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The impact of plants on the humidity of naturally-ventilated office indoor environments

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ABSTRACT

This study investigated the seasonal impact of indoor plants on the humidity and air temperature of three naturally-ventilated, unoccupied offices, with low air exchange rates. The introduction of 12 *Ficus* or 6 *Epipremnum* plants resulted in a small but significant increase in the office's (28 m^3) moisture content, measured every 5 min for 24-h periods for up to six test days during spring and winter, compared to the days without plants. Depending on the season, plants emitted between 35 g (in winter) and 58 g (in summer) of moisture via evapo-transpiration (ET), per plant, per day. In summer, however, due to higher room air exchange rates, we did not detect significant impact of plants despite higher plants' ET rates. Most of the moisture emitted from the plants in all seasons was removed through room air exchange and moisture sorption. Air exchange rate had a greater impact on indoor RH than plants.

Additional controlled-environment chamber studies showed there is a significant difference in the humidification capacity between five different indoor plant species. Leafy *Epipremnum* had the highest ET rate under all tested environmental conditions and would have the greatest humidification potential for indoor environments. Succulent *Sansevieria* had the lowest ET rate, not significantly higher than bare substrate; this species would present a good choice for environments where a low moisture contribution is required. ET rates were highest at low ambient humidity and high temperatures; thus, the greatest water vapour contribution by plants would be made to hot, dry indoor environments and lower in cool rooms with high humidity levels.

1. Introduction

The importance of the moisture content of indoor air due to its impact on the health, comfort and productivity of the building occupants is well established [1–3]. Within office environments, both low and high humidity levels are of concern. Low relative humidity (RH) is linked with drying of mucous membranes thus causing irritation of the eyes and upper airways [1], reduced performance in office tasks [2] and higher absenteeism [4]. The risk of infection for building occupants can increase at low humidity as the survival and airborne transmission of some bacteria and viruses increases [5,6]. The environmental conditions of the workplace can also impact workers' stress levels, which is a major cause of working days lost in the UK [7]. A study in the USA of 134 office workers, showed a 25% lower stress response, and better sleep quality when participants spent the majority of their time in 30–60% RH compared to drier environments [8]. Increasing the room humidity can help alleviate these problems.

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Ambient air temperature (T_a) and RH have been shown to have a significant impact on the perception of indoor air quality (IAQ) and thermal comfort of building occupants; typically, perceived IAQ decreases with increasing T_a and RH [9–12]. There is no single 'correct' value for thermal comfort as individual preferences vary, but the recommended values of T_a and RH within thermal comfort standards are important as they determine the energy consumption by a building's environmental systems [11]. Whilst there is no legal standard for humidity levels, maintaining the RH in the range of 40%–70% is generally recommended by professional bodies [13–15]. Excessively high humidity (above 70% for several days) is a serious concern due to the risk of condensation and mould growth, leading to a health risk for occupants and possible damage to the material condition of the building [14,16,17].

Maintaining the indoor RH within acceptable levels through natural ventilation relies on outdoor RH levels which can be low during wintertime, and mechanical systems are energy intensive and expensive. Thus there is a need for sustainable humidification systems (the term 'humidification' here refers to the addition of water vapour). Previous research conducted in controlled environmental chambers [18–21] had shown that through the process of evapotranspiration (ET; water loss via plants' stomata), indoor plants potentially offer a sustainable method for the humidification of dry indoor air. In one experiment the addition of plants (7% of chamber volume) was associated with an increase in RH of 15–60% [20] and in another study the RH levels in chambers of 0.21 m^3 volume, increased from 59% to 92%, and from 58% to 71% after the introduction of *Nephrolepis exaltata* and *Epipremnum aureum* plants, respectively [21].

The amount of water vapour emitted varied with species and is dependent on the T_a and RH of the air within the chambers which determine the vapour pressure deficit (VPD) of the atmosphere [18,22–24]. VPD is defined as the difference between the actual vapour pressure of the air (p) and the vapour pressure of the air when it is fully saturated (SVP) at the same temperature [14]. VPD affects stomatal opening in plants, which governs CO_2 uptake and transpiration [25]; stomata are apertures in the leaves' epidermis, which allow movement of gases in and out of the plants' intercellular space [26]. Higher T_a and lower RH increase the VPD which increases the ET rate [25]. This suggests that in hot, dry indoor environments plants could make a greater contribution to the air humidity levels, providing water content in the growing substrate is not limiting.

Plant species typically chosen for indoor use also come with inherently different levels of physiological activity (i.e. ET rates). In smaller scale, chamber studies, plant choice has been shown to have an impact on the extent of RH rise in that space [18,23]. Plants may also differ in their response to the environmental drivers of transpiration (T_a, RH, light levels) [27]. Although the range of environmental extremes is relatively small indoors, seasonal differences in environmental parameters are likely to exist. It is likely that the humidification potential of indoor plants will therefore vary with species and in different indoor environments, but this has not been addressed in existing studies. This paper aims to contribute to this knowledge gap and to broaden our understanding of how different plants (representing a range of inherent physiological activities) respond, and thus help inform optimal planting choices.

In real-world environments there are many additional variables which can influence the RH of the indoor air such as the occupants and their behaviour, the building design, the ventilation rate (described here as air changes per hour, ACH) and seasonal variation in outdoor weather conditions [28–30]. These need to be considered to accurately assess the humidification potential of indoor plants, but as they are difficult to measure and control they have often been overlooked in previous studies. Very few studies have investigated the impact of indoor plants on the humidity in real office environments and the findings have varied from no impact on RH, to 10% increase in RH over 24 h [31–35]. None of these studies have measured the water vapour contribution from the plant and its actual impact on indoor humidity whilst considering the ACH of the room or the outdoor climate and any seasonal variation.

Previous studies have shown that plants can add water vapour to the indoor [23,36–38] but it is likely that the humidification potential of indoor plants will vary with species and in different indoor environments, but this has not been addressed in existing studies. This paper aims to contribute to this knowledge gap and to inform optimal planting choices.

Given the importance of maintaining the indoor T_a and RH within recommended levels, the potential of plants to help with it, and the complexity of how different plant species respond to indoor environments, it is essential for building designers, managers and occupants that the impact of indoor plants on the humidity within real office environments is better understood.

The objectives of this study were therefore.

1. To determine how indoor plants affect the humidity and T_a within real office environments during the working day and to determine the extent, if any, of seasonal variations.
2. To investigate the impact of different indoor environmental conditions (T_a and RH) on the ET rate of a range of indoor plant species with different inherent levels of physiological activity.

2. Methods

Within this paper three complementary sets of experiments are presented (Table 1): Experiment set 1 and set 2 are conducted within real-world, unoccupied, offices to answer objective 1. Experiment set 3 provides supporting studies from controlled-environment chambers to answer objective 2. All experiments were conducted on the University of Reading (UoR) Whiteknights campus, UK.

2.1. The experimental test offices

The three naturally ventilated, cellular offices were situated within a pre-fabricated, well-insulated, modular building, constructed in 2015 on the University of Reading (UoR), UK Whiteknights campus.

The offices were selected as they had low ACHs (Table 1) measured by the concentration decay method [18]. They were heated by electric wall panel heaters controlled by a central Building Management System, enabled to maintain the T_a above 19 °C between 08:00–18:00 Monday to Friday, and above 12 °C outside of these hours; overnight, weekends and closure periods. These are described

Table 1
Summary of the office humidity experiments conducted, and the details of offices.

Season and year	Offices or Environmental chambers used (Total Floor Area, TFA, m^2) (Volume, V, m^3) Air changes per hour (ACH)*	Conditions tested
Experiment set 1		
Winter 2019 (December 2018–January 2019)	**Office 1** (TFA = 10.5) (V = 28.3) (ACH = 0.134 ± 0.004) **Office 2** (TFA = 11.3) (V = 30.4) (ACH = 0.134 ± 0.008)	With and without 12 *Ficus* plants in each office Out of hours heating regime
Spring 2019 (April 2019)	**Office 1** (ACH = 0.134 ± 0.011)>	With and without 12 *Ficus* plants Out of hours heating regime
Summer 2019 (August–September 2019)	**Office 1** (ACH = 0.132 ± 0.032)	With and without 12 *Ficus* plants No heating
Experiment set 2		
Winter 2021 (January–February 2021)	**Office 1** ACH = 0.124 ± 0.009) **Office 3** (TFA = 11.35) (V = 30.6) ACH = 0.069 ± 0.007)	With and without 6 *Epipremnum* plants in office 1, no plants in office 3 Working day heating regime
Experiment set 3		
September–October 2020	**Chambers** (V = 2.43)	Five plant species under five T_a/RH conditions

* Data for ACHs measured over 7.5 h in the office without plants [18].

as *working day* and *out of hours* heating regime respectively. To eliminate the effect of occupants on the T_a, RH and the ACH of the rooms, all experiments were conducted when the offices were unoccupied and with doors, windows and trickle vents closed. During 2019 this was typically over weekends and public holidays when the central heating was set to the out of hours regime. In winter 2021, due to national pandemic lockdown restrictions in the UK, experiments were conducted during weekdays when the building was unoccupied, and the heating control was set to working day regime.

