,42]. Thus, future research could employ indoor plant-based systems in office buildings to compare energy requirements for CO_2 drawdown to HVAC systems where occupancy behaviour is more variable. Similarly, as most existing studies on botanical biofiltration compare energy usage to office buildings [24,25,32,44], future comparisons for other building types such as residential, healthcare and educational facilities may provide more insight into developing guidelines for green wall assisted air purification.

Finally, our study was a laboratory-scale, sealed-chamber botanical system operating under steady lighting conditions, to which we compared a comparatively inefficient HVAC model by contemporary standards. The net effect of these two designs would be to increase the probability of the plant-based system demonstrating competitive performance: we have thus produced a best-case model for the plant system. The authors recognise that the incorporating real-world aspects such as occupant-tolerable lighting levels for the plants and high-performance building ventilation models would further increase the performance gap between the two systems. Whilst such criterial would have made our model comparison more *in situ* realistic, we believe that our best-case model provides a stronger hypothesis test to indicate the comparative inefficiency of artificially-lit plant systems for ventilation provision.

5. Conclusion

The current study is the first to quantify supplementary lighting energy requirements for CO_2 drawdown through botanical biofiltration, including both high and lower performing plant species. Our findings show that whilst botanical systems, especially those containing crop plants, are efficient at drawing down high concentrations of CO_2, systems that use supplementary lighting will not improve the ventilation energy efficiency of buildings. However well-designed systems that integrate natural lighting, recirculating indoor air systems and urban farming have the potential to make useful contributions to future building energy use reduction, and it is therefore proposed that future research aiming at developing energy efficient urban solutions focuses on naturally lit systems. Our findings indicate that very large plant areas will be required to provide ventilation energy savings. This will require considerable architectural and operational changes to current building typologies. A part of these changes will involve dynamic building energy simulation (e.g. coupling plant models with BES tools): such processes will be essential in determining the feasibility of the systems we propose in the current work.

Overall, the results of this study provide promising context for implementing green walls to reduce energy costs for HVAC consumption in urban buildings. Moreover, the other advantages of these systems — effective air pollutant removal, aesthetic value and food security, will ensure that green systems play a considerable role in low energy future cities.

CRediT authorship contribution statement

Ralph Fares: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **James D. Torpy:** Writing – review & editing, Writing – original draft. **Peter J. Irga:** Writing – review & editing, Supervision. **Fraser R. Torpy:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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