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Can houseplants improve indoor air quality by removing CO₂ and increasing relative humidity?

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Abbreviations:

RH:	Relative humidity (%)
DLI:	Daily light integral ($\text{mol m}^{-2} \text{d}^{-1}$)
SMC:	Substrate moisture content ($\text{m}^3 \text{m}^{-3}$)
LCP:	Light compensation point ($\mu\text{mol m}^{-2}\text{s}^{-1}$)
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})

1 **Abstract**

2 High indoor CO₂ concentrations and low relative humidity (RH) create an array of well-documented human health
3 issues. Therefore, assessing houseplants' potential as a low-cost approach to CO₂ removal and increasing RH is
4 important.

5 We investigated how environmental factors such as 'dry' (< 0.20 m³ m⁻³) or 'wet' (> 0.30 m³ m⁻³) growing substrates,
6 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
7 plants' net CO₂ assimilation ('A') and water-vapour loss. Seven common houseplant taxa – representing a variety of
8 leaf types, metabolisms and sizes – were studied for their ability to assimilate CO₂ across a range of indoor light
9 levels. Additionally, to assess the plants' potential contribution to RH increase, the plants' evapo-transpiration (ET)
10 was measured.

11 At typical 'low' indoor light levels 'A' rates were generally low (< 3.9 mg hr⁻¹). Differences between 'dry' and 'wet'
12 plants at typical indoor light levels were negligible in terms of room-level impact. Light compensation points (i.e.
13 light levels at which plants have positive 'A') were in the typical indoor light range (1-50 μmol m⁻² s⁻¹) only for two
14 studied *Spathiphyllum wallisii* cultivars and *Hedera helix*; these plants would thus provide the best CO₂ removal
15 indoors. Additionally, increasing indoor light levels to 300 μmol m⁻² s⁻¹ would, in most species, significantly increase
16 their potential to assimilate CO₂. Species which assimilated the most CO₂ also contributed most to increasing RH.

17

18 **Key words:** *Dracaena*; drought; *Hedera*; indoor light; indoor air quality; *Spathiphyllum*

19

20 **Introduction**

21 Indoor CO₂ concentrations are primarily dependent on the occupancy level and outdoor air supply rate (Zhang *et al.*,
22 2017). Humans produce and exhale CO₂; therefore, a greater occupancy coupled with lower ventilation rates –
23 intended to reduce energy consumption – gives rise to higher and often harmful CO₂ concentrations indoors (Satish
24 *et al.*, 2012). Additionally, even when ventilation by ambient air is employed, the problems may be exacerbated in
25 the future: ambient CO₂ concentrations increased by 40% over the last century, to 400 ppm – with a rise to 670 ppm
26 expected by 2100 (Hersoug *et al.*, 2012).

27 The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends a maximum
28 indoor CO₂ concentration of 1000 ppm (Torpy *et al.*, 2017). Concentrations indoors (e.g. in fully occupied offices or
29 meeting rooms) often reach 2000 to 2500 ppm but can rise as high as 5000 ppm (Zhang *et al.*, 2017). Although
30 discrepancies in the maximum safe exposure concentration are commonplace in literature, prior research suggests
31 typical indoor CO₂ concentrations will continue to present unwanted health issues (Zhang *et al.*, 2017). These include
32 mucus membrane symptoms (i.e. sore/dry throat, dry eyes and sneezing) and respiratory problems (i.e. tight chest,
33 wheezing/coughing and shortness of breath) (Seppanen *et al.*, 1999; Erdmann and Apte, 2004). Elevated CO₂ can
34 also reduce the cognitive performance of students in schools, while long-term, regular exposure has been linked to
35 increased absenteeism, weight gain and obesity (Hersoug *et al.*, 2012; Satish *et al.*, 2012; Gaihre *et al.*, 2014;
36 Nieuwenhuis *et al.*, 2014; Vehvilainen *et al.*, 2016; Zhang *et al.*, 2017).

37 An additional challenge in indoor environments is low relative humidity (RH). An RH below 30% has been shown to
38 cause eye irritation and skin dryness, with an RH below 10% causing dryness of the nasal mucus membrane. Low RH
39 can also increase the likelihood of influenza transmission, enhance indoor ozone concentration and produce static
40 electricity (Arundel *et al.*, 1986; Berglund, 1998; Sunwoo *et al.*, 2006; Lowen *et al.*, 2007; Abusharha and Pearce,
41 2013; Zhang and Yoshino, 2010). However, high RH (> 60%) too can cause issues by encouraging fungal/mould
42 growth and contributing to the deterioration of building materials (Berglund, 1998; Bin, 2002; Zhang and Yoshino,
43 2010; Frankel *et al.*, 2012). The majority of adverse health effects concerning RH can be avoided by maintaining
44 indoor levels between 40 and 60% (Arundel *et al.*, 1986).

45 Various techniques are used in the built environment to control and regulate CO₂ levels. They include highly
46 engineered approaches to ventilation (Hesaraki *et al.*, 2015; Mateus and da Graca, 2017) as well as low-tech
47 approaches which can include the use of plants (Raji *et al.*, 2015; Charoenkit and Yiemwattana, 2016). A number of
48 studies investigate a houseplants' potential to sequester CO₂ from indoor environments (Oh *et al.*, 2011; Pennisi and
49 van Iersel, 2012; Torpy *et al.*, 2014). Studies vary in scale and focus – from those focusing on individual plants in
50 experimental chambers, to room scale studies *in situ*.