Figs. 1–4 provide a visual insight into the experimental context: look of the building and the experimental offices, with and without plants.

2.2. Measurements within the offices

The light intensity, monitored using a Testo 545 lux meter (Testo Ltd, Hants, UK) and Skye PAR light meter (Skye instruments, Llandrindod Wells, Wales, UK), was maintained in each office to a background level of 1000 lux (~15 μmol m^{-2} s^{-1}). Light was provided by daylight from one window per office and additional lighting supplied between 09:30 and 17:30 each day from two electric panel ceiling lights (Sylva Ecoline bulbs FHO 20w, 4000 k, Sylvania, Newhaven, UK) and four electric desk lamps (Litepod, Internet Fusion Ltd., Kettering, UK) positioned as shown in Fig. 4.

Where possible, all experiments were set to start at 09:30 and were considered complete after 24 h. The air pressure within all offices, measured at the start of each experiment ranged between 985 and 1019 hPa and the indoor air velocity was below 0.02 m s^{-1}.

Fig. 1. Building elevations A = South facing B = East facing and C = North facing.

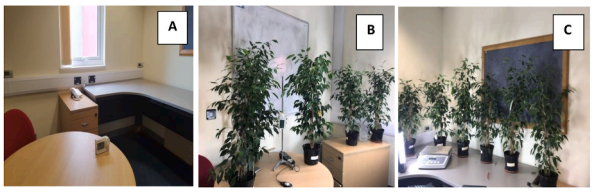

Fig. 2. Example of Office 1 interior. A = without plants. B and C = with Ficus plants.

Fig. 3. Office interiors. A and B = Office 3 interior. C= Internal corridor.

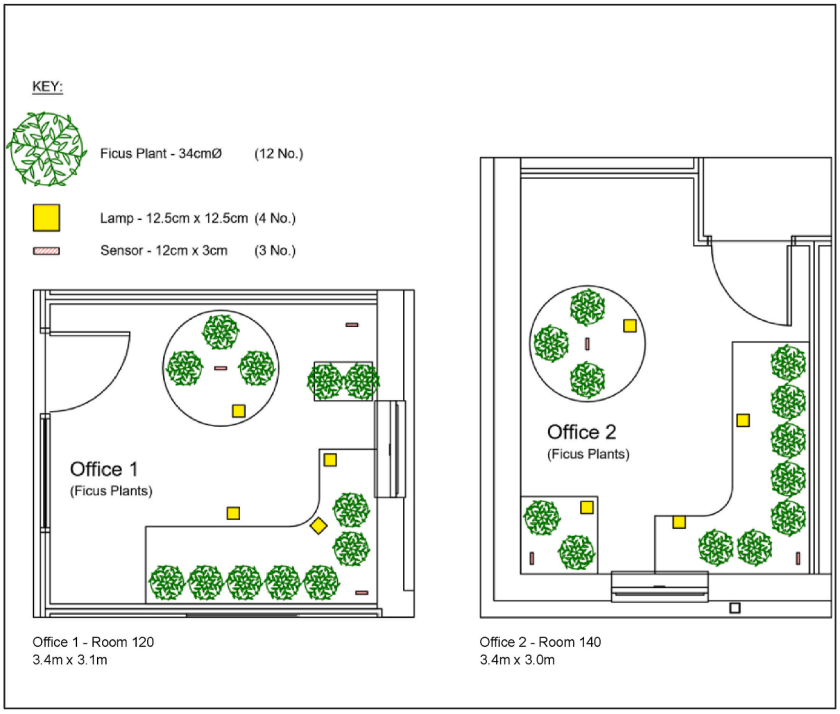

Fig. 4. Plan showing location of plants, extra lights and sensors in office 1 and 2.

Following pre-studies of the T_a, CO_2 and RH profiles [18], three calibrated data loggers (Hobo MX1102, Onset Computer Corporation, Bourne, USA Accuracy: T_a ±0.2 °C from 0° to 50 °C, RH ±2%, CO_2 ±3% or ±50 ppm) were used within the study offices (Fig. 4); and an additional one placed in the adjoining corridor to measure the T_a, CO_2 and RH at 5-min intervals for 24 h per experiment.

In this study comparisons of the air humidity were made using Absolute Humidity (AH), where AH is defined as the mass of water vapour in a given volume of air, expressed as grams per cubic metre of air [14]. This provides a measure of the true water vapour concentration of the air independent of T_a and was considered a more accurate measurement of the impact of plants on the indoor water vapour concentration [39]. Details of how AH was calculated are provided in Section 2.5.1, equation (1).

2.3. Plant material

For the first office studies during winter 2019 (Experiment 1), twelve *Ficus benjamina* plants were selected, as these demonstrated the highest CO_2 uptake capability during preceding chamber experiments [18,40]. This was taken as an indicator that this species would have highest ET rates, as leaf-level water loss takes place through the same stomatal openings as CO_2 uptake [26]. For Experiment 3 (Environmental chamber studies), a selection of five common indoor plant species (Fig. 5) were chosen to represent a range of different plant physical and physiological characteristics (size, leaf size and shapes, plant metabolism – C3 or CAM).

When findings from Experiment 3 revealed that *Epipremnum* plants had the highest ET rate out of the range of plants tested, this species was then selected for use in winter 2021 (Experiment 2, see Table 1) as it could be expected to have the greatest impact on the indoor humidity.

The plants were approximately two years old, maintained in 3-L plastic containers with a professional pot-plants' substrate and acclimatized in an office environment (17–22 °C, 40–60 % RH, ~1000 lux) for three months prior to testing. Plant dimensions were measured at the start of the trials and leaf area was measured at the end of the trials (Fig. 5). The plants and bare substrate were watered 1 h prior to the start of each experiment to maintain the same comparable substrate moisture content (SMC) at a starting level of

Fig. 5. Images of plants used in the controlled environment experiment (Experiment 3). Showing mean dimensions (height x canopy diameter, cm), Leaf Area (LA) (cm^2) ± SEM. Data are the means of 6 replicates per species, except for *Ficus* leaf area where data are the mean of two replicates. Images are actual photographs of used plants, but not to scale.

45%, measured at three positions per container using a capacitance-type probe (WET sensor) connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of ±2.5%).

2.4. Experimental detail

2.4.1. Experiment set 1: The impact of Ficus plants on the seasonal indoor humidity within a cellular office

During winter 2019, experiments were conducted in Office 1 and office 2 with and without twelve *Ficus* plants in each office. Due to office availability, experiments were repeated in Office 1 only during spring and summer and in Results we therefore only provide all seasonal data for Office 1.

The CO_2 concentration was raised at the start of the experiments to approximately 2000 ppm to simulate a working office environment [18] by adding CO_2 from a gas cylinder (BOC UN1013). Measurements of the T_a and RH within the rooms before and after the addition of the CO_2 gas showed there was no measurable impact of gas introduction on either parameter. Additionally, to describe outdoor T_a, RH and air pressure for the same time periods, we used the data from the University of Reading's Meteorological office observation site, located about 1 km away from the study offices. Experiments were conducted on days without strong winds or heavy rain.

To determine the ET rate within the office, each plant was weighed in its container, including substrate, at the start (0 h) and end (24 h) of each experiment. The daily ET rate was assumed to be the total weight loss per container over 24 h. This method gives a direct measure of water released by the plants which has been reliably used in previous research [23,41,42]. The substrate surface was left uncovered during the experiments. For the purposes of the determination of the impact of the plant on the AH within the offices, it was assumed that all the water lost was emitted into the office as water vapour and contributed to the moisture content of the indoor air.

2.4.2. Experiment set 2: The impact of Epipremnum plants on the indoor humidity within a cellular office during winter

During winter 2021, the same procedures were followed as in Experiment 1, but experiments were conducted in Office 1 with and without six *Epipremnum* plants (Table 1) and the adjacent Office 3 was used as a control without any plants at all times.

2.4.3. Experiment set 3: The influence of varying air temperature and humidity on the ET rate of different plant species within environmental chambers

To determine how the ET rate of five plant species plus bare substrate, varied under differing environmental conditions of T_a and RH, experiments were conducted in four environmental chambers ('Fitotron HGC', Loughborough, UK) of internal volume 2.43 m^3, between 7th September - 30th October 2020.

Five typical office conditions of T_a/RH (Table 2) were simulated within the cabinets, with ambient CO_2 concentration (approx. 400 ppm). Conditions in each cabinet were monitored at 10-min intervals using a Hobo MX1102 sensor/data logger. Two plants per chamber were tested at one time. The air circulation system within the cabinets generated an air flow of less than 0.2 m s^{-1} within each cabinet, measured at the start of the experiments with a Kestrel 4200 Air flow tracker (Nielsen-Kellerman, Boothwyn, USA).

