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Research Article

Evapotranspiration Performance of Vertical Indoor Greening—Influence of Indoor Climate Conditions on the Transpiration Performance of Tropical Ornamental Plants and Contribution of Greenings to Indoor Comfort in Offices

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In indoor offices, it is often difficult to ensure high air quality and thermal comfort. Common problems are low relative humidity and the need for cooling. Previous research has shown that indoor greening can contribute to keeping the relative humidity and temperature at an appropriate level. In order to quantify the contribution of transpiration to evapotranspiration of vertical greening systems, various tropical ornamental plants were characterized in this study with regard to their transpiration rate and stomatal conductance under different indoor climatic parameters. Light intensity (PAR) showed a positive and air temperature a negative correlation with transpiration rate and stomatal conductance, while the dependence on relative humidity and soil moisture was not significant. Furthermore, two vertical greening systems with *Philodendron hederaceum* 'Brasil' were investigated in a parallel room set-up, where one room contained the greening system and the other room served as a reference. The vertical greening systems showed an evapotranspiration rate in the range of 55 to almost 100 $g\,m^{-2}\,h^{-1}$, which increased the relative humidity from 20%–40% in the reference room to 40%–60% during the 3-week measurements in March 2023. This improved the comfort in the rooms.

Keywords: cooling; evapotranspiration; relative humidity; stomatal conductance; vertical greening

1. Introduction

During the heating period, dry air is a common issue in heated buildings, which is detrimental to the resident's health and comfort. Low indoor air humidity causes dryness of skin, eyes, and airways [1, 2]. Dry eyes in particular lead to reduced work performance [3]. A 25% stress reduction (measured by lower heart rate variability) was observed for office workers which were exposed most of the time to relative humidities between 30% and 60% compared to those who were exposed to drier conditions [4]. According to Razjouyan et al. [4], the optimal values for relative humidity exist within an even narrower range around 45% than otherwise mentioned in the literature (i.e., [3]) with 40%–60%.

Since the cold air streaming into the building from the outside cannot carry much humidity, the relative humidity of the warm indoor environment decreases to physiologically unpleasant values. The Mollier hx diagram can be used to calculate the effect of increasing temperature on relative humidity levels for a constant absolute humidity [5]. Under the assumptions of 1°C outside temperature and a room temperature of 21°C, with no change in absolute humidity, air at 50% relative humidity outside reduces to 13% inside [6]. To dampen this effect, technical air humidification

systems are used, which bear the risk of dispersing pathogens with the mist they produce if not cleaned regularly [7].

Alternatively, functional greening can be used to humidify the air. In previous research, Bucher and Kohlrausch [8] show that vertical greening can raise relative humidity levels by up to 20 percentage points. A similar average increase in humidity of 15% is also observed in the vicinity of a geotextile living wall [9]. Although the basic effectiveness of vertical greening in increasing relative humidity is known, there is still a lack of data on its performance in different indoor climate situations and building configurations.

An increase in relative humidity due to vertical greening systems in the room is caused by evaporation via the growing media on the one hand and transpiration of the plants on the other, summing up to evapotranspiration. However, the expected contribution of plants, that is, transpiration, to evapotranspiration is still unclear.

The transpiration rate (E) is determined by the stomatal opening, measured as stomatal conductance (GS). Therefore, all factors that affect stomatal conductance provide an influence on the transpiration rate of plants. These are primarily light intensity, air humidity, temperature, water supply (growing media moisture), CO_2 concentration, and wind speed [10]. In addition, plant species–specific differences are also to be expected [11]. For tropical ornamental plants, which are generally used for indoor greening, data on transpiration rates and the behavior of the stomatal opening under different climatic conditions are scarce.

From a horticultural point of view, the evapotranspiration performance of indoor greenings is difficult to control. As plants need to be supplied with water as required, the range for regulating air humidity is limited. Thus, in this project, an additional evaporation area without greening was used to adjust the evaporation performance easily.

Furthermore, preliminary tests by Bucher et al. [12] indicate that even a nonoptimized greening wall requires over 10 times less electrical energy than conventional humidifiers. A large part of the electricity required is caused by the automatic irrigation, which can be further optimized by choosing a growing medium with long-term water retention, which allows for less frequent usage of the water pumps.