51 A range of studies investigated houseplants' ability to sequester CO₂ in home, school, and office environments.
52 Various combinations of houseplants were found to generally reduce room CO₂ concentrations and increase RH;
53 however, studies rarely specify exact plant numbers and plant types. Plant species commonly used include *Dracaena*

54 *deremensis*, *Dracaena marginata*, *Ficus benjamina*, *Hedera helix*, and *Spathiphyllum clevelandii* (Raza et al., 1991;
55 Lohr and PearsonMims, 1996; Jeong et al., 2008; Lim et al., 2009; Oh et al., 2011; Pegas et al., 2012).

56 Light levels and substrate moisture are the key factors influencing gas exchange between the plant and the
57 environment, with 'low' light and 'dry' substrate both reducing houseplants' ability to sequester CO₂ and contribute
58 to RH increases indoors *via* transpiration (Lawlor and Cornic, 2002; Flexas et al., 2006; Torpy et al., 2017). In indoor
59 environments light levels are typically at least 100-fold lower compared to outdoors (on a clear summer day for
60 example) and are maintained in the range of approximately 1 – 50 μmol m⁻² s⁻¹ (Thimijan and Heins, 1983; Boyce and
61 Raynham, 2009; Lai *et al.*, 2009; Hawkins, 2011). Research suggests however, that having higher indoor light levels
62 (approximately 30 – 50 μmol m⁻² s⁻¹) would greatly increase occupant comfort (Lai *et al.*, 2009; Huang *et al.*, 2012).
63 As previously proposed, indoor light is the most limiting factor for CO₂ assimilation (Pennisi and van Iersel, 2012).

64 The positive contribution of plants to the reduction of CO₂ levels and RH increases indoors are based on the premise
65 that plants function optimally and are sequestering CO₂/releasing water vapour at their maximum capacity.
66 However, the main challenges for maintaining plant function in the indoor environment are 'low' indoor light levels
67 and issues arising from plants' (miss) management, most frequently plants' being under or over watered without the
68 correct nutrients (RHS, 2017). A few studies addressed these questions in part by investigating a wide range of light
69 levels and their effect on CO₂ assimilation (Pennisi and van Iersel, 2012; Torpy *et al.*, 2014). However, no study to our
70 knowledge investigated the effect of differing substrate moisture content (SMC) – namely investigating the effect of
71 'wet' (> 0.30 m³ m⁻³) and 'dry' (< 0.20 m³ m⁻³) SMC conditions. Additionally, previous studies have not specifically
72 focused on plants' cultivar-level differences; this may be of interest as for many houseplant species there are a range
73 of cultivars available, which may potentially offer augmented service compared to straight species if they are larger
74 in size or more physiologically active.

75 Pennisi and van Iersel (2012) investigated the CO₂ assimilation of 17 houseplant species in both a simulated
76 controlled environment utilising light levels of 10, 20 and 30 μmol m⁻²s⁻¹ and a public office building in Atlanta (USA).
77 In the public office, the amount of CO₂ assimilated by plants varied depending on plant size. In the controlled
78 environment, most species exhibited positive carbon assimilation over a 10-week period. The study found that in
79 both environments larger, woody plants (such as *Ficus benjamina*) assimilated more CO₂ than herbaceous species.

80 Torpy *et al.* (2014) investigated the CO₂ assimilation of eight common indoor plant species by producing light
81 response curves and light compensation points (LCPs) using an infra-red gas analyser. The results indicated that at
82 least some CO₂ sequestration could be expected from the studied species under current indoor lighting systems and
83 plants could be effectively utilised in the built environment to sequester CO₂ given a moderate increase in the
84 targeted lighting levels.

85 Our research aims to improve the understanding of which taxa (i.e. plant species and cultivars) as well as which light
86 and substrate moisture conditions are best placed to regulate indoor CO₂ and RH. Specifically, the aims of the study
87 were to determine:

1. The impact of drying substrate on CO₂ removal capacity by different taxa
2. The impact of light levels on net CO₂ 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.

2 Material and Methods

2.1 Plant material

Five common houseplant species, including two cultivars, were selected for the study to represent a range of leaf types (succulent and herbaceous), metabolisms and plant sizes (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 10cm - 60cm 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) at ambient temperatures and 'low' light levels 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).

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)
<i>Dracaena fragrans</i> 'Lemon Lime'	<i>Asparagaceae</i>	C3	1742 ± 91	51 ± 1
<i>Dracaena fragrans</i> 'Golden Coast'	<i>Asparagaceae</i>	C3	1438 ± 10	60 ± 1
<i>Guzmania</i> 'Indian Night'	<i>Bromeliaceae</i>	C3/CAM	1230 ± 6	32 ± 1
<i>Hedera helix</i>	<i>Araliaceae</i>	C3	1509 ± 243	9 ± 0
<i>Spathiphyllum wallisii</i> 'Bellini'	<i>Araceae</i>	C3	1766 ± 189	35 ± 1
<i>Spathiphyllum wallisii</i> 'Verdi'	<i>Araceae</i>	C3	5451 ± 1104	36 ± 1
<i>Zamioculcas zamiifolia</i>	<i>Araceae</i>	CAM	1388 ± 88	57 ± 1

2.2 Net leaf-level CO₂ 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 CO₂ 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) 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 m²). 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

114 source (50 W, 12 V). Each light increment was administered for seven minutes and the net CO₂ assimilation rate
115 recorded at the end of the seven-minute period.