Each experiment started at 09:00 and ran for 24 h. To replicate bright office lighting and provide sufficient light under which photosynthesis could be expected to occur [18,43,44], lighting of intensity 1500 lux (20 μmol m^{-2} s^{-1}) was provided by Fusion, EDF 39/840 4000 k cool white fluorescent tubes installed within the cabinet ceiling, between 09:00 and18:00.

To determine the ET rate, the pots of plants with substrate, or just the bare substrate, were weighed at the start (0 h) of the experiments and after 24 h. The daily ET rate was assumed to be the total weight loss per container over 24 h and the proportion of ET accounted for by transpiration was assumed to be: Total weight loss (plant + substrate) minus the weight loss through evaporation from bare substrate [41,42]. To provide a more detailed picture of the plant ET activity, an automatic weight data logger (custom made by Reading University, facilities department) attached to one balance within each experimental chamber was used to record the weight of three samples per treatment (plant species + substrate, or substrate only) every 30 min.

2.5. Data treatment and statistical analysis

2.5.1. Calculation of absolute humidity

To provide a measure of the mass of moisture in the air and take account of the effect of variation in T_a, the measurements of T_a (°C) and RH (%) were used in equation (1) to calculate the absolute humidity (AH) of the indoor and outdoor air for each experiment [14].

$$\mathbf{AH = (2170*p)/ (T_a + 273.3)} \quad (1)$$

AH = Absolute humidity (moisture content) of air (g m^{-3}).
P = (Actual vapour pressure in kPa) = SVP x (RH/100).
RH = (P/SVP) *x*100.
SVP = (saturation vapour pressure in kPa) = 0.6105*EXP ((17.269*T)/(237.3 + T))
T_a = Dry bulb Temperature in ^{0}C.

2.5.2. Comparison of the daytime changes in T_a and AH in study offices

The starting time for the data analysis of the indoor and outdoor T_a and RH was taken as 10.00 a.m. when the sensor readings had stabilised after the experiments had been set up. Data were analysed for the time periods of 1 h, 3.5 h and 7.5 h after the start, to represent the working periods until lunchtime (13:30) and the end of a typical working day in the office (17:30). The mean of the three readings (within a 10 min interval) around each time was taken as the data point to be used for each time period (e.g. the mean of the readings at 09:55, 10:00 and 10:05 were taken as the starting value at time "0 h"). To examine how the presence of plants influenced the change in moisture content over the course of the working day and to take account of variation in the AH concentration across the different test days, the change in AH and T_a were determined by subtracting the starting values (time "0 h") from the measurements after 1 h, 3.5 h and 7.5 h.

Statistical analyses were carried out using SPSS version 25 (IBM).

To assess the effect of 'plants' versus 'no plants' on the change in AH and T_a over different time periods within each office, for each season, two-way paired t Tests were used. To compare differences between seasons Repeated Measures analysis of variance (ANOVA) and Post-hoc Scheffé multiple comparison tests were used. Variance within the data was checked for normality assumptions and homogeneity (Levene's test). Differences are reported as statistically significant where $p \leq 0.05$ [18,45].

Table 2
Average air temperature (T_a) and humidity (RH) conditions measured within the controlled environment cabinets. VPD was calculated from the actual RH and T_a measurements using equation (3) provided in section 2.5.4.

Office condition	Actual recorded		
	RH (%)	T_a (^{0}C)	VPD (kPa)
Cool	54	17.5	0.92
Warm (Standard)	55	22	1.19
Hot	54	26	1.55
Dry	34	22	1.74
Humid	72	22	0.74

2.5.3. Calculation of the moisture generation and excess using moisture balance model

Moisture balance models are based on the conservation of mass of water vapour and are widely used to estimate the indoor humidity levels and moisture generation within buildings [39,46–48]. The change in moisture content within a room over time depends on the amount of moisture entering and leaving the room plus the amount generated within the room, plus the moisture lost or gained by adsorption/desorption from the building and interior materials. The model takes into account the air exchange within the room and the differences in indoor and outdoor AH concentrations over a given time. They are therefore a useful method of comparing the changes in moisture content within the offices on different test days and calculating the theoretical moisture generation from the plants.

The rate of change in the moisture concentration within a room, under non-steady state conditions can be expressed by the moisture balance equation (2) [46].

$$\mathbf{V\ dci/dt = G - Q\ (M_i - M_o) - M_{sorb}} \quad (2)$$

Assuming steady conditions:

$G = Q\ (Mi - Mo) + M_{sorb}$

Where:

G = moisture generated in room (g h^{-1}).

V = Volume room (m^3).

Q = Air flow rate (m^3 h^{-1}) (where Q = ACH x Volume room).

M_o = outdoor moisture concentration (AH) (g m^{-3}).

M_i = indoor moisture concentration (AH) (g m^{-3}).

M_{sorb} = moisture added or removed by absorption/desorption (g h^{-1}).

T = time (h).

The left side of equation (2) gives the mass rate of change of water vapour in the room, and the right side includes the main factors which affect this; the apparent moisture production rate within the room, the rate of water vapour removed by air exchange, and the moisture sorption rate. Under steady conditions, where the indoor water vapour concentration is relatively constant, the left side goes to zero.

Q was calculated using the ACHs previously determined [18] and the volume of each office. The materials within each room remained the same for each experiment and assuming steady state conditions the contribution from sorption was neglected, as proposed by Loudon [49]. As there were no occupants or other sources of moisture production in the offices, it is assumed that G (moisture generated in the room) = moisture production from the plants.

2.5.4. Calculation of the vapour pressure deficit

To determine the vapour pressure deficit (VPD), equation (3) was used. The actual vapour pressure (p) and SVP of the air was calculated from measurements of the T_a and RH of the air surrounding the plant. [14]

Vapour Pressure Deficit (VPD) = Saturation Vapour Pressure (SVP) – Actual Vapour Pressure (p)

$$p = SVP \times (RH/100)\ (kPa) \quad (3)$$

$$RH = (P/SVP) \times 100 \quad (4)$$

$$VPD = SVP \times (1 - RH/100)\ (kPa) \quad (5)$$

$$SVP = 0.6105*EXP((17.269*T)/(237.3 + T))\ (kPa) \quad (6)$$

T = Temperature in ^{0}C.

RH = Relative humidity %

2.5.5. Chamber studies' statistical analysis

ANOVA and post-hoc Tukey HSD tests were used to assess the effect of environmental conditions and plant species on the measured ET rates after checking the data for normality and homogeneity of variance (Levene's test).; repeated measures ANOVA was used to compare the effect of environmental conditions within the same species. Bonferroni adjustment was included to account for inflated Type 1 error (the risk of rejecting the null hypothesis when it is true) due to multiple comparisons. Variance within the data was checked for normality assumptions and homogeneity. Paired comparison t-tests were used to further test for significant differences between light and dark ET rates for individual species.

In addition to ANOVA analyses, corelation and regression analysis were conducted to investigate the relationship between VPD and ET rate and to identify which plant parameters had the strongest correlation with ET rate. Regressions were conducted for each set of climate conditions, using ET rate as the dependent variable and leaf area and leaf area density, as the independent variables.

Further details on all statistical tests used can be found in Refs. [18,45].

3. Results

Results are reported for each set of experiments (sections 3.1 - 3.3). Section 3.5 examines in detail the differences between the amount of moisture emitted by the plants and the measured changes in AH within the offices. This is compared with the results using a moisture balance model in 3.6, to provide a deeper understanding of the findings.

3.1. Experiment set 1: Seasonal office studies (2019)

Initially, the 24 h, 5-min data means for the indoor and outdoor T_a, RH and AH, were plotted for each experiment to provide detailed response patterns which generated an extensive number of plots. From these, we created summary graphs for the repeated test days for each season shown below.

3.1.1. Winter 2019

During winter 2019, the mean daytime indoor AH within Office 1 across all test days ranged between 8.9 and 10.5 g m^{-3} and was significantly higher (typically 40–50%) than outside of the building, where the AH ranged between 4.7 and 7.7 g m^{-3} (Fig. 6. A and B).

The mean indoor AH was lower on the test days with plants in the office, compared to the days without plants. From the different starting concentrations, the indoor AH gradually settled during the morning, peaking during the afternoon between 15:00–18:00. The outdoor AH also increased during the morning but reached its peak concentration earlier, between 12:30–14:00. When taking account of the different starting concentrations and comparing the change in AH from 10:00–13:30 and 10:00–17:30, the results of the paired t-Tests showed there were no significant differences in the change in AH concentration within Office 1, on the days with *Ficus* plants in the office compared to the days without plants (all $p > 0.05$).

The T_a within both offices was higher than outdoors, and remained stable throughout the working day, typically with only 1 °C variation between 10:00 and 17:30. There were no significant differences in the change in the office temperatures on the days with or without plants (all $p > 0.05$).