Another key benefit of interior vertical greening could be the reduction in temperature resulting from evapotranspiration. While a cooling effect due to evapotranspiration for outside plants is well understood [13], the effect of interior vertical greening on indoor temperatures has been little reported in the literature to date [14]. Few studies on indoor greening report on temperature changes inside or in the immediate vicinity of green walls but have not attempted to quantify the effects on the overall indoor temperature. For example, inside the canopy of a living wall, 2.5°C–4.5°C or 1.2°C–3.6°C lower temperatures compared to the center of the room were measured when the HVAC is on or off, respectively [11]. The highest difference in temperature is observed during times of high transpiration of the plants on the living wall [11]. Cooling effects of a similar order of magnitude of 0.8°C–4.8°C for an active living wall are reported by Pérez-Urrestarazu et al. [15] and with 4°C–6°C by Fernández-Cañero et al. [9]. However, the more meaningful and relevant quantity is the room temperature with greening walls compared to a room without vertical greening. From a previous study by Bucher et al. [12], an air temperature difference of −2.5 K can be estimated for a 1 m^2 vertical greening in a 15 m^2 room throughout the day compared to a room without vertical greening. Such a temperature decrease would be a significant contribution to indoor climate control.

Additional benefits of indoor plants include a reduction in CO_2, NOx, VOC, and particulate matter in the air and sound, as well as an increase in O_2, thus improving indoor climate [16–25]. A positive mental effect of greening on inhabitants has also been shown, reducing stress and promoting relaxation [26–29]. These factors are not the subject of this study.

To date, indoor greening systems have been designed to optimize plant growth and enhance the value of rooms over many years. In this project, the existing positive factors are to be expanded to include additional parameters such as evapotranspiration performance and the associated adiabatic cooling capacity. Measuring and optimizing these will pave the way for greening systems to be used in the future for a healthy and energy-efficient indoor climate with minimal additional energy input. Greening systems can thus contribute to controlled active indoor climate improvement.

The aim of the research is a control strategy that enables an evapotranspiration rate and cooling capacity adapted to the room humidity and temperature on the one hand and avoids overloading the air with moisture on the other. The tests were carried out in the temperate climate zone of southern Germany and relate to the use of greenings in offices.

In order to achieve these goals, processing is planned in several consecutive steps. At first, the transpiration rate and stomatal conduction of individual plants are to be characterized. The objective is to identify plant species that can keep stomata open and thus maintain a high transpiration rate and contribute to evapotranspiration even under low humidity and low light intensity, that is, conditions that are frequently given in indoor situations. In the next step, the limits and potential of the performance of indoor greening systems and an additional evaporation area are to be demonstrated regarding evapotranspiration and cooling capacity. This is followed by a determination of the influence of greenings on comfort level in offices regarding room humidity, air, and radiation temperature, as well as the contribution of transpiration by plants to the total evapotranspiration. Additionally, system design, plant selection, regulation of the water supply, and growing medium moisture are to be optimized with regard to humidity release and cooling capacity.

2. Materials and Methods

2.1. Measurement of Photosynthesis Parameters

2.1.1. Plants. For the measurement of photosynthesis parameters, tropical ornamentals in pots were chosen, which are commonly used in practice due to their robustness. They were cultivated in hydroculture with expanded clay (H.) or

in growing medium with peat (G.): *Chlorophytum comosum* (H.), *Cissus rotundifolia* (H.), *Epipremnum aureum* 'Enjoy' (H.), *Epipremnum aureum* 'Marble Queen' (H.), *Ficus pumila* (H.), *Microsorum diversifolium* (H.), *Pellionia repens* (G.), *Philodendron hederaceum* 'Brasil' (H., G.), *Philodendron hederaceum* green (H.), *Scindapsus pictus* (H.), *Syngonium podophyllum* (G.), and *Tradescantia zebrina* (G.). The plants, as received at the time of purchase, are shown in Figure 1.

Plants were grown in a greenhouse at heating temperature 20°C/18°C, ventilation temperature 24°C, and with permanent shade.

2.1.2. Phytochamber Settings. Trials were conducted in the period from June 2021 to August 2022.

The photosynthesis parameters were measured in an air-conditioned phytochamber. The target temperature of 22°C was mostly not reached, and temperatures in the chamber were typically around 25°C. Target humidity in the chamber of 20% was almost reached, with real values in the range of 21%–23% relative humidity. The daily light period was from 6:00 to 18:00. Target light intensity (PAR) on the leaf surface to be measured was set to 80 μmol m^{-2} s^{-1} and achieved by adapting the distance to the LED light or using the LED light unit on the cuvette. Monitoring of climate parameters (temperature, relative humidity, air pressure, and PAR) in the phytochamber was done with an Almemo 2590-4S V5.