116 Substrate moisture content (SMC) based on volume of water per volume of substrate was measured daily for each
117 plant, in two locations per container using a SM300 capacitance-type probe connected to a HH2 Moisture Meter
118 (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of $\pm 2.5\%$). At the start of the
119 experiment, substrate moisture was at the container capacity (SMC > 30%, 0.3 m³ m⁻³) and plants were thus
120 considered optimally watered (Vaz Monteiro *et al.*, 2016). Measurements were also made on ‘dry’ plants (SMC <
121 20%, 0.2 m³ m⁻³). Measurements were made over approximately one month.

122 **2.2.1 Calculation of the respiration of the potted-plant microcosm**

123 To ensure that CO₂ removal by the aboveground parts of the plant (i.e. leaves and stem) was not cancelled out by
124 respiration of the potted-plant microcosm (PPM) (i.e. substrate and non-photosynthetic plant parts) the PPM was
125 investigated for CO₂ contributions at both ‘high’ and ‘low’ light and under ‘wet’ and ‘dry’ SMC conditions (n = 3). The
126 PPM respiration values were then subtracted from all the leaf CO₂ assimilation values made, to obtain the overall
127 contribution of the plant and substrate.

128 Measurements of the PPM respiration were made utilising a 150 L (45 x 45 x 75 cm, 0.15 m³) Perspex chamber (The
129 plastic people, Leeds, West Yorkshire, UK) sealed with Swagelok’s (Swagelok, Bristol, South Gloucestershire, UK).
130 Enclosed inside the Perspex chamber was a HOBO MX1102 CO₂ logger (Onset Computer Corporation, Bourne, MA,
131 U.S.A), a 12 V DC brushless fan (RS Components, Corby, Northants, UK), and a calibrated (20 – 90 % RH, 0 – 40 °C)
132 Tinytag RH/temperature logger (Gemini data loggers, Chichester, West Sussex, UK). The external RH/temperature
133 surrounding the chamber was also monitored with another, identical Tinytag logger. Inside the chamber ‘low’ light
134 levels were achieved as described in Section 2.2; ‘high’ levels were generated by two LED lights (V-TAC Europe Ltd,
135 Sofia, Bulgaria) and measured with a calibrated light sensor (Skye instruments, Llandrindod Wells, Wales, UK). Bare
136 substrate was prepared for the experiment as explained in Section 2.2. Experiments were undertaken for 2 hr, with
137 the chamber analysed for leakage prior, during and after experimentation; leakage was found to be < 2% of the
138 starting concentration over a 2-hr test period. Measurements were made over approximately one week.

139 Data obtained in Section 2.2 was normalised by leaf area by multiplying CO₂ assimilation (mg m⁻² hr⁻¹) with leaf area
140 (m²), providing CO₂ assimilation in mg hr⁻¹ for each taxon. Data were also corrected for PPM respiration and leakage
141 by calculation of an average conversion value (mg hr⁻¹) for both ‘wet’ and ‘dry’ SMC conditions.

142 **2.3 Generating light response curves**

143 To generate light response curves, measurements of the net photosynthetic rate ($\mu\text{mol m}^{-2}\text{s}^{-1}$) were made as
144 explained in Section 2.2 on four plants per taxon. Environmental conditions within the leaf cuvette were:
145 temperature controlled at 25 °C, ambient CO₂ concentration (~400-450 ppm) and an ambient RH of 35-45%. Plants
146 were prepared for the experiment as explained in Section 2.2, achieving a SMC > 0.30 m³ m⁻³ and were considered

147 optimally watered on the commencement of each experiment (Vaz Monteiro *et al.*, 2016). SMC was maintained at
148 this level for the duration of the experiment.

149 To generate the light response curve the light was supplemented in the following set increments: 0, 50, 300, 1200
150 $\mu\text{mol m}^{-2} \text{s}^{-1}$ as described in Section 2.2. An increment of 0 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was chosen to investigate each species CO_2
151 assimilation in the dark; 50 $\mu\text{mol m}^{-2} \text{s}^{-1}$ the highest indoor light level; 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was chosen to represent the
152 highest feasible light level which could be engineered (with supplementary artificial lighting) in an indoor
153 environment; 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (a sunny day in a UK climate) was chosen to present information on a plant's
154 maximal capacity for net CO_2 assimilation. Measurements were made over approximately one week.

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



159

160 **Figure 1:** Images of the experimental setup for leaf CO_2 assimilation measurements, equipment pictured includes
161 infra-red gas analyser, leaf cuvette and external halogen source.

162 **2.4 Plants' water use/evapo-transpiration (ET) experiments**

163 Water use/ET of the plant taxa were inferred by consecutive plant/pot weight measurements using a precision
164 balance (CBK 32, Adam Equipment, Milton Keynes, Buckinghamshire, UK) under indoor office conditions (RH > 35%).
165 Plants were prepared for the experiment as explained in Section 2.2, starting the experiment with SMC at full water-
166 holding capacity and were not watered for the duration of the experiment. Measurements were made at 0 h and
167 then every 24 hr over a three-week period on a whole 'plant – substrate system' (i.e. potted plant, with uncovered
168 substrate) enabling the calculation of the water loss at each time-point. We were interested in total potential RH
169 contribution of the plant along with substrate, mimicking a real-life scenario of an indoor plant. Each plant was
170 removed from the experiment when its SMC dropped < 20% ($0.2 \text{ m}^3 \text{ m}^{-3}$). Destructive measurements of LA were

171 made using a LA meter (Delta-T Devices, Cambridge, Cambridgeshire, UK) on two plants per taxon, at the end of the
172 experiment. While we appreciate that measuring the leaf area at the end of the experiment may lead to under/over-
173 estimating assimilation measured earlier in the experiment, we were limited by the number of experimental plants
174 we could destructively harvest. Given that this approach was applied to all taxa, that the leaf areas were assessed
175 within two months of the assimilation experiments, and that plants did not increase in size significantly over this
176 period (as evidenced by height measurements which we made at the start and the end of the experiment), we
177 believe that the risk of the error is small and evenly spread. SMC was measured daily as explained in Section 2.2.
178 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
179 plant in a 24-hr period by the mean leaf area.

