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Can houseplants improve indoor air quality by removing CO_2 and increasing relative humidity?

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Abstract

High indoor CO_2 concentrations and low relative humidity (RH) create an array of well-documented human health issues. Therefore, assessing houseplants' potential as a low-cost approach to CO_2 removal and increasing RH is important. We investigated how environmental factors such as 'dry' (< 0.20 m^3 of water per m^3 of substrate, m^3 m^{-3}) or 'wet' (> 0.30 m^3 m^{-3}) growing substrates, and indoor light levels ('low' 10 μmol m^{-2} s^{-1}, 'high' 50 μmol m^{-2} s^{-1}, and 'very high' 300 μmol m^{-2} s^{-1}) influence the plants' net CO_2 assimilation ('A') and water vapour loss. Seven common houseplant taxa—representing a variety of leaf types and sizes—were studied for their ability to assimilate CO_2 across a range of indoor light levels. Additionally, to assess the plants' potential contribution to RH increase, the plants' evapo-transpiration (ET) was measured. At typical 'low' indoor light levels, 'A' rates were generally low (< 3.9 mg h^{-1}). Differences between 'dry' and 'wet' plants at typical indoor light levels were negligible in terms of room-level impact. Light compensation points (i.e. the light level where the CO_2 assimilation equals zero) were in the typical indoor light range (1–50 μmol m^{-2} s^{-1}) only for two studied *Spathiphyllum wallisii* cultivars and *Hedera helix*; these plants would thus provide the best CO_2 removal indoors. Additionally, increasing indoor light levels to 300 μmol m^{-2} s^{-1} would, in most species, significantly increase their potential to assimilate CO_2. Species which assimilated the most CO_2 also contributed most to increasing RH.

Keywords *Dracaena* · Drought · *Hedera* · Indoor light · Indoor air quality · *Spathiphyllum*

Abbreviations

RH	Relative humidity (%)
DLI	Daily light integral (mol m^{-2} d^{-1})
SMC	Substrate moisture content (m^3 m^{-3})
LCP	Light compensation point (μmol m^{-2} s^{-1})
ET	Evapo-transpiration (g)
PPM	Uptake or emission of CO_2 by potted-plant microcosm
LA	Leaf area (m^2)
ETLA	Evapo-transpiration per unit leaf area (g cm^{-2})

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Introduction

Indoor CO_2 concentrations are primarily dependent on the occupancy level and outdoor air supply rate (Zhang et al. 2017). Humans produce and exhale CO_2; therefore, a greater occupancy coupled with lower ventilation rates—intended to reduce energy consumption—gives rise to higher and often harmful CO_2 concentrations indoors (Satish et al. 2012). Additionally, even when ventilation by ambient air is employed, the problems may be exacerbated in the future: ambient CO_2 concentrations increased by 40% over the last century, to 400 ppm—with a rise to 670 ppm expected by 2100 (Hersoug et al. 2012).

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends a maximum

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indoor CO_2 concentration of 1000 ppm (Torpy et al. 2017). Concentrations indoors (e.g. in fully occupied offices or meeting rooms) often reach 2000 to 2500 ppm but can rise as high as 5000 ppm (Zhang et al. 2017). Although discrepancies in the maximum safe exposure concentration are commonplace in literature, prior research suggests typical indoor CO_2 concentrations will continue to present unwanted health issues (Zhang et al. 2017). These include mucus membrane symptoms (i.e. sore/dry throat, dry eyes and sneezing) and respiratory problems (i.e. tight chest, wheezing/coughing and shortness of breath) (Seppanen et al. 1999; Erdmann and Apte 2004). Elevated CO_2 can also reduce the cognitive performance of students in schools, while long-term, regular exposure has been linked to increased absenteeism, weight gain, and obesity (Hersoug et al. 2012; Satish et al. 2012; Gaihre et al. 2014; Nieuwenhuis et al. 2014; Vehvilainen et al. 2016; Zhang et al. 2017).

An additional challenge in indoor environments is low relative humidity (RH). An RH below 30% has been shown to cause eye irritation and skin dryness, with an RH below 10% causing dryness of the nasal mucus membrane. Low RH can also increase the likelihood of influenza transmission, enhance indoor ozone concentration, and produce static electricity (Arundel et al. 1986; Berglund 1998; Sunwoo et al. 2006; Lowen et al. 2007; Abusharha and Pearce 2013; Zhang and Yoshino 2010). However, high RH (> 60%) too can cause issues by encouraging fungal/mould growth and contributing to the deterioration of building materials (Berglund 1998; Bin 2002; Zhang and Yoshino 2010; Frankel et al. 2012). The majority of adverse health effects concerning RH can be avoided by maintaining indoor levels between 40 and 60% (Arundel et al. 1986).

Various techniques are used in the built environment to control and regulate CO_2 levels. They include highly engineered approaches to ventilation (Hesaraki et al. 2015; Mateus and da Graca 2017) as well as low-tech approaches which can include the use of plants (Raji et al. 2015; Charoenkit and Yiemwattana 2016). A number of studies investigate a houseplants' potential to sequester CO_2 from indoor environments (Oh et al. 2011; Pennisi and van Iersel 2012; Torpy et al. 2014). Studies vary in scale and focus—from those focusing on individual plants in experimental chambers to room scale studies in situ.

A range of studies investigated houseplants' ability to sequester CO_2 in home, school, and office environments. Various combinations of houseplants were found to generally reduce room CO_2 concentrations and increase RH; however, studies rarely specify exact plant numbers and plant types. Plant species commonly used include *Dracaena deremensis*, *Dracaena marginata*, *Ficus benjamina*, *Hedera helix*, and *Spathiphyllum clevelandii* (Raza et al. 1991; Lohr and PearsonMims 1996; Jeong et al. 2008; Lim et al. 2009; Oh et al. 2011; Pegas et al. 2012).