Data for Office 2 is not included here for simplicity, but were comparable with office 1, and the results of the paired t-tests showed there were no significant differences in either the change in AH concentration or the T_a within Office 2, on the days with *Ficus* plants in the office compared to the days without plants (all $p > 0.05$). For full details refer to Ref. [18].

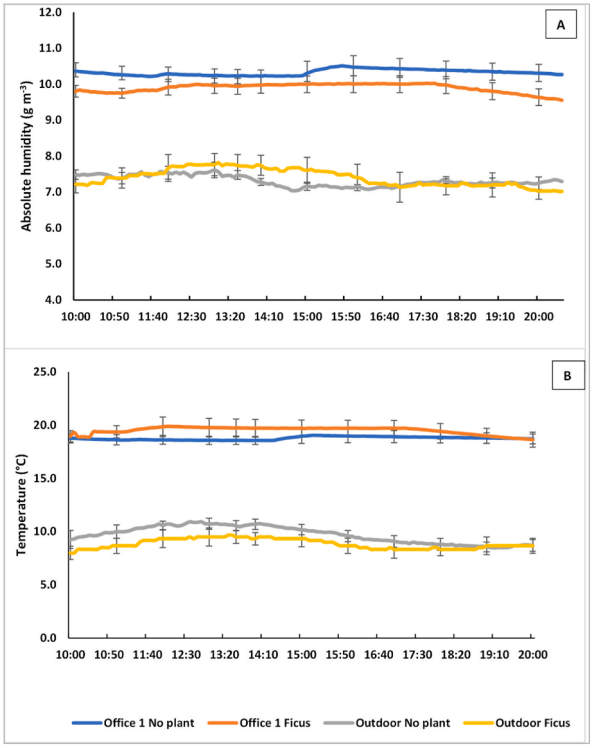

Fig. 6. A comparison of the mean AH (Fig. 6A) and T_a (Fig. 6B) within Office 1 and outdoors, during the winter 2019 experiments. Where: 'No plant', represents the AH or T_a within the office on the test days with no plants and, '*Ficus*' represents the days with plants in the office. 'Outdoor No plant', and 'Outdoor *Ficus*' represent the outdoor AH or T_a on the same days. Data are the means of three days of repeat measurements per condition (N = 3) ± SEM.

3.1.2. Spring 2019

During springtime, the mean daytime indoor AH within Office 1 across all test days ranged between 8.6 and 13.1 g m^{-3} and was significantly higher (28–60 % higher) than outdoors for all time periods where the outdoor AH ranged between 6.7 and 8.1 g m^{-3} as shown in Fig. 7.

During the test days with *Ficus* plants in the office the AH was significantly higher, typically by 20–30%, than on the days without plants. The mean indoor starting AH at 10:00 on the days with No plants was 8.6 g m^{-3} and this steadily increased during the day. By lunchtime (13:30) the AH had increased to 8.7 g m^{-3}, and by the end of the working day (17:30) the mean AH was 8.9 g m^{-3}, an increase of 3.5% over the course of the day. By comparison, during the days with plants in the office the mean starting AH was 11.0 g m^{-3}, which increased to 12.3 g m^{-3} by lunchtime and 13.2 g m^{-3} by 17:30, an increase of 20% over the course of the day.

The mean outdoor AH at the start of the test days without any plants in the office was 7.1 g m^{-3} compared to 8.1 g m^{-3} (14% lower) on the days with plants in the office. However, unlike the indoor AH, the outdoor AH dropped significantly during the daytime, to reach the lowest AH concentration around 15:00 on the days with plants in the office whereas it increased marginally on the days with no plants in the office.

To account for the differences in the starting concentrations of AH, the changes in AH during the day were compared. The paired tests showed the AH within office 1 increased significantly on the days with plants in the office compared to the days without plants, between 10:00–13:30, ($p < 0.05$) and between 10:00–17:30, ($p < 0.001$). In contrast, when comparing the change in the outdoor AH, the paired t-tests showed there was a significant reduction in AH on the days with plants in the office compared to the days without plants, between 10:00–13:30, ($p < 0.05$), but no significant difference in the AH change between 10:00–17:30, ($p > 0.05$). The change in indoor AH on the days with plants in the office is not therefore attributed to the change in outdoor AH.

Fig. 7B shows the mean indoor T_a followed a similar pattern to that of the AH, rising from the start of the day and reaching a maximum of 24.8 °C between 17:30–18:30. The outdoor T_a followed a similar pattern of rising during the day, but it reached the peak T_a earlier than indoors, between 14:30–16:00, it fluctuated more than the indoor Ta and was typically 30–60 % lower. It was significantly warmer in the office, and there was a significantly greater increase in the mean indoor T_a on the days with plants compared to the days without plants in the office, between 10.00 and 13:30 and 10:00–17:30 ($p < 0.05$ and $p < 0.001$ respectively). There was no significant difference in the change in the outdoor temperatures on the days with plants compared to the days without plants for the same time periods ($p > 0.05$).

3.1.3. Summer 2019

During summer 2019, the average daytime indoor AH within Office 1 was higher than during winter or spring and ranged between 13.3 and 14.5 g m^{-3} across all test days (10–50% higher). It was also significantly higher (typically by 30–43%) and more stable than

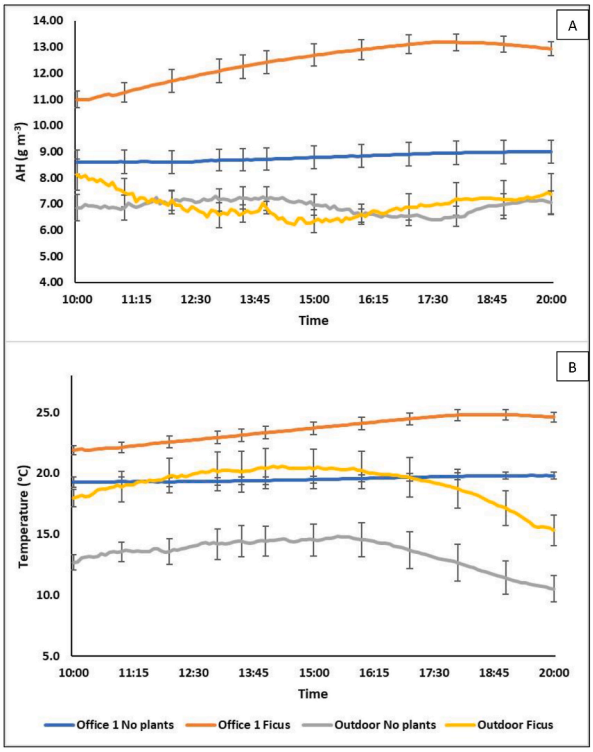

Fig. 7. A comparison of the mean indoor and outdoor AH (Fig. 7A) and T_a (Fig. 7B) during spring 2019 for Office 1. Where: "Office 1 No plant" and "Office 1 *Ficus*" represent the AH or T_a within the office on the test days with either no plants or twelve *Ficus* plants in the office respectively. "Outdoor No plant" and "Outdoor *Ficus*" represent the outdoor AH or T_a on the same days. Data are the means of six days of measurements per condition ($N = 6$) ± SEM.

the outdoor AH for all time periods where the mean outdoor AH ranged between 9.3 and 10.0 g m^{-3} as shown in Fig. 8. There was also more variation in AH outdoors compared to the indoors (±0.4–0.7 SEM vs ± 0.3–0.5 SEM) (Fig. 8).

The mean indoor AH at the start of the day (10:00), was comparable on the days with and without plants in the office, with values of 12.8 g m^{-3} and 13.3 g m^{-3} respectively. The AH increased steadily during the day, at lunchtime the mean AH had reached 14.2 g m^{-3} and 13.7 g m^{-3} on the days with and without plants and by the end of the working day (17:30) the AH had increased to 14.6 g m^{-3} and 14.3 g m^{-3} on the same days respectively (5% higher on the days with plants) (Fig. 8).

Although the increase in indoor AH was greater on the days with plants compared to the days without plants, there was also more variation across the test days and the two-way paired t-tests showed the increase in AH was not statistically significant after 3.5 h ($p = 0.09$) or 7.5 h ($p = 0.28$) on the days with plants compared to the days without plants in the office. There were also no significant differences in the changes in the outdoor AH after 3.5 h or 7.5 h on the days with or without plants in the office (p's > 0.05) (Fig. 8A). The error bars show the significant variation which occurred in the outdoor humidity both between the test days and throughout the day.

The T_a at the start of the experimental days with plants in the office were typically 2 °C warmer than the days without plants (Fig. 8B). The T_a rose steadily during the day and on the days with plants it reached a peak of 26.5 °C (±0.18). The paired t-tests showed the rise in indoor T_a was significantly greater on the days with plants compared to the days without plants in the office after 3.5 h and 7.5 h (all $p < 0.05$).