180 **2.5 Statistical analysis**

181 Experimental data (gas exchange parameters and water loss/ET) were analysed using GENSTAT (16th Edition, VSN
182 International, Hemel Hempstead, Hertfordshire, UK). An analysis of variance (ANOVA) was performed to compare
183 means for each measured parameter between different taxa and/or over time. Values were presented as means
184 with associated Tukey's 95% confidence intervals for multiple comparisons. Data on plants' water loss were log-
185 transformed and Tukey's 95% confidence intervals were used to compare between taxa in the text (Section 3.3).

186 **3 Results**

187 **3.1 Net leaf-level CO_2 assimilation at 'low' and 'high' indoor light levels under 'dry' and 'wet' conditions**

188 At 'low' indoor light 'dry' *Spathiphyllum wallisii* 'Verdi' was statistically significantly respiring the most (-87.6 mg hr^{-1} ,
189 $p < 0.001$), and was therefore the only taxon to measure significant differences between 'dry' and 'wet' substrate. In
190 'dry' substrate statistically significant differences in CO_2 assimilation were measured between the cultivars of
191 *Spathiphyllum wallisii* 'Bellini' and 'Verdi' (-19.6 and -60.7 mg h^{-1} , respectively; $p < 0.001$). In 'wet' substrate, there
192 were no significant differences in CO_2 between any studied taxa (Table 2).

193
194 At 'high' indoor light only *Spathiphyllum wallisii* 'Verdi' measured statistically significant differences between 'dry'
195 and 'wet' substrate (-60.7 and 60.0 mg hr^{-1} , respectively; $p < 0.001$; Table 2). No statistically significant differences in
196 CO_2 assimilation were measured between cultivars under the same SMC conditions; significant differences were
197 measured with *Spathiphyllum wallisii* cvs 'Bellini' and 'Verdi' between 'dry' (-19.6 and -60.7 mg h^{-1} , respectively) and
198 'wet' (11.7 and 60.0 mg h^{-1} , respectively) SMC conditions ($p < 0.001$, Table 2).

200

201 **Table 2:** Net leaf-level CO₂ assimilation of each species at 'low' and 'high' indoor light (< 10 and 50 μmol m⁻² s⁻¹) in
 202 'wet' (> 0.30 m³ m⁻³) and 'dry' (< 0.20 m³ m⁻³) conditions. Data are a mean of five plants of each species, three young,
 203 fully expanded leaves per plant (n=15). Data are adjusted to account for PPM respiration and chamber leakage and is
 204 normalised by leaf area (Table 1). Different letters next to means correspond to statistically significant differences
 205 between means based on Tukey's 95% confidence intervals. (-) values signify respiration (i.e. the release of CO₂).

'Low' Light (< 10 μmol m ⁻² s ⁻¹)	Net CO ₂ assimilation (mg hr ⁻¹)	
	Taxa	'Wet' (> 0.30 m ³ m ⁻³)
<i>Dracaena fragrans</i> 'Lemon Lime'	-17.4 ^b	-35.7 ^b
<i>Dracaena fragrans</i> 'Golden Coast'	-28.4 ^b	-25.3 ^b
<i>Guzmania</i> 'Indian Night'	-14.3 ^b	-23.8 ^b
<i>Hedera helix</i>	-9.5 ^b	-27.3 ^b
<i>Spathiphyllum wallisii</i> 'Bellini'	-14.8 ^b	-22.7 ^b
<i>Spathiphyllum wallisii</i> 'Verdi'	3.9 ^b	-87.6 ^a
<i>Zamioculcas zamiifolia</i>	-17.5 ^b	-23.9 ^b
'High' Light (50 μmol m ⁻² s ⁻¹)	Net CO ₂ assimilation (mg hr ⁻¹)	
Taxa	'Wet' (> 0.30 m ³ m ⁻³)	'Dry' (< 0.20 m ³ m ⁻³)
<i>Dracaena fragrans</i> 'Lemon Lime'	-5.5 ^{abc}	-41.97 ^{ab}
<i>Dracaena fragrans</i> 'Golden Coast'	-21.8 ^{ab}	-24.0 ^{ab}
<i>Guzmania</i> 'Indian Night'	-11.5 ^{ab}	-19.6 ^{ab}
<i>Hedera helix</i>	-6.6 ^{abc}	9.4 ^{bc}
<i>Spathiphyllum wallisii</i> 'Bellini'	11.7 ^{bc}	-19.6 ^{ab}
<i>Spathiphyllum wallisii</i> 'Verdi'	60.0 ^c	-60.7 ^a
<i>Zamioculcas zamiifolia</i>	-12.2 ^{ab}	-20.9 ^{ab}

206

207

208 **3.2 Generating light response curves and light compensation points**

209 Light compensation points (LCPs), which represent the minimum light level required for a positive net CO₂
 210 assimilation to occur, were calculated for each species (Table 3). Of the studied species, *Spathiphyllum wallisii* 'Verdi'
 211 and *Hedera helix* had the lowest LCPs of 20 and 31 μmol m⁻² s⁻¹ respectively. The highest LCP was recorded for
 212 *Dracaena fragrans* 'Golden Coast' (96 μmol m⁻² s⁻¹), with both *Dracaena fragrans* 'Lemon Lime' and *Zamioculcas*
 213 *zamiifolia* also having LCP values outside of the light level typically experienced in indoor environments (93 and 65
 214 μmol m⁻² s⁻¹ respectively, Table 3).