Light levels and substrate moisture are the key factors influencing gas exchange between the plant and the environment, with 'low' light and 'dry' substrate both reducing houseplants' ability to sequester CO_2 and contribute to RH increases indoors via transpiration (Lawlor and Cornic 2002; Flexas et al. 2006; Torpy et al. 2017). In indoor environments, light levels are typically at least 100-fold lower compared to outdoors (on a clear summer day for example) and are maintained in the range of approximately 1–50 μmol m^{-2} s^{-1} (Thimijan and Heins 1983; Boyce and Raynham 2009; Lai et al. 2009; Hawkins 2011). Research suggests however that having higher indoor light levels (approximately 30–50 μmol m^{-2} s^{-1}) would greatly increase occupant comfort (Lai et al. 2009; Huang et al. 2012). As previously proposed, indoor light is the most limiting factor for CO_2 assimilation (Pennisi and van Iersel 2012).

The positive contribution of plants to the reduction of CO_2 levels and RH increases indoors are based on the premise that plants function optimally and are sequestering CO_2/releasing water vapour at their maximum capacity. However, the main challenges for maintaining plant function in the indoor environment are 'low' indoor light levels and issues arising from plants' (mis) management, most frequently plants' being under or over watered without the correct nutrients (RHS 2017). A few studies addressed these questions in part by investigating a wide range of light levels and their effect on CO_2 assimilation (Pennisi and van Iersel 2012; Torpy et al. 2014). However, no study to our knowledge investigated the effect of differing substrate moisture content (SMC)—namely, investigating the effect of 'wet' (> 0.30 m^3 m^{-3}) and 'dry' (< 0.20 m^3 m^{-3}) SMC conditions. Additionally, previous studies have not specifically focused on plants' cultivar-level differences; this may be of interest as for many houseplant species, there is a range of cultivars available, which may potentially offer augmented service compared to straight species if they are larger in size or more physiologically active.

Pennisi and van Iersel (2012) investigated the CO_2 assimilation of 17 houseplant species in both a simulated controlled environment utilising light levels of 10, 20, and 30 μmol m^{-2} s^{-1} and a public office building in Atlanta (USA). In the public office, the amount of CO_2 assimilated by plants varied depending on plant size. In the controlled environment, most species exhibited positive carbon assimilation over a 10-week period. The study found that in both environments, larger, woody plants (such as *Ficus benjamina*) assimilated more CO_2 than herbaceous species.

Torpy et al. (2014) investigated the CO_2 assimilation of eight common indoor plant species by producing light response curves and light compensation points (LCPs) using an infrared gas analyser. The results indicated that at least some CO_2 sequestration could be expected from the studied species under current indoor lighting systems and plants could be effectively utilised in the built environment to sequester CO_2 given a moderate increase in the targeted lighting levels.

Our research aims to improve the understanding of which taxa (i.e. plant species and cultivars) as well as which light and substrate moisture conditions are best placed to regulate indoor CO_2 and RH. Specifically, the aims of the study were to determine:

1. The impact of drying substrate on CO_2 removal capacity by different taxa
2. The impact of light levels on net CO_2 assimilation of taxa (i.e. to test the potential to improve the performance by supplementing indoor light levels)
3. The evapo-transpiration (ET) rates of each taxon and their potential contribution to increasing indoor RH.

Material and methods

Plant material

Five common houseplant species, including two cultivars, were selected for the study to represent a range of leaf types (succulent and herbaceous), plant sizes, and plant metabolisms often found in indoor environments (Table 1). Selected plants were 2 years old at the time of purchase in July 2016 from the RHS plant centre (Wisley, Surrey, UK), ranging between 10 and 60 cm in height, depending on the taxon. Within the species, plant height and stature were uniform (data not shown). Plants were maintained in Sylvamix growing medium (6:2:2 sylvafibre:growbark pine:coir; Melcourt, Tetbury, Gloucestershire, UK) in 3-L containers, with a slow release fertiliser feed (Osmocote, Marysville, OH, USA). For 3 months prior to experimentation, plants were kept at ambient temperatures (17–22 °C) and 'low' light levels (10 μmol m^{-2} s^{-1}) in an indoor office environment within the Crops Laboratory in the Glasshouse Complex of the School of Agriculture, Policy and Development, at the University of Reading (UK).

Net leaf-level CO_2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions

Experiments were conducted on five plants per taxon. Measurements of the net CO_2 assimilation rate (μmol m^{-2} s^{-1}) were made using a LCPro infrared gas analyser (ADC Bioscientific, Hoddesdon, Hertfordshire, UK) on three young, fully expanded leaves per plant (with consistent leaf selection, i.e. third fully expanded leaf from the plant tip (Fig. 1)) under office conditions (16.6–21.8 °C, RH > 35%) at 'low' and 'high' indoor light levels (Hawkins 2011; Huang et al. 2012). 'Low' 10 μmol m^{-2} s^{-1} lighting was achieved in the usual lighting conditions of the room (eight fluorescent lights, Osram, Munich, Germany lighting a floor area of 20 m^2). To achieve 'high' 50 μmol m^{-2} s^{-1} during measurements, the photosynthetic photon flux density (i.e. light level, μmol m^{-2} s^{-1}) was supplemented at the leaf by an external halogen source (50 W, 12 V). Each light increment was administered for 7 min and the net CO_2 assimilation rate recorded at the end of the seven-minute period.