The outdoor T_a at 10:00 was comparable across the days with plants and without plants in the office ranging between 17.6 °C and 19.7 °C, but it fluctuated significantly during the day and the large SEM highlights the considerable variation across the test days. The paired t-tests confirmed the differences in outdoor T_a change between the plant and No plant days were not significant ($p > 0.05$) (Fig. 8B).

3.2. Experiment set 2: Winter office studies (2021)

Fig. 9A shows the mean daytime indoor AH within both offices ranged between 8.6 and 10.9 g m^{-3} and was consistently 40–50% higher than outdoors. The indoor AH was also more stable across the test days as shown by the SEM which ranged between ±0.1–0.4 g m^{-3} for the indoor AH and ±0.5–0.9 g m^{-3} for the outdoor AH.

Although office 1 had a consistently higher AH than office 3 (3–24 % higher) with no plants in the office, the indoor AH within both offices followed a typical pattern of remaining stable and showing only a small rise during the day to a peak at around 17:30 when the office door was opened, and the lights were turned off (Fig. 9A). On the days without plants in either office, the mean indoor AH at the start of the day (10:00) in office 1 was 9.5 g m^{-3} which had increased to 9.9 g m^{-3} and 10.0 g m^{-3} by 13:30 and 17:30 respectively, an increase of 5% by the end of the working day. For the same time periods, the mean AH within office 3 started at 9.2 g m^{-3} and increased to 9.3 g m^{-3} by 13:30 and remained at this concentration until 17:30, an increase of 1% over the working day. On the days with plants in Office 1 the mean AH had increased by 10% by lunchtime and 15% at the end of the working day

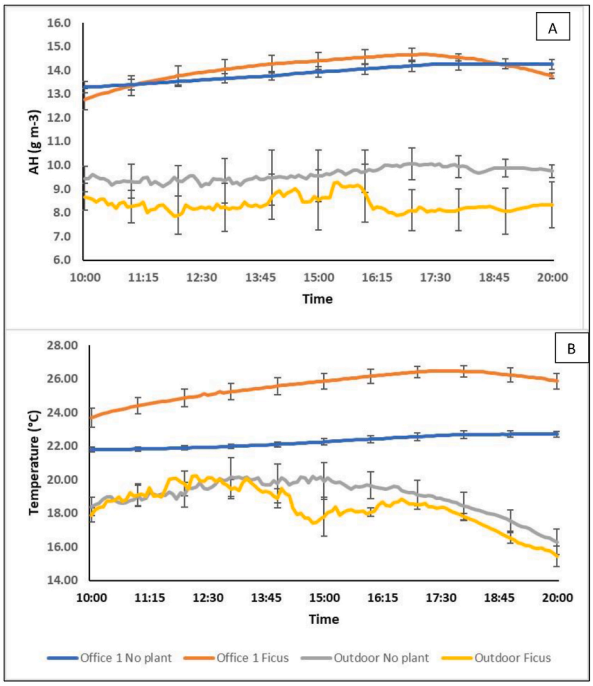

Fig. 8. A comparison of the mean indoor and outdoor AH (Fig. A) and T_a (Fig. B) during summer 2019 for Office 1. Where: "Office 1 No plant" and "Office 1 *Ficus*" represent the AH or T_a within the office on the test days with either no plants or twelve *Ficus* plants in the office respectively. "Outdoor No plant" and "Outdoor *Ficus*" represent the outdoor AH or T_a on the same days. Data are the means of three days of measurements per condition (N = 3) ± SEM.

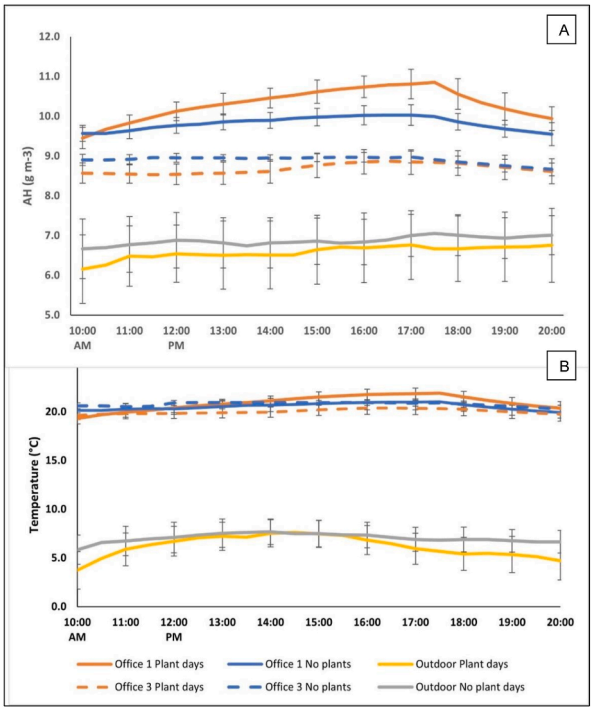

Fig. 9. Comparison of the mean indoor and outdoor AH (Fig. A) and T_a (Fig. B) during the test days in January 2021. "Plant days" refer to the test days when six *Epipremnum* plants were present in Office 1 but no plants in Office 3 (the control). "No plants" refers to the test days with no plants in either office. "Outdoor No plant" and "Outdoor Plant days" represent the outdoor AH and T_a on the same days. Data are the mean of 5 days of measurements per condition (N = 5) ± SEM. Heating was set to Working hours regime.

(from 9.5 g m^{-3} to 10.9 g m^{-3} between 10:00 and 17:30). By comparison within Office 3, which had no plants, the AH remained constant between 8.6 g m^{-3} and 8.8 g m^{-3} throughout the day.

The two-way paired t-tests confirmed the increase in AH within Office 1 was significantly greater on the days with *Epipremnum* plants in the office compared to the days without plants after 3.5 h and 7.5 h (all $p < 0.05$) and significantly greater than the changes in office 3. In Office 3, which had no plants for all tests, there was no significant differences in the AH change over the same test days after 3.5 or 7.5 h ($p = 0.84$ and $p = 0.39$).

The offices were well insulated and with the central heating in operation, the indoor T_a during working hours were maintained within a comfortable range, the mean T_a ranging between 19.5 and 21.9 °C for both offices across all the test days. The paired t-tests showed there were no significant differences in the T_a changes between 10:00 and either 13:30 or 17:30 within Office 1 or Office 3 on the days with plants compared to the days without plants (all $p > 0.05$). The indoor temperatures were consistently more stable, and 10–15 °C warmer than outside (Fig. 9B). The central heating also helped to maintain the indoor daytime T_a typically 2–3 °C higher during the winter 2021 experiments compared to winter 2019, when the mean daytime T_a ranged between 16.6 and 19.7 °C.

3.3. Experiment set 3: Environmental chamber measurements of plant ET rates

3.3.1. Impact of plant species and environmental conditions on ET rate

There was a significant difference in the ET rates of different plant species under all imposed environmental (T_a, RH, VPD) conditions, ($p < 0.001$) (Fig. 10). All plants, except *Sansevieria,* had a significantly higher water loss than bare substrate under all conditions (all $p < 0.05$); there was no significant difference between the ET rate of *Sansevieria* and bare substrate under any conditions. There was a similar trend across all conditions, where *Epipremnum* had significantly the highest ET rate of all plants (all $p < 0.001$), typically three to four times higher than *Sansevieria,* which had the lowest ET rate. To account for the effect of differences in the size and weight of the plants (Fig. 5), the water loss per plant as a percentage of the total weight (plant + substrate) was compared (data not shown) but the order of species in terms of magnitude of ET rate remained the same, indicating that plant species choice, rather than plant size, was the major factor affecting ET rate differences.

Within the same species, including the bare substrate, there were significant differences in the ET rates between different environmental conditions, ($p < 0.001$) (Fig. 10). The highest ET rates were always under 'dry' conditions (30% RH 22 °C) and the lowest ET was under 'humid' conditions (70% RH and 22 °C). When the T_a was held constant at 22 °C and the humidity varied, the ET rate decreased with increasing humidity.

When the RH was held constant at 50% and the T_a was varied, the ET rates increased with increasing T_a, but the differences were only statistically significant for *Asplenium* and *Calathea* at 26 °C compared to 17 °C, and for *Asplenium* at 22 °C compared to 17 °C, ($p < 0.001$). The biggest differences were observed For *Asplenium*, where the ET rate at 26 °C (130 g $plant^{-1}$ day^{-1}) was approxi-

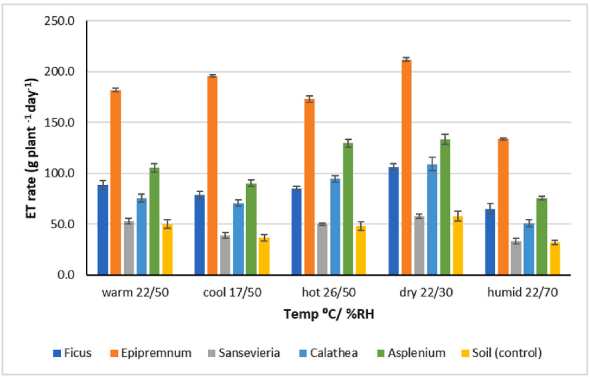

Fig. 10. ET rates (expressed as grams of water loss per plant per day) of different plant species under different environmental conditions (T/RH). Data are the average of six replicates per treatment (N = 6) ± SEM.

mately 45% greater than at 17 °C (90 g plant^{-1} day^{-1}). There was no significant difference between the ET rates at 17 °C, 22 °C or 26 °C for *Ficus, Sansevieria, Epipremnum* or bare substrate.