215

216

217 **Table 3:** Light compensation points (LCPs) for each of the studied species.

Taxa	LCP ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
<i>Dracaena fragrans</i> 'Lemon Lime'	92.9
<i>Dracaena fragrans</i> 'Golden Coast'	95.6
<i>Guzmania</i> 'Indian Night'	N. A
<i>Hedera helix</i>	30.9
<i>Spathiphyllum wallisii</i> 'Bellini'	31.9
<i>Spathiphyllum wallisii</i> 'Verdi'	20.1
<i>Zamioculcas zamiifolia</i>	64.7

218

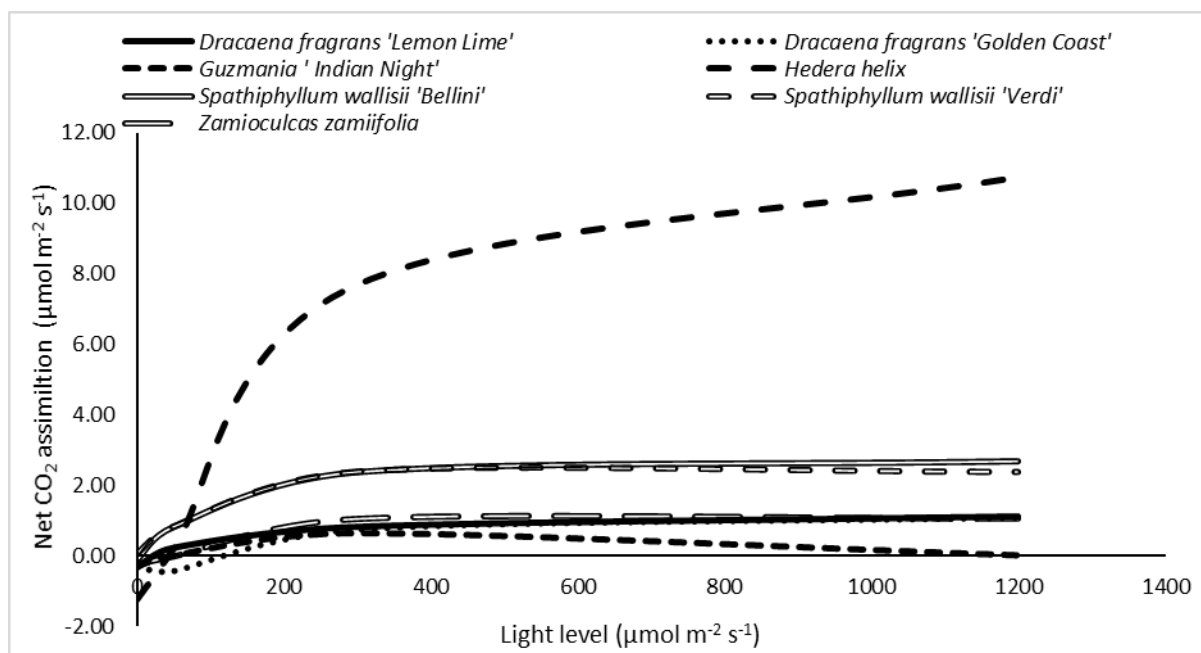
219 At $0 \mu\text{mol m}^{-2} \text{s}^{-1}$, *Hedera helix* was statistically significantly respiring the most ($-1.2 \mu\text{mol m}^{-2} \text{s}^{-1}$, $p < 0.001$; Figure 2),
 220 no significant differences were measured in net assimilation between other studied taxa.

221 At $300 \mu\text{mol m}^{-2} \text{s}^{-1}$, all taxa were assimilating CO_2 . Net assimilation was highest in *Hedera helix* ($7.7 \mu\text{mol m}^{-2} \text{s}^{-1}$) and
 222 was statistically significantly different to all other taxa ($p < 0.001$). *Spathiphyllum wallisii* 'Bellini' and *S. wallisii* 'Verdi'
 223 (2.4 and $2.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ respectively) measured a net assimilation that was statistically significantly higher than
 224 three other studied taxa (*Dracaena fragrans* 'Lemon Lime', *Dracaena fragrans* 'Golden Coast' and *Guzmania* 'Indian
 225 Night', $p < 0.001$; Figure 2). At this highest indoor photosynthetic photon flux density, there were no cultivar level
 226 differences within the same species in net assimilation.

227

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

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Figure 2: Net CO₂ assimilation across three light levels (0, 300, 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$); 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.

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3.3 Plants' water use/evapo-transpiration experiments

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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 hr was statistically significantly different between *Spathiphyllum wallisii* cultivars ($p < 0.001$; Figure 3A).

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In terms of ET per leaf area per day, when well-watered the ET was statistically significantly higher for *Hedera helix* (0.047 g cm^{-2}) in comparison to other taxa ($p < 0.001$). ET 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; $p < 0.001$; Figure 3B).