Substrate moisture content (SMC) based on volume of water per volume of substrate was measured daily for each plant, in two locations per container using a SM300 capacitance-type probe connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of ± 2.5%). At the start of the experiment, substrate moisture was at the container capacity (SMC > 30%, 0.3 m^3 m^{-3}) and plants were thus considered optimally watered (Vaz Monteiro et al. 2016). Measurements were also made on 'dry' plants (SMC < 20%, 0.2 m^3 m^{-3}). Measurements were made over approximately 1 month.

Calculation of the respiration of the potted-plant microcosm

To ensure that CO_2 removal by the aboveground parts of the plant (i.e. leaves and stem) was not cancelled out by respiration of the potted-plant microcosm (PPM) (i.e. substrate and non-photosynthetic plant parts), the PPM was investigated for CO_2 contributions at both 'high' and 'low' light and under 'wet' and 'dry' SMC conditions ($n = 3$). The PPM respiration values were then subtracted from all the leaf CO_2 assimilation values made, to obtain the overall contribution of the plant and substrate.

Measurements of the PPM respiration were made utilising a 150 L (45 × 45 × 75 cm, 0.15 m^3) Perspex chamber (The plastic people, Leeds, West Yorkshire, UK) sealed with Swagelok's (Swagelok, Bristol, South Gloucestershire, UK). Enclosed inside the Perspex chamber was a HOBO MX1102 CO_2 logger (Onset Computer Corporation, Bourne, MA, U.S.A), a 12 V DC brushless fan (RS Components, Corby, Northants, UK), and a calibrated (20–90% RH, 0–40 °C) Tinytag RH/temperature logger (Gemini data loggers, Chichester, West Sussex, UK). The external RH/temperature surrounding the chamber was also monitored with another, identical Tinytag logger. Inside the chamber 'low' light levels were achieved as described in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section; 'high' levels were generated by two LED lights (V-TAC Europe Ltd., Sofia, Bulgaria) and measured with a calibrated light sensor (Skye instruments, Llandrindod Wells, Wales, UK). Bare substrate was prepared for the experiment as explained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section. Experiments were undertaken for 2 h, with the chamber analysed for leakage prior, during and after experimentation; leakage was found to be < 2% of the

Table 1 Characteristics of the houseplant taxa (i.e. plant species and cultivars) chosen for experiments. Leaf area ($n = 2$) and plant height ($n = 5$) are means ± SEM. Species' Latin name is given in italic and cultivar, where applicable, follows

Species/cultivars	Family	Metabolism	Leaf area (cm^2)	Plant height (cm)
Dracaena fragrans 'Lemon Lime'	*Asparagaceae*	C3	1742 ± 91	51 ± 1
Dracaena fragrans 'Golden Coast'	*Asparagaceae*	C3	1438 ± 10	60 ± 1
Guzmania 'Indian Night'	*Bromeliaceae*	C3/CAM	1230 ± 6	32 ± 1
Hedera helix	*Araliaceae*	C3	1509 ± 243	9 ± 0
Spathiphyllum wallisii 'Bellini'	*Araceae*	C3	1766 ± 189	35 ± 1
Spathiphyllum wallisii 'Verdi'	*Araceae*	C3	5451 ± 1104	36 ± 1
Zamioculcas zamiifolia	*Araceae*	CAM	1388 ± 88	57 ± 1

starting concentration over a 2-h test period. Measurements were made over approximately 1 week.

Data obtained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section was normalised by leaf area by multiplying CO_2 assimilation (mg m^{-2} h^{-1}) with leaf area (m^2), providing CO_2 assimilation in mg h^{-1} $plant^{-1}$ for each taxon. Data were also corrected for PPM respiration and leakage by calculation of an average conversion value (mg h^{-1}) for both 'wet' and 'dry' SMC conditions.

Generating light response curves

To generate light response curves, measurements of the net photosynthetic rate (μmol m^{-2} s^{-1}) were made as explained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section on four plants per taxon and two leaves per plant. Environmental conditions within the leaf cuvette were temperature controlled at 25 °C, ambient CO_2 concentration (~400–450 ppm) and an ambient RH of 35–45%. Plants were prepared for the experiment as explained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section, achieving a SMC > 0.30 m^3 m^{-3} and were considered optimally watered on the commencement of each experiment (Vaz Monteiro et al. 2016). SMC was maintained at this level for the duration of the experiment.

To generate the light response curve, the light was supplemented in the following set increments: 0, 50, 300, and 1200 μmol m^{-2} s^{-1} as described in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section. An increment of 0 μmol m^{-2} s^{-1} was chosen to investigate each species CO_2 assimilation in the dark; 50 μmol m^{-2} s^{-1} the highest indoor light level; 300 μmol m^{-2} s^{-1} was chosen to represent the highest feasible light level which could be engineered (with supplementary artificial lighting) in an indoor environment; 1200 μmol m^{-2} s^{-1} (a sunny day in a UK climate) was chosen to present information on a plant's maximal capacity for net CO_2 assimilation. Measurements were made over approximately 1 week.

The light response curves were based on an equation proposed by Prioul and Chartier (1977) and were produced using the model by Lobo et al. (2013). Light compensation points, LCPs (which represent the light level where the CO_2 assimilation is equal to zero) (Torpy et al. 2014), were calculated with the same model (Lobo et al. 2013) for all taxa apart from *Guzmania* 'Indian night', which was omitted due to very low assimilation rates and therefore, unreproducible results.