3.3.2. Relationship between VPD and ET rate

For all plants and bare substrate, the highest ET rates were at high VPD ('dry' condition) (Fig. 11). Regression analysis revealed a strong, positive, linear relationship between ET rate and VPD for all plant species, including the bare substrate, which was statistically significant for all plants ($p < 0.05$) except for *Epipremnum* ($p = 0.24$) (Fig. 11). The strongest relationship between ET and VPD is for *Asplenium* ($R^2 = 0.99$, slope = 59.2), and *Calathea* ($R^2 = 0.962$, slope = 52.6). *Epipremnum* had the highest ET rate but the weakest correlation with VPD ($R^2 = 0.41$, slope = 45.1). The relationship between *Sansevieria* and VPD is comparable with that of bare substrate, showing this plant is having only a marginal effect on the changing ET rate with VPD.

3.3.3. Contribution of plants' transpiration and soil evaporation to total water loss

The contribution of plant transpiration to total water loss from a potted plant varied with plant species, although the order of species, in terms of highest to lowest contribution, remained the same across the majority of the environmental conditions (data not shown but detailed in Ref. [18]). *Epipremnum* had the highest contribution from transpiration which ranged from 72 to 76% across all conditions, followed by *Asplenium, Ficus* and *Calathea*. The lowest contribution was for *Sansevieria,* where approximately 95% of the water loss was due to evaporation from the soil.

3.3.4. Diurnal plants' water loss

The weight loss every 30 min over 24 h showed that the mass of water loss varied with environmental conditions and with species, but the distribution of water loss over 24 h followed a similar pattern under all conditions for each species (data not shown). Fig. 12 illustrates the pattern of water loss over a 24-h period under 'dry' conditions.

For the C3 plants, *Ficus, Epipremnum, Calathea* and *Asplenium,* the greatest water loss coincided with the lighting period, between 09:00–18:00 when ET rates were between 30 and 80% higher than during the dark period (Fig. 12.). The water losses from *Sansevieria* were considerably smaller than all other plants and followed a similar pattern to bare substrate. Under 'dry' and 'cool' conditions the water losses for *Sansevieria* were higher during the dark compared to the light period.

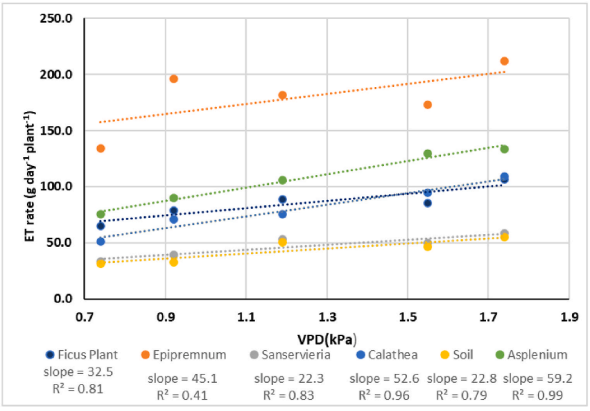

Fig. 11. Relationship between ET rate and VPD for each plant species. ET rates are based on the mean of six replicates (N = 6) per treatment. The regression coefficient (R^2) and slope are provided under each species' name.

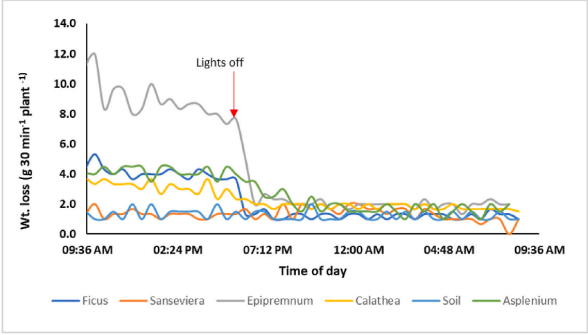

Fig. 12. Diurnal water loss for all plant species under 'dry' conditions (22 °C and 30% RH). Data are the mean of 3 replicates per treatment. The approximate time when the lights were turned off is shown with the arrow.

3.4. The contribution of moisture from plants to indoor AH within real-world office environments

There were significant differences in the amount of water vapour emitted by the *Ficus* plants in different seasons, ranging from 35 g plant^{-1} day$^{-1,}$ in winter [i], 44 g plant^{-1} day^{-1} in spring to 58 g plant^{-1} day^{-1} in summer [18]. *Epipremnum* had a higher ET rate and contributed on average 67 g plant^{-1} day^{-1}.

To investigate in more detail how the water vapour lost from the plants through ET may have influenced the actual AH within the office, the approximate water vapour released from the plants, versus the change in moisture content within the room, was examined hourly during a 24-h period and an example from winter 2021 is provided in Fig. 13.

The water vapour contribution from the plants was determined by applying the percentage weight loss per plant for each hour measured in the chamber experiments and multiplying this by the 24 h weight loss measured in the offices for 6 plants. The actual increase in water vapour concentration in the office is determined from the hourly difference in the AH measured in the office for the same time period.

Fig. 13 shows the AH within the office increases each hour from 10:00 until approximately 18:00 when the door is opened and the lights are turned off. When the door is opened, air from within the room is exchanged with the corridor air and measurements showed the AH of the corridor (data not shown) was approximately 2 g m^{-3} lower than the air within the office at the same time, hence the AH in the office falls as the AH concentration equilibrates. The room AH concentration continues to fall during the night. Based on the findings of Experiment 3, the moisture emitted by the *Epipremnum* plants is highest during the daytime when the lights are on and reduces significantly when the lights are turned off. The hourly increase in moisture content of the air within the office is significantly less, between 0.4 g m^{-3} and 1.95 g m^{-3} lower over 24 h, than the approximated moisture emitted by the plants. The difference can be explained by moisture being removed through the air exchange or being absorbed by the materials within the room and this is examined in more detail below, between 65% and 100% of the water vapour emitted by the plants was lost in this way.

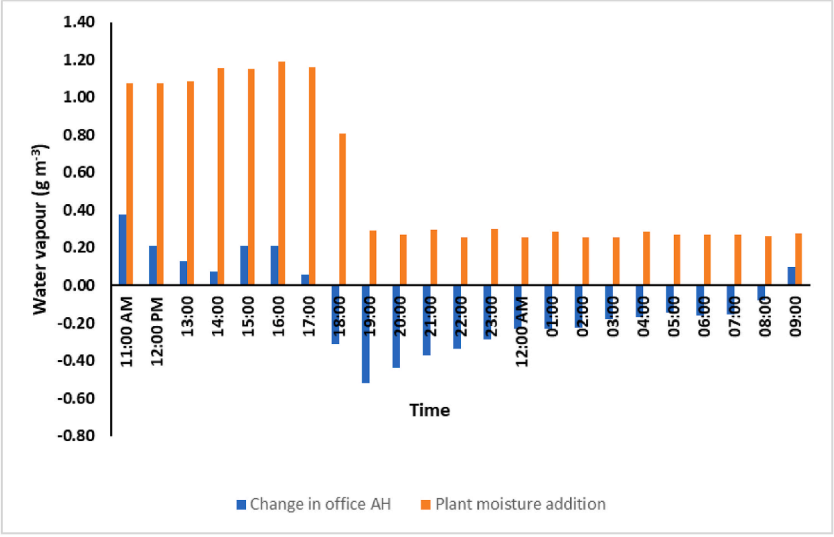

Fig. 13. A detailed example comparing the hourly change in absolute humidity (g water vapour m^{-3}) within Office 1 on a day with plants in the office, against the hourly water vapour released via evapotranspiration (g water vapour m^{-3}) from six *Epipremum* plants on January 28, 2021. ET rate is determined from the plant + pot weight loss, assuming that the weight loss is all due to ET, and that all of this is added to the indoor air within the office.

3.5. Comparison of the theoretical moisture contribution determined from moisture balance model and the actual moisture change

Using the moisture balance equation (2), assuming the moisture sorption is constant and there were no other sources of moisture production in the offices, the moisture production rate of the plants can be theoretically calculated (Table 3).