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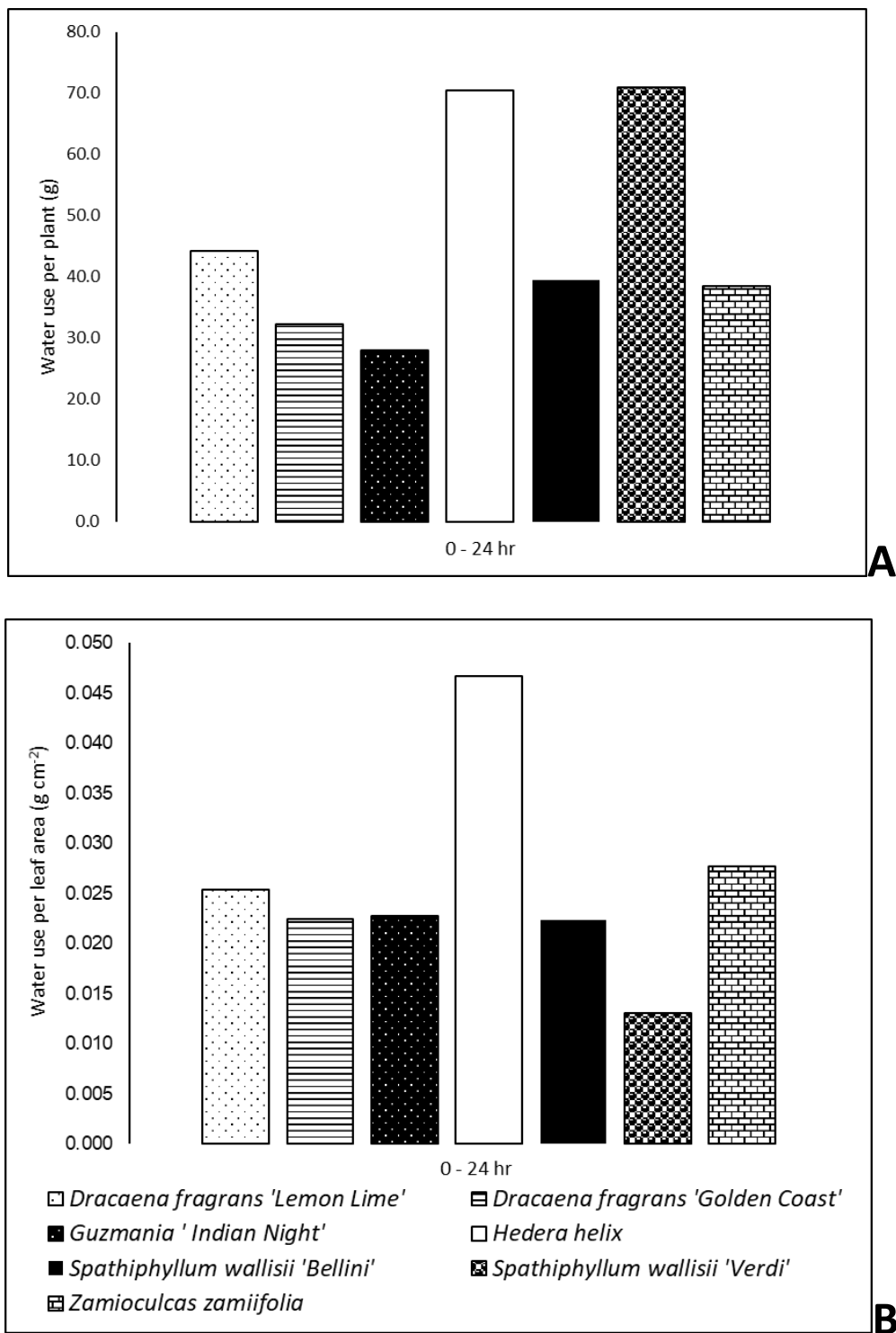
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At the time when SMC decreased to 20%, ET reduction ranged between 7% (*Spathiphyllum wallisii* 'Verdi') and 63% (*Guzmania* 'Indian Night') (data not shown). The time taken for the SMC to decrease to $< 20\%$ ranged between 10 days (*Dracaena fragrans*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

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Figure 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 were generated in the analysis of the transformed data are used for species comparison in text.

262 4 Discussion

263 The current work presents the first insight into leaf-level CO₂ assimilation - from plants in both 'dry' and 'wet'
264 substrate – and potential RH increases for a range of common houseplant taxa (i.e. species and cultivars), differing in
265 structure and physiology.

266 In this study we demonstrate that little potential is offered by the studied houseplants alone to reduce CO₂
267 concentrations in 'low' light indoor environments – with only three taxa's light compensation points falling within
268 the typical indoor light level range (0 – 50 μmol m⁻² s⁻¹; Table 3). However, our findings demonstrate that although
269 respiration was generally occurring in houseplants grown in 'dry' substrate, the net CO₂ exchange recorded was
270 extremely low and thus likely to have little or no negative impact on the CO₂ levels at a room scale. Our results
271 suggest that increasing light levels to a technically feasible 300 μmol m⁻² s⁻¹ (e.g. through use of supplementary
272 lighting) would provide a significant increase in CO₂ assimilation in most of the studied taxa. The study also indicates
273 that the best performing taxa for CO₂ assimilation will also contribute the most to raising RH indoors.

274 From the results of this study we estimated the mass (in grams) of CO₂ removed per hour, per plant and per m² of
275 each taxon. In home and office environments, each person contributes 30g (CO₂)/hour and 36g (CO₂)/hour,
276 respectively (Persily and de Jonge, 2017) and these different values are consequences of the level of individual's
277 activity in various environments. Using both these values, we calculated the number of plants required to remove
278 10% of a single person's CO₂ contribution at the 'very high' (300 μmol m⁻² s⁻¹) indoor light level (Supplementary Table
279 1). The plant numbers range from 15 (for more active plants like *Hedera* and *Spathiphyllum*) to >100 for
280 physiologically less active plants. Estimates of the number of plants required to remove the CO₂ generated by human
281 contributions were also made by Pennisi and van Iersel (2012) and Torpy *et al.* (2014). However, widely different
282 estimates of the CO₂ generated per person were used by each study – making direct comparisons difficult.