Plants' water use/evapo-transpiration (ET) experiments

Water use/ET of the plant taxa were inferred by consecutive plant/pot weight measurements using a precision balance (CBK 32, Adam Equipment, Milton Keynes, Buckinghamshire, UK) under indoor office conditions (RH > 35% and at 'low' light levels, 10 μmol m^{-2} s^{-1}. Plants were prepared for the experiment as explained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section, starting the experiment with SMC at full water-holding capacity and were not watered for the duration of the experiment. Measurements were made at 0 h and then every 24 h over a 3-week period on a whole 'plant – substrate system' (i.e. potted plant, with uncovered substrate) enabling the calculation of the water loss at each time-point. We were interested in total potential RH contribution of the plant along with substrate, mimicking a real-life scenario of an indoor plant. Each plant was removed from the experiment when its SMC dropped < 20% (0.2 m^3 m^{-3}). Destructive measurements of LA were made using a LA meter (Delta-T Devices, Cambridge, Cambridgeshire, UK) on two plants per taxon, at the end of the experiment. While we appreciate that measuring the leaf area at the end of the experiment may lead to under/over-estimating assimilation measured earlier in the experiment, we were limited by the number of experimental plants we could destructively harvest. Given that this approach was applied to all taxa that the leaf areas were assessed within 2 months

of the assimilation experiments and that plants did not increase in size significantly over this period (as evidenced by height measurements which we made at the start and the end of the experiment), we believe that the risk of the error is small and evenly spread. SMC was measured daily as explained in "Net leaf-level CO2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions" section. Water use/ET per unit leaf area (ETLA, expressed in g cm^{-2}) was calculated by dividing the ET (i.e. water loss) from a plant in a 24-h period by the mean leaf area.

Statistical analysis

Experimental data (gas exchange parameters and water loss/ET) were analysed using GENSTAT (16th Edition, VSN International, Hemel Hempstead, Hertfordshire, UK). An analysis of variance (ANOVA) was performed to compare means for each measured parameter between different taxa and/or over time. Values were presented as means with associated standard errors of the mean (SEM) and Tukey's 95% confidence intervals for multiple comparisons. Data on plants' water loss were log-transformed and Tukey's 95% confidence intervals were used to compare between taxa in the text ("Plants' water use/evapo-transpiration experiments" section).

Results

Net leaf-level CO_2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions

At 'low' indoor light, 'dry' *Spathiphyllum wallisii* 'Verdi' was statistically significantly respiring the most (− 87.6 mg h^{-1}, $p < 0.001$) and was therefore the only taxon to measure significant differences between 'dry' and 'wet' substrate. In 'dry' substrate, statistically significant differences in CO_2 assimilation were measured between the cultivars of *Spathiphyllum wallisii* 'Bellini' and 'Verdi' (− 19.6 and − 60.7 mg h^{-1}, respectively; $p < 0.001$). In 'wet' substrate, there were no significant differences in CO_2 between any studied taxa (Table 2).

At 'high' indoor light, only *Spathiphyllum wallisii* 'Verdi' measured statistically significant differences between 'dry' and 'wet' substrate (− 60.7 and 60.0 mg h^{-1}, respectively; $p < 0.001$; Table 2). No statistically significant differences in CO_2 assimilation were measured between cultivars under the same SMC conditions; significant differences were measured with *Spathiphyllum wallisii cvs* 'Bellini' and 'Verdi' between 'dry' (− 19.6 and − 60.7 mg h^{-1}, respectively) and 'wet' (11.7 and 60.0 mg h^{-1}, respectively) SMC conditions ($p < 0.001$, Table 2).

Generating light response curves and light compensation points

Light compensation points (LCPs), which represent the light level where the CO_2 assimilation is equal to zero, were calculated for each species (Table 3). Of the studied species, *Spathiphyllum wallisii* 'Verdi' and *Hedera helix* had the lowest LCPs of 20 and 31 μmol m^{-2} s^{-1} respectively. The highest LCP was recorded for *Dracaena fragrans* 'Golden Coast' (96 μmol m^{-2} s^{-1}), with both *Dracaena fragrans* 'Lemon Lime' and *Zamioculcas zamiifolia* also having LCP values outside of the light level typically experienced in indoor environments (93 and 65 μmol m^{-2} s^{-1} respectively, Table 3).

At 0 μmol m^{-2} s^{-1}, *Hedera helix* was statistically significantly respiring the most (− 1.2 μmol m^{-2} s^{-1}, $p < 0.001$; Fig. 2), no significant differences were measured in net assimilation between other studied taxa.

At 300 μmol m^{-2} s^{-1}, all taxa were assimilating CO_2. Net assimilation was highest in *Hedera helix* (7.7 μmol m^{-2} s^{-1}) and was statistically significantly different to all other taxa ($p < 0.001$). *Spathiphyllum wallisii* 'Bellini' and *S. wallisii* 'Verdi' (2.4 and 2.4 μmol m^{-2} s^{-1} respectively) measured a net assimilation that was statistically significantly higher than three other studied taxa (*Dracaena fragrans* 'Lemon Lime', *Dracaena fragrans* 'Golden Coast', and *Guzmania* 'Indian Night', $p < 0.001$; Fig. 2). At this highest indoor photosynthetic photon flux density, there were no cultivar-level differences within the same species in net assimilation.

At 1200 μmol m^{-2} s^{-1}, all taxa were assimilating CO_2. Net assimilation was highest in *Hedera helix* (10.7 μmol m^{-2} s^{-1}) and was statistically significantly higher than all other taxa ($p < 0.001$). *Spathiphyllum wallisii* 'Bellini' (2.7 μmol m^{-2} s^{-1}) measured a net assimilation that was statistically significantly higher than three other studied taxa (*Dracaena fragrans* 'Lemon Lime', *Dracaena fragrans* 'Golden Coast', and *Guzmania* 'Indian Night', $p < 0.001$; Fig. 2). Again, no net assimilation was statistically significantly different between cultivars of the same species.