Using the data for the AH concentrations for the indoor and outdoor air, measured for the 7.5-h period between 10:00 and 17:30, for each test day the hourly moisture production rate per cubic metre (g h^{-1} m^{-3}) within each office was estimated using equation (2). The air flow rate (Q) was calculated from the ACH determined for each office [18]. The difference in the average moisture production rate for the test days with plants in the office minus the rate for the days with no plants in the office was calculated and is shown as "moisture excess" in Table 3. Assuming the moisture adsorbed or desorbed by the materials in the room remains constant, then the difference between the Plant and No plant days should be due to the moisture emitted by the plants.

To compare the estimated moisture change determined from the model against the actual change in the room, the mean hourly change in AH measured within each office was determined for the period 10:00–17:30 for the same Plant and No plant test days and the difference between the plant and No plant test days, is shown in Table 3 as actual moisture excess. The actual moisture emitted by the six plants for the same time periods, calculated from the total weight loss of the plants as described above is included in Table 3.

The moisture excess determined from the moisture balance models was higher than the actual measured increase in moisture content within the room, but within the standard errors associated with the means. Although the model overestimated the moisture excess compared to the actual data both sets of results showed the same order of seasonal moisture production and excess (i.e. lowest in winter then summer and highest in spring).

Models assume perfect and uniform mixing of the air and in this calculation they do not account for the absorption by the walls and materials in the room [50,51]. In addition, the model also assumes that all the air exchange is made with the outdoor air, whereas in reality some of the air exchange is made between the office and the air in the corridor through the gaps around the internal door, and the indoor air has a higher AH than the outdoor air.

4. Discussion

4.1. T_a and AH in naturally-ventilated offices in different seasons

All plant species contributed water vapour to the indoor air within the three offices used in these experiments, as shown by the water loss from the plants, but there was a seasonal variation. The water loss from the plants increased progressively from winter through to summer with 12 *Ficus* plants contributing 422 g moisture day $^{-1}$ (35 g $plant^{-1}$ day^{-1}) in winter and 696 g day $^{-1}$ (58 g $plant^{-1}$ day^{-1}) in summer. The seasonal increase in moisture contribution corresponded with increasing daytime T_a, higher light intensity and longer daylight hours, and an increasing VPD within the office. This supports the findings from the experiments in the environmental chambers which showed that ET rate had a positive linear relationship with VPD and temperature. Plant activity (photosynthesis and transpiration) has also been shown to respond to seasonal changes in day length, light intensity and light wavelength and colder nights [26,52,53] which helps to further explain the variation in ET rates.

There were significant differences in the ET rates between plant species. When comparing the ET rate of *Ficus* and *Epipremnum* in the same office during winter, *Epipremnum* had the higher ET rate (66.5 g $plant^{-1}$ day^{-1}) ($p < 0.05$). This supports the findings from the chamber experiments where *Epipremnum* also had the highest ET rate. This higher ET rate in *Epipremnum* is partly explained by the plants having a 40% higher leaf area than *Ficus;* as stomata are found in the leaves this would increase the number of stomata available for plant transpiration. Additionally, previous studies have shown that *Epipremnum* has a high stomatal density which has a positive linear correlation with ET rate [21]. The experiments involving *Epipremnum* were also conducted during winter 2021 when the room T_a and VPD were slightly higher (VPD 15% higher) than for the experiments with *Ficus.* Both factors are associated with higher ET rates [25,54,55] and the environmental conditions are therefore also likely to have contributed to the higher *Epipremnum* ET rates.

Table 3
A comparison of the difference in the moisture generation calculated using moisture balance models and the actual measured changes of air moisture content within the office, and the total water vapour emitted by the plants for each season. Data are the means of multiple days of repeat measurements per condition, in winter and summer 2019, (N = 3) ± SEM, in spring 2019 (N = 6) ± SEM and in winter 2021 (N = 5) ± SEM.

	Calculated moisture excess g h^{-1} m^{-3}	Actual moisture excess g h^{-1} m^{-3}	Moisture emitted by plants g h^{-1} m^{-3}
Winter 2019 Office 1 Plants = Ficus	−0.05 (±0.09)	−0.02 (±0.08)	1.2 (±0.02)
Spring 2019 Office 1 Plants = Ficus	0.67 (±0.12)	0.25 (±0.02)	1.5 (±0.02)
Summer 2019 Office 1 Plants = Ficus	0.55 (±0.09)	0.12 (±0.04)	2.0 (±0.06)
Winter 2021 Office 1 Plants = Epipremnum	0.17 (±0.16)	0.11 (±0.02)	1.13 (±0.02)
Winter 2021 Office 3 No plants	0.01 (±0.08)	0.02 (±0.02)	0.00

In previous research of indoor plants in an office environment, Gubb et al. [23], measured ET rates of 28–71 g plant^{-1} day^{-1} for a range of species, which are comparable to the rates measured here.

The ET rates of the plants measured in the offices were lower than those measured in the environmental chambers, although the order of magnitude of ET rates between species was the same. The difference is most likely due to better light provision in the chambers which would contribute to higher photosynthesis and transpiration rates [23,43,56].

One of the main aims of this paper was to determine if indoor plants significantly impacted the ambient moisture content within an office environment during daytime working hours. This is a complex issue as there are a many interacting factors which affect the moisture content within a room and the first step was to compare the change in moisture content in the same office with plants and without plants.

During winter 2019 with the central heating set to low, the introduction of 12 *Ficus* plants did not lead to any significant differences in the AH within office 1 or office 2 compared to the days without plants. During spring 2019, and winter 2021 the increase in AH concentration was significantly higher on the days with plants in the office (12 *Ficus* plants were used in 2019 or 6 *Epipremnum* plants in 2021), compared to the days without plants and increased steadily through the day to reach a peak between 17:00–18:00 ($p < 0.05$).

The above findings do not take account of variations in outdoor T_a, humidity or ACH over the different experimental days although other studies have shown these can have a significant influence on the moisture concentration [39,46]. In our research, preparatory studies of the offices under different weather scenarios, showed that the indoor T_a and RH were extremely well shielded from short term changes in the outdoor conditions probably due to the high air tightness and good insulation of the building. When moisture balance equations were used to take account of these factors, the results showed that in spring 2019, summer 2019 and winter 2021, the mean moisture generated in the office between 10:00–17:30, was significantly higher on the days with plants in the office compared to the days without plants ($p < 0.05$). There was no difference in winter 2019.

For all seasons the increase in AH concentration within the office was considerably lower than the amount of water vapour emitted by the plants. Between 65% and 100% of the water vapour emitted by the plants was lost through the air exchange and through absorption by the materials within the room. Although it is not possible to quantify the amount or time of moisture sorption from this study, previous research has shown that moisture adsorption begins 30 min to 2 h after the moisture generation and increases with increasing RH [50,51].

During transpiration, when changing the physical state of liquid water within the plant to the transpired vapour, plants use sensible heat and convert it to latent heat, eliciting a cooling effect in the surrounding air (e.g. Ref. [57]). However, there was no evidence from these studies that the plants had any measurable cooling effect within the offices. Whilst there may have been a cooling effect from the plants this is likely to have been very small localised around the leaves of the plants and insignificant compared to the heat gains from other sources such as the central heating, lighting and electrical equipment and increases in the outdoor T_a. Studies in outdoor environments, have shown that plants and trees can make significant contributions to air cooling due to a combination of shading and transpiration effects and cooling effect varied with species [58–61]. The differences between indoor and outdoor cooling effects are readily explained by the difference in outdoor environmental conditions (lighting, wind speed, T_a and RH), size and leaf areas of the plants.

Other research studies have reported varying impacts on room T_a and humidity by indoor plants [31,32,34,62,63] but the experimental parameters have varied and the ventilation rates were not specified, making it difficult to make direct comparisons of the results. Findings from a study by Su and Lin [32], partially support our findings as they reported 10% increase in RH within a room when *Asplenium nidus* plants were introduced, but contrary to our study they measured a 1.5 °C reduction in T_a in a room of 39 m^3 volume. However, they calculated the mean T_a over 24 h which would include the reduction in room T_a typically observed overnight whereas this present study focussed on changes during the daytime. In addition, they used 189 potted plants which is considerably more than this study and the influence of the infiltration rate and outdoor T_a on their results were not included. Researchers in Spain observed average T_a decreases of 4 °C and up to 15% increase in RH following the introduction of a passive indoor living wall [64]. They also showed that increasing the air flow through the substrate and plants, increased the cooling and humidification effect near the living wall, but the effect was not sustained after the fan in the active living wall was turned off [65].

The findings from a study of a passive green wall in a classroom, reported an increase in RH in the greened classroom but no impact on T_a and the study also showed that occupants were more comfortable in the greened classroom in winter [34]. When mechanical ventilation is in operation in the room, some studies have shown the presence of plants has had no impact on the RH or T_a [31,33] whereas others have reported small increases in RH [35,62,66]. However, these studies were conducted with occupants in the offices and the moisture removal by the HVAC system was not specified, it is therefore difficult to assess the true impact of the plants on the indoor humidity.