283 In typical indoor environments with 'low' light levels, only one taxon, in 'wet' substrate conditions was assimilating
284 CO₂ (*Spathiphyllum wallisii* 'Verdi') and would contribute to CO₂ concentration reduction (3.9 mg hr⁻¹, respectively;
285 Table 2). Additionally, only three taxa were found to possess light compensation points that fall within the range of
286 typical indoor light levels (i.e. *Hedera helix* and *Spathiphyllum wallisii* 'Verdi' and 'Bellini'). Both *Hedera helix* and
287 *Spathiphyllum wallisii* would require an unrealistic number of plants to see any significant CO₂ concentration
288 reduction (data not shown); at typical 'low' indoor light levels, the study indicates that a plants' potential benefits
289 psychologically or in productivity terms (Thomsen *et al.*, 2011; Raanaas *et al.*, 2011; Nieuwenhuis *et al.*, 2014) would
290 be more important than their contribution to indoor CO₂ removal. Furthermore, as suggested in Torpy *et al.* (2014)
291 plants should not be expected to completely replace ventilation systems, but to act as a supplement in reducing the
292 energy load required.

293 In typical 'low' light indoor environments, when grown in 'dry' substrate, all studied taxa were respiring. The results
294 also indicated that in the range of typically observed indoor light levels, six of the studied species (*Dracaena fragrans*
295 cvs 'Lemon Lime' and 'Golden Coast', *Guzmania* 'Indian Night', *Hedera helix*, *Spathiphyllum wallisii* 'Bellini' and
296 *Zamioculcas zamiifolia*) were respiring in both 'dry' and 'wet' SMC conditions (Table 2). The (miss) management and

297 under watering of houseplants is anecdotally a common problem; therefore, determining if a 'dry' houseplant is
298 releasing significant amounts of CO₂ into an indoor environment and detrimentally impacting health is important;
299 our results however, suggest this is not the case. In 'dry' SMC conditions, in typical office light, *Spathiphyllum wallisii*
300 'Verdi' was releasing the most CO₂ into the indoor environment out of all studied taxa at 0.0876 g hr⁻¹. In
301 comparison, a single person, in an office environment would release 36 g/hour into the indoor environment (Persily
302 and de Jonge, 2017). This confirms that in typical office light conditions – even for plants growing in drying substrate
303 – the contribution of plants to room-level CO₂ is negligible.

304 At a 'high' indoor light level (50 μmol m⁻² s⁻¹), a greater net CO₂ assimilation was generally measured for all taxa, but
305 no statistically significant differences were found between cultivars of the same species in 'dry' or 'wet' conditions.
306 Although measurements were only made under 'wet' SMC conditions, this trend for the lack of cultivar differences
307 continued at higher light levels of 300 and 1200 μmol m⁻² s⁻¹ suggesting that cultivar level differences were not
308 pronounced in this study.

309 Our study suggests that for most studied taxa, light saturation occurs at around 300 μmol m⁻² s⁻¹ and further
310 increases beyond this show little difference in assimilation terms (Figure 2). As discussed in Torpy *et al.* (2014)
311 targeted indoor lighting could be used to maximise a houseplants CO₂ assimilation potential. Extensive research has
312 been undertaken into various light systems for plant cultivation and development on indoor living walls but not
313 specifically with potted houseplants or concerning CO₂ assimilation (Yeh and Chung, 2009; Egea *et al.*, 2014). Our
314 findings support the notion that increased light levels maximise plant gas exchange and we suggest future research
315 should investigate the suitability of testing targeted lighting installations in indoor environments. Light compensation
316 points calculated in our study are generally higher, but comparable with other indoor species previously tested
317 (Burton *et al.*, 2007; Pennisi and van Iersel, 2012; Torpy *et al.*, 2014; Torpy *et al.*, 2017; Tan *et al.*, 2017).

318 Earlier attempts at estimating the CO₂ removal of houseplants (Pennisi and van Iersel, 2012) did not take into
319 account ambient CO₂ concentrations or consider the effects of substrate moisture on CO₂ assimilation. A more
320 robust study by Torpy *et al.* (2014) investigated several factors which could influence assimilation including different
321 acclimatisation treatments, the respiration of the 'potted-plant microcosm', but again did not consider impact of
322 substrate moisture conditions. Other studies did not specify the exact number or type of houseplant (Lim *et al.*,
323 2009; Pegas *et al.*, 2012) which contributed to any CO₂ concentration reduction or, only considered a single light
324 level (Oh *et al.*, 2011).