Plants' water use/evapo-transpiration experiments

In terms of ET per plant per day, when well-watered, the ET was statistically significantly higher for *Hedera helix* (70.5 g) and *Spathiphyllum wallisii* 'Verdi' (71.0 g) compared to all the other taxa ($p < 0.001$). ET per plant was also statistically significantly different between the taxa *Guzmania* 'Indian Night' (28.0 g) and *Dracaena fragrans* 'Lemon Lime' (44.3 g, $p < 0.001$); ET per plant at 24 h was statistically significantly different between *Spathiphyllum wallisii* cultivars ($p < 0.001$; Fig. 3a).

In terms of ET per leaf area per day, when well-watered, the ET was statistically significantly higher for *Hedera helix* (0.047 gcm^{-2}) in comparison to other taxa ($p < 0.001$). ET

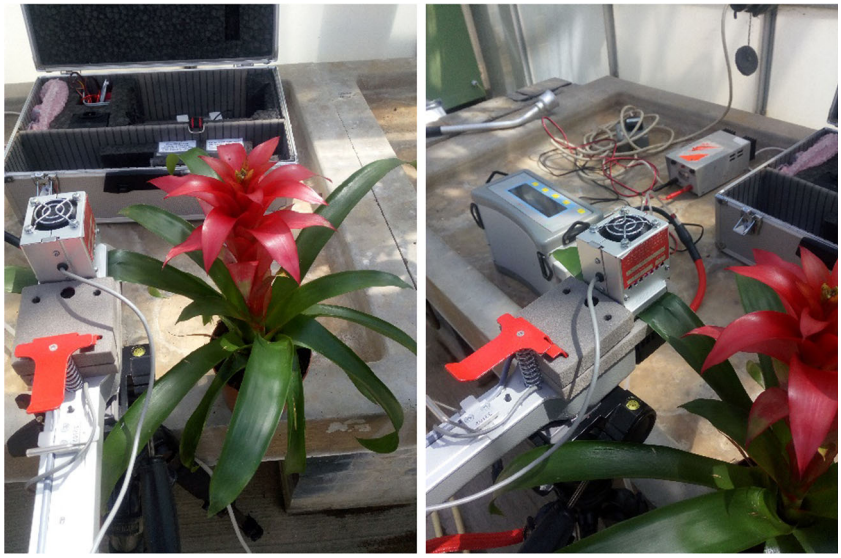

Fig. 1 Images of the experimental setup for leaf CO_2 assimilation measurements, equipment pictured includes infrared gas analyser, leaf cuvette, and external halogen light source

per leaf area was statistically significantly lower for *Spathiphyllum wallisii* 'Verdi' (0.013 g cm^{-2}), in comparison to the other taxa tested ($p < 0.001$); no ET per leaf area was statistically significantly different between any other taxa. The ET per leaf area was statistically significantly different between one pair of cultivars: *Spathiphyllum wallisii* 'Bellini' and *Spathiphyllum wallisii* 'Verdi' (0.02 g cm^{-2} and 0.013 g cm^{-2}, respectively; $p < 0.001$; Fig. 3b).

At the time when SMC decreased to 20%, ET reduction ranged between 7% (*Spathiphyllum wallisii* 'Verdi') and 63% (*Guzmania* 'Indian Night') (data not shown). The time taken for the SMC to decrease to < 20% ranged between 10 days (*Dracaena fragrans* 'Golden Coast' and *Spathiphyllum*) and 23 days (*Zamioculcas zamiifolia*) across studied taxa.

Discussion

The current work presents the first insight into leaf-level CO_2 assimilation—from plants in both 'dry' and 'wet' substrate—and potential RH increases for a range of common houseplant taxa (i.e. species and cultivars), differing in structure and physiological function.

In this study, we demonstrate that little potential is offered by the studied houseplants alone to reduce CO_2 concentrations in 'low' light indoor environments—with only three taxa's light compensation points falling within the typical indoor light level range (0–50 μmol m^{-2} s^{-1}; Table 3). However, our findings demonstrate that although respiration was generally occurring in houseplants grown in 'dry' substrate, the net CO_2 exchange recorded was extremely low and thus likely to have little or no negative impact on the CO_2 levels at a room scale. Our results suggest that increasing light levels to a technically feasible 300 μmol m^{-2} s^{-1} (e.g. through use of supplementary lighting) would provide a significant increase in CO_2 assimilation in most of the studied taxa. The study also indicates that the best performing taxa for CO_2 assimilation will also contribute the most to raising RH indoors.

From the results of this study, we estimated the mass (in grams) of CO_2 removed per hour, per plant, and per m^2 of each taxon. In home and office environments, each person contributes 30 g (CO_2)/h and 36 g (CO_2)/h, respectively (Persily and de Jonge 2017) and these different values are consequences of the level of individual's activity in various environments. Using both these values, we calculated the number of plants required to remove 10% of a single person's CO_2 contribution at the 'very high' (300 μmol m^{-2} s^{-1}) indoor light level (Supplementary Table 1). The plant numbers range from 15 (for more active plants like *Hedera* and *Spathiphyllum*) to > 100 for physiologically less active plants, highlighting how correct plant choice can result in a different air quality outcome. Of the taxa we investigated, *Guzmania*, *Dracaena*, and *Zamioculcas* would be better placed to provide services other than CO_2 reduction (e.g. pollutant sequestration (Yang et al. 2009; Kim et al. 2010). *Hedera* and *Spathyphyllum* would have more effect on room-level CO_2 exchange, and in numbers which can be realistically installed in small living walls. Estimates of the number of plants required to remove the CO_2 generated by human contributions were also made by Pennisi and van Iersel (2012) and Torpy et al. (2014). However, widely different estimates of the CO_2 generated per person were used by each study, making direct comparisons difficult.