Throughout all experiments in this study, with the doors, windows and trickle vents closed, the mean indoor daytime RH ranged between 50 and 71% RH and the mean T_a was between 17.5 and 26.5 °C. The T_a meets the requirements for the minimum working T_a [67] but during the summertime the T_a and RH exceed or reach the limit of the UK recommendations [14,68]. The thermal comfort of occupants was not investigated in this study, but working in these offices with the doors, trickle vents and windows closed is not recommended for the comfort of building occupants.

The risk of mould growth occurs if the average RH within a room stays above 70% for several days [14]. During these experiments, levels of RH above 70% were only measured for a few days during the daytime in summertime, therefore no risk of mould growth was identified. In this study, the addition of plants did not increase the humidity levels sufficiently to increase the risk of mould growth.

A study in Australia by Torpy et al. [69], of 55 offices, found that the addition of indoor plants had no significant impact on either the mould spore count or the species composition within the offices and mould count was significantly higher outdoors than indoors. In our study, the extensive trees and vegetation surrounding the building are likely to have a much greater impact on the indoor mould spores than indoor plants. However, due the building design and the low ACH rate of the offices, during sustained periods of high outdoor humidity or if the offices are used without the trickle vents or windows opened, there is a potential risk of mould growth within the building. The risk will increase when the building is occupied as people contribute significant amounts of moisture to the indoor air. Further monitoring of the indoor T_a and RH within the building, over longer periods is recommended to better understand the risk of mould growth.

Irrespective of changes in T_a and humidity, previous research has shown that the presence of plants can improve people's thermal comfort during winter [33,34] and their perception of air quality [70]. The psychological benefit from adding plants to the office for people's thermal comfort and wellbeing may therefore have a more significant impact than the impact of the plants on indoor humidity.

4.2. Impact of simulated T_a and RH office conditions (chamber studies) on the capacity of several plant species for evapo-transpiration

The 'humidification potential' of indoor plants depends on their ET rate. Two key parameters of indoor environments that affect the comfort of building occupants, T_a and RH, can also impact plant ET rates. The results of the experiments in controlled environment chambers revealed significant differences in the ET rates between the five plant species tested under all environmental conditions ('warm', 'hot', 'cool', 'dry', 'humid'). *Epipremnum* had the highest ET rate under all conditions, so was identified as having the greatest 'humidification potential' for indoor environments. *Sansevieria* had the lowest ET rate, with 95% of the water loss occurring from the growing medium, rather than the plant itself.

The ambient T_a and RH had a significant impact on the ET rate of the plants, but the size of the effect was species-dependent. All plants had the greatest water loss under 'dry' (low RH, or high VPD) conditions. The ET rates decreased with increasing RH and with decreasing T_a and the lowest ET rates were under 'humid' (high humidity, low VPD) conditions. In indoor environments, the water vapour contribution of the plants is therefore likely to decrease as the air humidity level increases.

Both physical and physiological characteristics influenced the ET rate of the plants. Greater plant leaf area was associated with higher ET rates, but comparison of ET rates on a unit of leaf area basis showed inherent differences between species. *Calathea* had the highest ET rate per square metre of leaf area, but it had a lower leaf area per plant compared to other plants and so a greater quantity of plants would be required to equal the leaf area of other species. Based on the findings of previous studies, stomatal size, density and response are likely to account for some of the differences in ET rates between species [21,71]. As the stomata control both ET rate and photosynthesis, factors which affect the stomatal response for CO_2 uptake, including light intensity, will also influence ET rate. Comparisons of the ET rates under light levels similar to a bright room (20 μmol m^{-2} s^{-1} in our experiment) and dark conditions highlighted differences between CAM and C3 species; all C3 plants had higher ET rates under light conditions whereas *Sansevieria*, a CAM plant, had a higher ET rate under dark conditions. There is a dynamic interaction between the plant, the environmental conditions (T_a, RH, light intensity, and water availability) and the ET rate. The findings showed that species selection and leaf area are of major importance when considering the use of indoor plants for room humidification purposes, either for increasing the room humidity or minimising the risk of condensation formation. The greatest impact from plants on indoor humidity levels is likely to be within hot, dry, brightly lit indoor environments and the least impact will be in cool, humid, dark environments. The choice of plant species can be tailored to suit different humidification requirements or environmental conditions. To maximize the daytime moisture contribution from plants, C3 plant species with high ET rates and high leaf area (high stomatal numbers) should be selected. From a practical maintenance viewpoint, however, plants with low ET rates would be expected to minimise water use for plant maintenance and reduce the frequency of watering required.

4.3. Limitations of the office-based research

For consistency, the same *Ficus* plants were used throughout 2019 and pruned lightly before each set of seasonal experiments to maintain the size. The plants therefore matured over the test period and as the plant age affects its physiological activity, this could have impacted the results.

The experiments were conducted at raised CO_2 concentrations. Measurements of ambient humidity showed this did not impact the indoor AH but it may have impacted the ET rate of the plants. However, real occupied offices and indoor spaces are often places where the CO_2 concentration is elevated compared to the ambient, so we feel there is a value in testing plant activity in that context. Additionally, there is evidence in the literature that elevating the CO_2 actually increases plants' physiological activity [72] so this gave us the opportunity to look at plants' maximal capacity to contribute.

The experiments were conducted over different days and although steps were taken to account for and minimise the influence of outdoor weather conditions (e.g. by choosing to experiment on days when comparable weather was forecasted), there was day to day variation which could not be avoided. Comparisons on different days and in different years may produce different findings. Limited access to the otherwise occupied offices, inevitably resulted in smaller number of day-repeats, leading to lower statistical power in the analysis of the results. To raise the statistical power in future work, a greater number of repeat tests is recommended.

5. Conclusions

The overarching aim of this study was to investigate and quantify how indoor plants affect the humidity and T_a within indoor office environments. Through a series of experiments in real-world offices and controlled environment chambers, some of the dynamic interactions between the plant and the indoor environment were examined.

The findings show that the introduction of 12 *Ficus* plants or 6 *Epipremnum* plants resulted in a small but significant increase in the moisture content of a naturally-ventilated office (28 m^3), during a series of test days in spring and winter respectively, compared to the days without plants. No cooling effect from the addition of plants was found.

There was significant seasonal variation, in the amount of water vapour emitted by the plants. This was affected by the environmental conditions within the office, with 66% more water vapour being emitted during warm summer days compared to cool winter ones. Most of the moisture emitted from the plants, however, was removed through room air exchange and moisture sorption. Factors which affect these such as the building design, the T_a, RH and air flow, determined the magnitude of impact that the plants had on the indoor humidity.

The study offices had low ACHs; in rooms with higher ACHs such as buildings of older constructions or where HVAC systems are used, the impact of the same number of plants on indoor humidity is likely to be insignificant compared to the removal through air exchange.

In office environments the main moisture contribution is from human respiration and perspiration, varying between 30 and 90 g h^{-1} $person^{-1}$, depending on the person, activity level and environmental conditions [68]. In the studied offices, the plants emitted between 35 and 58 g of moisture, per plant, per day (1.5–2.8 g h^{-1} $plant^{-1}$). The moisture contribution from one potted plant is therefore small in comparison to other sources. To equal the amount of moisture emitted by one person, depending on the room conditions, an estimated 11–60, physiologically highly active, *Epipremnum* plants would be required and a greater number of plants if using other species.

Experiments in controlled environment chambers confirmed a significant difference in the humidification capacity between different indoor plant species: *Epipremnum* (a vigorous and highly transpiring species) had the highest ET rate and would have the greatest humidification potential for indoor environments. *Sansevieria* (a succulent, low transpiring but also low maintenance needs plant) had the lowest ET rate which was similar to bare substrate and it would have very little impact on the humidity levels of indoor environments. *Sansevieria* would therefore be a good choice for environments where a low moisture contribution is required or there are concerns about 'over-humidification' or mould. Changes in the ambient temperature and humidity, had a significant impact on the ET rate of the plants. ET rates were highest at low humidity levels and high temperatures; thus, the greatest water vapour contribution from plants would be made to hot, dry indoor environments and as the ET rate decreased with increasing RH, the moisture contribution from plants would be lower in cool rooms with high humidity levels.

This study provides new evidence that indoor plants can have a small but significant impact on increasing the humidity within a naturally ventilated office environment of low ACH. The choice of plant species, building construction and environmental conditions have a significant influence on the impact of plants on indoor humidity. This is the first study to the authors' knowledge which has investigated in detail the seasonal variation and dynamic interaction between the plant ET rate, the indoor AH and the ACH within a naturally ventilated office.

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CRediT authorship contribution statement

Jenny Berger: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Emmanuel Essah:** Writing – review & editing, Supervision, Methodology. **Tijana Blanusa:** Writing – review & editing, Supervision, Methodology.

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.

Data availability

Data will be made available on request.

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