325 The results from the ET experiment indicate that the best performing species in CO₂ assimilation terms (*Hedera helix*
326 and *Spathiphyllum wallisii* 'Verdi') both have the highest ET rates per plant. However, the comparative water use per
327 area results show *Spathiphyllum wallisii* 'Verdi' having the lowest ET *per leaf area*; this species is therefore,
328 inherently more water use efficient and only uses more water *per plant* due to its large size. We found a difference
329 between the *Spathiphyllum wallisii* cultivar pair in terms of water use per plant and per area – with no difference per
330 plant or per area measured for the *Dracaena fragrans* pair. This confirms that our hypothesis that inherent
331 physiological differences can be measured in water use terms down to a cultivar level. The results also suggest that

332 certain species (i.e. *Spathiphyllum wallisii* 'Verdi') do not restrict their water loss under water stress conditions (SMC
333 < 20%). *Spathiphyllum wallisii* 'Verdi' would therefore, in a drying substrate, continue to contribute the most to RH
334 increases. We suggest that future studies should evaluate the CO₂ assimilation ability of other more physiologically
335 active, vigorous species (i.e. *Osmunda japonica*, *Selaginella tamariscina* and *Hemigraphis alternata*), which also
336 performed well in pollutant sequestration experiments (Yang *et al.*, 2009; Kim *et al.*, 2010) under 'high' indoor light
337 levels (300 μmol m⁻² s⁻¹).

338 From the results of the ET experiment we estimated the contribution of studied taxa to raising RH indoors.
339 Calculations of the amount of water vapour in the air were made through the equation: RH (%) = 100 * actual vapour
340 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
341 *et al.*, 2005). A RH of 40 – 60% is considered optimal in terms of human health (Arundel *et al.*, 1986), we therefore
342 calculated the number of plants – per taxon - required to raise RH from 40 to 60 % in a static 100 m³ office
343 (Supplementary Table 2). Calculations assume that 100% of the water vapour 'lost' by taxa (Figure 3A) was released
344 into the surrounding environment. The results do not take into account the impact of ventilation, occupancy or the
345 feedback effect of taxa (i.e. as RH increases plants release less water vapour into the indoor environment). These
346 calculations are intended to act as a guide on how the studied taxa could influence RH indoors. Our results indicate
347 that five *Spathiphyllum wallisii* 'Verdi' or *Hedera helix* plants growing in an unmulched (i.e. uncovered) growing
348 medium - over a 24-hr hour period - could raise the RH from 40 to 60% (Supplementary Table 2).

349 **5 Conclusions**

350 The results indicate that net CO₂ assimilation of all studied plants was generally 'low', with *Spathiphyllum* cultivars
351 and *Hedera helix* removing most CO₂.

352 While CO₂ assimilation of plants in 'wet' substrate was higher than in 'dry' conditions, in practical terms however (i.e.
353 when considering the plant's potential to influence indoor CO₂ levels), net CO₂ assimilation differences between 'dry'
354 and 'wet' plants at 'high' and 'low' indoor light levels were negligible for the taxa studied. Light compensation points
355 were in the typical indoor light range for both *Spathiphyllum wallisii* 'Verdi' and *Hedera helix*, suggesting that these
356 plants would be best suited to provide most CO₂ removal in a typical indoor setting. Additionally, both these taxa,
357 per plant, had the highest transpiration rates, suggesting the highest potential for influencing the RH. Finally, our
358 study indicates that increasing indoor light levels to 300 μmol m⁻² s⁻¹ would, in most taxa, have a significant impact
359 on the potential for houseplants to assimilate CO₂ and increase RH in indoor environments.

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473 **Supplementary Information**

474 **Supplementary table 1:** Net CO₂ assimilation (mg hr⁻¹) of each species and number of taxa required to remove 10 %
 475 of the CO₂ generated per person at 'very high' indoor light (300 μmol m⁻² s⁻¹) in 'wet' (> 0.30 m³ m⁻³) conditions. Data
 476 is taken from Figure 2 and adjusted to account for PPM respiration and chamber leakage and is normalised by leaf
 477 area (Table 1). Plant numbers for each taxon were calculated by dividing the 30 g (CO₂)/hour or 36 g (CO₂)/hour
 478 exhaled per person in home and office environments respectively (Persily and de Jonge, 2017) by the net CO₂
 479 assimilation of each taxon (mg hr⁻¹).

'Very high' Light (300 μmol m ⁻² s ⁻¹) Taxa	mg hr ⁻¹ 'Wet' (> 0.30 m ³ m ⁻³)	Number of plants	
		Home	Office
<i>Dracaena fragrans</i> 'Lemon Lime'	10.9	275	330
<i>Dracaena fragrans</i> 'Golden Coast'	5.7	526	632
<i>Guzmania</i> 'Indian Night'	0.9	3333	4000
<i>Hedera helix</i>	172.3	17	21
<i>Spathiphyllum wallisii</i> 'Bellini'	55.0	55	65
<i>Spathiphyllum wallisii</i> 'Verdi'	194.9	15	18
<i>Zamioculcas zamiifolia</i>	11.5	261	313

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481 **Supplementary table 2:** Number of plants required to raise the RH from 40 to 60% in a static 100 m³ office. Numbers
 482 of plants were generated from our data in Figure 3A at a temperature of 22 °C, where ventilation, occupancy and the
 483 feedback effect were not considered. Calculations of the amount of water vapour in the air were made through the
 484 equation: RH (%) = 100 * actual vapour density (g m⁻³) / saturation vapour density (g m⁻³) (using a saturation vapour
 485 density of 19.1 g m⁻³ at 22 °C) (Galindo *et al.*, 2005).

Species/cultivar	Number of Plants
<i>Dracaena fragrans</i> 'Lemon Lime'	9
<i>Dracaena fragrans</i> 'Golden Coast'	12
<i>Guzmania</i> 'Indian Night'	14
<i>Hedera helix</i>	5
<i>Spathiphyllum wallisii</i> 'Bellini'	10
<i>Spathiphyllum wallisii</i> 'Verdi'	5
<i>Zamioculcas zamiifolia</i>	10

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