In typical indoor environments with 'low' light levels, only one taxon, in 'wet' substrate conditions, was assimilating CO_2 (*Spathiphyllum wallisii* 'Verdi') and would contribute to CO_2 concentration reduction (3.9 mg h^{-1}, respectively; Table 2). Additionally, only three taxa were found to possess light compensation points that fall within the range of typical indoor light levels (i.e. *Hedera helix and Spathiphyllum wallisii*

Table 2 Net leaf-level CO_2 assimilation of each species at 'low' and 'high' indoor light (< 10 and 50 μmol m^{-2} s^{-1}) in 'wet' (> 0.30 m^3 m^{-3}) and 'dry' (< 0.20 m^3 m^{-3}) conditions. Data are a mean of five plants of each species, three young, fully expanded leaves per plant ± SEM (n = 15). Data are adjusted to account for PPM respiration and chamber leakage and is normalised by leaf area (Table 1). Different letters next to means correspond to statistically significant differences between means based on Tukey's 95% confidence intervals. (−) values signify respiration (i.e. the release of CO_2)

Taxa	Net CO_2 assimilation per plant (mg h^{-1})	
	'Wet' (> 0.30 m^3 m^{-3})	'Dry' (< 0.20 m^3 m^{-3})
'Low' light (< 10 μmol m^{-2} s^{-1})		
Dracaena fragrans 'Lemon Lime'	$-17.4^{b} \pm 2.1$	$-35.7^{b} \pm 4.9$
Dracaena fragrans 'Golden Coast'	$-28.4^{b} \pm 3.0$	$-25.3^{b} \pm 2.2$
Guzmania 'Indian Night'	$-14.3^{b} \pm 1.1$	$-23.8^{b} \pm 1.0$
Hedera helix	$-9.5^{b} \pm 2.2$	$-27.3^{b} \pm 1.0$
Spathiphyllum wallisii 'Bellini'	$-14.8^{b} \pm 4.5$	$-22.7^{b} \pm 2.5$
Spathiphyllum wallisii 'Verdi'	$3.9^{b} \pm 5.2$	$-87.6^{a} \pm 33.3$
Zamioculcas zamiifolia	$-17.5^{b} \pm 2.0$	$-23.9^{b} \pm 1.8$
'High' light (50 μmol m^{-2} s^{-1})		
Dracaena fragrans 'Lemon Lime'	$-5.5^{abc} \pm 6.0$	$-41.97^{ab} \pm 11.3$
Dracaena fragrans 'Golden Coast'	$-21.8^{ab} \pm 4.7$	$-24.0^{ab} \pm 4.7$
Guzmania 'Indian Night'	$-11.5^{ab} \pm 6.7$	$-19.6^{ab} \pm 1.3$
Hedera helix	$-6.6^{abc} \pm 8.2$	$9.4^{bc} \pm 4.7$
Spathiphyllum wallisii 'Bellini'	$11.7^{bc} \pm 9.3$	$-19.6^{ab} \pm 3.8$
Spathiphyllum wallisii 'Verdi'	$60.0^{c} \pm 31.3$	$-60.7^{a} \pm 24.5$
Zamioculcas zamiifolia	$-12.2^{ab} \pm 2.8$	$-20.9^{ab} \pm 0.8$

'Verdi' and 'Bellini'). Both *Hedera helix and Spathiphyllum wallisii* would require an unrealistic number of plants to see any significant CO_2 concentration reduction (data not shown); at typical 'low' indoor light levels, the study indicates that a plants' potential benefits psychologically or in productivity terms (Thomsen et al. 2011; Raanaas et al. 2011; Nieuwenhuis et al. 2014) would be more important than their contribution to indoor CO_2 removal. Furthermore, as suggested in Torpy et al. (2014), plants should not be expected to completely replace ventilation systems, but to act as a supplement in reducing the energy load required.

In typical 'low' light indoor environments, when grown in 'dry' substrate, all studied taxa were respiring. The results also indicated that in the range of typically observed indoor light levels, six of the studied species (*Dracaena fragrans* cvs 'Lemon Lime' and 'Golden Coast', *Guzmania* 'Indian Night', *Hedera helix, Spathiphyllum wallisii* 'Bellini' and *Zamioculcas zamiifolia*) were respiring in both 'dry' and 'wet' SMC conditions (Table 2).The (mis) management and under watering of houseplants is anecdotally a common problem; therefore, determining if a 'dry' houseplant is releasing significant amounts of CO_2 into an indoor environment and detrimentally impacting health is important; our results, however, suggest this is not the case. In 'dry' SMC conditions, in typical office light, *Spathiphyllum wallisii* 'Verdi' was releasing the most CO_2 into the indoor environment out of all studied taxa at 0.0876 g h^{-1}. In comparison, a single person, in an office environment would release 36 g/hour into the indoor environment (Persily and de Jonge 2017). This confirms that in typical office light conditions—even for plants growing in drying substrate—the contribution of plants to room-level CO_2 is negligible.

At a 'high' indoor light level (50 μmol m^{-2} s^{-1}), a greater net CO_2 assimilation was generally measured for all taxa, but no statistically significant differences were found between cultivars of the same species in 'dry' or 'wet' conditions. Although measurements were only made under 'wet' SMC conditions, this trend for the lack of cultivar differences continued at higher light levels of 300 and 1200 μmol m^{-2} s^{-1} suggesting that cultivar level differences were not pronounced in this study.

Our study suggests that for most studied taxa, light saturation occurs at around 300 μmol m^{-2} s^{-1} and further increases beyond this show little difference in assimilation terms (Fig. 2). As discussed in Torpy et al. (2014), targeted indoor lighting could be used to maximise a houseplants CO_2 assimilation potential. Extensive research has been undertaken into various light systems for plant cultivation and development on indoor living walls but not specifically with potted houseplants or concerning CO_2 assimilation (Yeh and Chung 2009; Egea et al. 2014). Our findings support the notion that increased light levels maximise plant gas exchange and we suggest future research should

Table 3 Light compensation points (LCPs) are means of eight leaves per species ± SEM for each of the studied species

Taxa	LCP (μmol m^{-2} s^{-1})
Dracaena fragrans 'Lemon Lime'	92.9 ± 7.1
Dracaena fragrans 'Golden Coast'	95.6 ± 13.2
Guzmania 'Indian Night'	N. A
Hedera helix	30.9 ± 3.9
Spathiphyllum wallisii 'Bellini'	31.9 ± 11.7
Spathiphyllum wallisii 'Verdi'	20.1 ± 9.8
Zamioculcas zamiifolia	64.7 ± 15.7

investigate the suitability of testing targeted lighting installations in indoor environments. Light compensation points calculated in our study are generally higher, but comparable with other indoor species previously tested (Burton et al. 2007; Pennisi and van Iersel 2012; Torpy et al. 2014; Torpy et al. 2017; Tan et al. 2017).

Earlier attempts at estimating the CO_2 removal of houseplants (Pennisi and van Iersel 2012) did not take into account ambient CO_2 concentrations or consider the effects of substrate moisture on CO_2 assimilation. A more robust study by Torpy et al. (2014) investigated several factors which could influence assimilation including different acclimatisation treatments, the respiration of the 'potted-plant microcosm', but again did not consider impact of substrate moisture conditions. Other studies did not specify the exact number or type of houseplant (Lim et al. 2009; Pegas et al. 2012) which contributed to any CO_2 concentration reduction or, only considered a single light level (Oh et al. 2011).

The results from the ET experiment indicate that the best performing species in CO_2 assimilation terms (*Hedera helix* and *Spathiphyllum wallisii* 'Verdi') both have the highest ET rates per plant. However, the comparative water use per area results show *Spathiphyllum wallisii* 'Verdi' having the lowest ET *per leaf area*; this species is, therefore, inherently more water use efficient and only uses more water *per plant* due to its large size. We found a difference between the *Spathiphyllum wallisii* cultivar pair in terms of water use per plant and per area, with no difference per plant or per area measured for the *Dracaena fragrans* pair. This confirms that our hypothesis that inherent physiological differences can be measured in water use terms down to a cultivar level. The results also suggest that certain species (i.e. *Spathiphyllum wallisii* 'Verdi') do not restrict their water loss under water stress conditions (SMC < 20%). *Spathiphyllum wallisii* 'Verdi' would therefore, in a drying substrate, continue to contribute the most to RH increases. To achieve the optimal function for the studied taxa, which would then support biggest improvements in IAQ—based on results from "Plants' water use/evapo-transpiration experiments" section and authors' experience—we suggest a watering regime of 200 ml per week for all studied species other than *Spathiphyllum wallisii* 'Verdi' and *Hedera helix*, where 250 ml is recommended twice a week. We also suggest that future studies should evaluate the CO_2 assimilation ability of other more physiologically active, vigorous species (i.e. *Osmunda japonica*, *Selaginella tamariscina*, and *Hemigraphis alternata*), which also performed well in pollutant sequestration experiments (Yang et al. 2009; Kim et al. 2010) under 'high' indoor light levels (300 μmol m^{-2} s^{-1}).

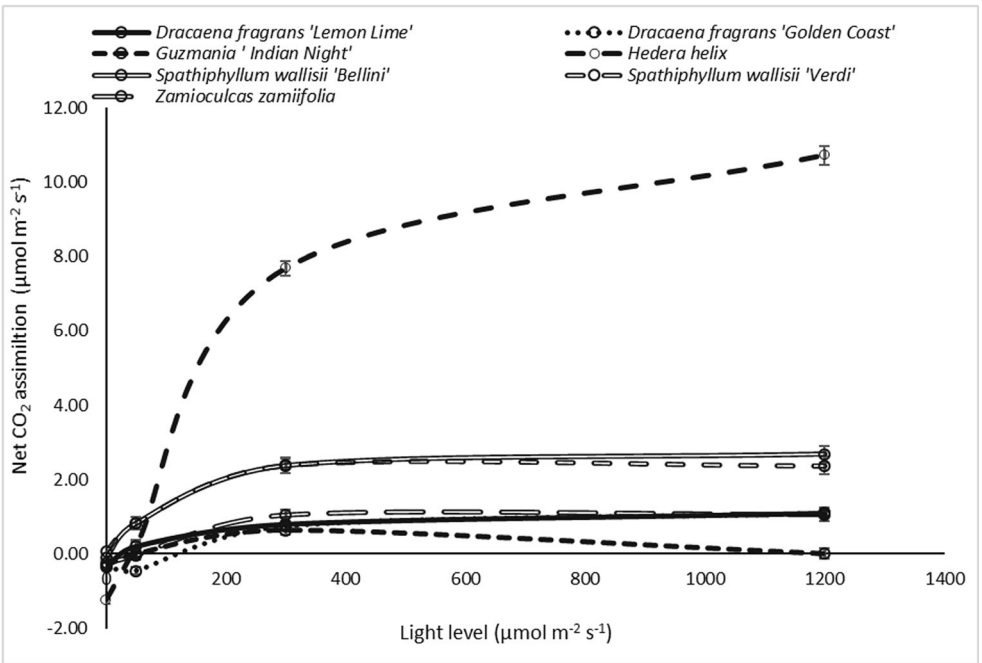

Fig. 2 Net CO_2 assimilation across three light levels (0, 50, 300, 1200 μmol m^{-2} s^{-1}); data are a mean of four containers of each species and two young fully expanded leaves per plant ($n = 8$). Tukey's 95% confidence intervals are used for species comparison in text; error bars represent SEM

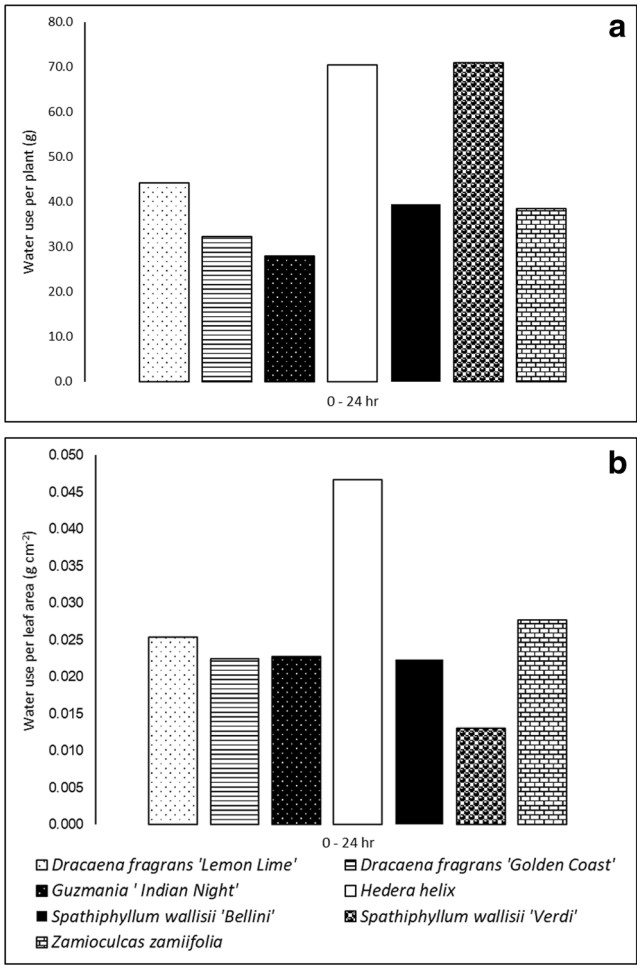

Fig. 3 Water use per plant (**a**) and per leaf area (**b**) per day; data are a mean of four containers of each species ($n = 4$). ANOVA was performed on the log-transformed data only (data not shown); Tukey's 95% confidence intervals generated in the analysis of the transformed data are used for species comparison in text

From the results of the ET experiment, we estimated the contribution of studied taxa to raising RH indoors. Calculations of the amount of water vapour in the air were made through the equation: RH (%) = 100 * actual vapour density (g m^{-3})/saturation vapour density (g m^{-3}) (using a saturation vapour density of 19.1 g m^{-3} at 22 °C) (Galindo et al. 2005). A RH of 40–60% is considered optimal in terms of human health (Arundel et al. 1986); we therefore calculated the number of plants—per taxon—required to raise RH from 40 to 60% in a static 100 m^3 office (Supplementary Table 2). Calculations assume that 100% of the water vapour 'lost' by taxa (Fig. 3a) was released into the surrounding environment. The results do not take into account the impact of ventilation, occupancy, or the feedback effect of taxa (i.e. as RH increases plants release less water vapour into the indoor environment). These calculations are intended to act as a guide on how the studied taxa could influence RH indoors. Our results indicate that five *Spathiphyllum wallisii* 'Verdi' or *Hedera helix* plants growing in an unmulched (i.e. uncovered) growing medium—over a 24-h period—could raise the RH from 40 to 60% (Supplementary Table 2). It also suggests that less physiologically active plants (such as *Guzmania*, *Dracaena*, and *Zamioculcas*) could be used in larger numbers (10+) as part of installations such as indoor living walls within even smaller offices, without a risk of office RH raising above 60%. Conversely, *Hedera* and large *Spathiphyllum* cultivars would be suitable in smaller numbers (5 or below) or in larger rooms with greater overall volume where their RH-influencing effect would be diluted.

Conclusions

The results indicate that net CO_2 assimilation of all studied plants was generally 'low', with *Spathiphyllum* cultivars and *Hedera helix* removing most CO_2.

While CO_2 assimilation of plants in 'wet' substrate was higher than in 'dry' conditions, in practical terms however (i.e. when considering the plant's potential to influence indoor CO_2 levels), net CO_2 assimilation differences between 'dry' and 'wet' plants at 'high' and 'low' indoor light levels were negligible for the taxa studied. Light compensation points were in the typical indoor light range for both *Spathiphyllum wallsii* 'Verdi' and *Hedera helix*, suggesting that these plants would be best suited to provide most CO_2 removal in a typical indoor setting. Additionally, both these taxa, per plant, had the highest transpiration rates, suggesting the highest potential for influencing the RH. Finally, our study indicates that increasing indoor light levels to 300 μmol m^{-2} s^{-1} would, in most taxa, have a significant impact on the potential for houseplants to assimilate CO_2 and increase RH in indoor environments.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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