2.1.3. Procedure and Measurement. The plants were acclimatized to the conditions in the phytochamber for at least 16 h prior to measurements, which were started 2 h after light was switched on. For measurements without a LED light unit on the cuvette, a light intensity of 80 μmol m^{-2} s^{-1} was set on the leaf surface by LED lights above the plant. Temperature, humidity, and CO_2 were adjusted in the cuvette depending on the test question. The LED light unit on the cuvette was used to run light exposure curves. Measurements were always taken on medium-aged leaves (highest activity in test measurements) and, if available, with comparable coloration.

Transpiration rate (E/mmol m^{-2} s^{-1}), stomatal conductivity (GS/mol m^{-2} s^{-1}), photosynthesis rate (A/μmol m^{-2} s^{-1}), and CO_2 uptake (Δ CO_2/vpm) were at first determined with the portable LCpro-SD and from 12-2021 on with an LCpro-T (ADC BioScientific Ltd., 2004) both using a nondispersive infrared (NDIR) technology for gas analysis.

2.2. Vertical Greening Systems. Two vertical greening systems with different growing media were selected according to their potentially high water release, possible controllability, and positive experiences made in practice. These were as follows:

1. Fleece system: Vertiko (Vertiko GmbH, Germany). Sewn fleece and glass basalt knitted fabric, whose pockets are filled with Vertiko special "indoor" substrate, serve as vegetation substrates. Drip hoses are integrated into the fleece for irrigation, which are supplied from the water tank via a submersible pump with a timer. The greenable fleece area has eight pockets on 1.00×1.65 m (= 1.65 m^2). The greening system as received before planting is shown in Figure 2b.
2. Rock wool system: Wallflore prototype (Cloud Garden B.V., Netherlands). The panels consist of rock wool slabs wrapped in HDPE foil, which are held in place by a steel wire basket. The version that can be planted on one side has 66 predrilled planting holes in the rock wool and foil over an area of 0.9×1.35 m (= 1.215 m^2). The panels are mounted in a vertical suspension construction with a water tank and a submersible pump. Water is distributed by pressure-compensated pipes above each row of panels, whereas excess water is collected below the panel and returned to the reservoir. The greening system as received before planting is shown in Figure 2a.

2.2.1. Improvement of the Rock Wool System. Furthermore, to increase the evaporation potential of the rock wool system, modifications were made to its HDPE foil covering the rock wool. The foil is necessary for fire hazard regulations, but can be punctured to allow for better air circulation through it. For this, the foil was punctured in various ways, and the resulting evaporation rate was measured. From these experiments, perforating the foil with a heated meat tenderizer was concluded to be preferable, due to a significantly increased evaporation rate compared to nonperforated foil, while having both smaller individual holes and less total hole area compared to holes created with hole punch irons. The thus-created holes were measured to have an average size of 3.54 mm^2, and the proportion of these small holes of the total foil area was 4.13%. In combination with the area of the holes for the plant roots, which was 10.11%, the total hole percentage was 15.12%. The evaporation rates as well as the hole sizes created by the methods tested are shown in Figure 3.

2.2.2. Plants for Vertical Greening Systems and Planting of the Systems. Philodendron hederaceum 'Brasil' was used for the greening of the vertical systems, as this species is robust and grows densely. The plants are suitable for completely greening a vertical surface within a short time and are therefore often used in practice. In initial tests, *Philodendron hederaceum* 'Brasil' showed an intermediate transpiration rate compared to the other species. They were used anyway, as the other species tested in the climate chamber trials were either very sensitive, showed inadequate growth, or were unsuitable in habitus for use in flat vertical systems.

Young plants were purchased in October 2021 in 9 cm pots with commercial growing medium (G).

Planting of the removed rock wool slabs of the rock wool system took place in November 2021 after thorough watering while lying on greenhouse tables. After removing the growing medium by hand, the root balls were placed in the specified planting holes, pressed down, and watered. Rooting took place at 20°C/18°C heating temperature, 24°C ventilation temperature, 40%–50% relative humidity, permanently shaded, and with fertigation (50% tap water + 50% demineralized water with 0.5 g L^{-1} Ferty 9 Hydro

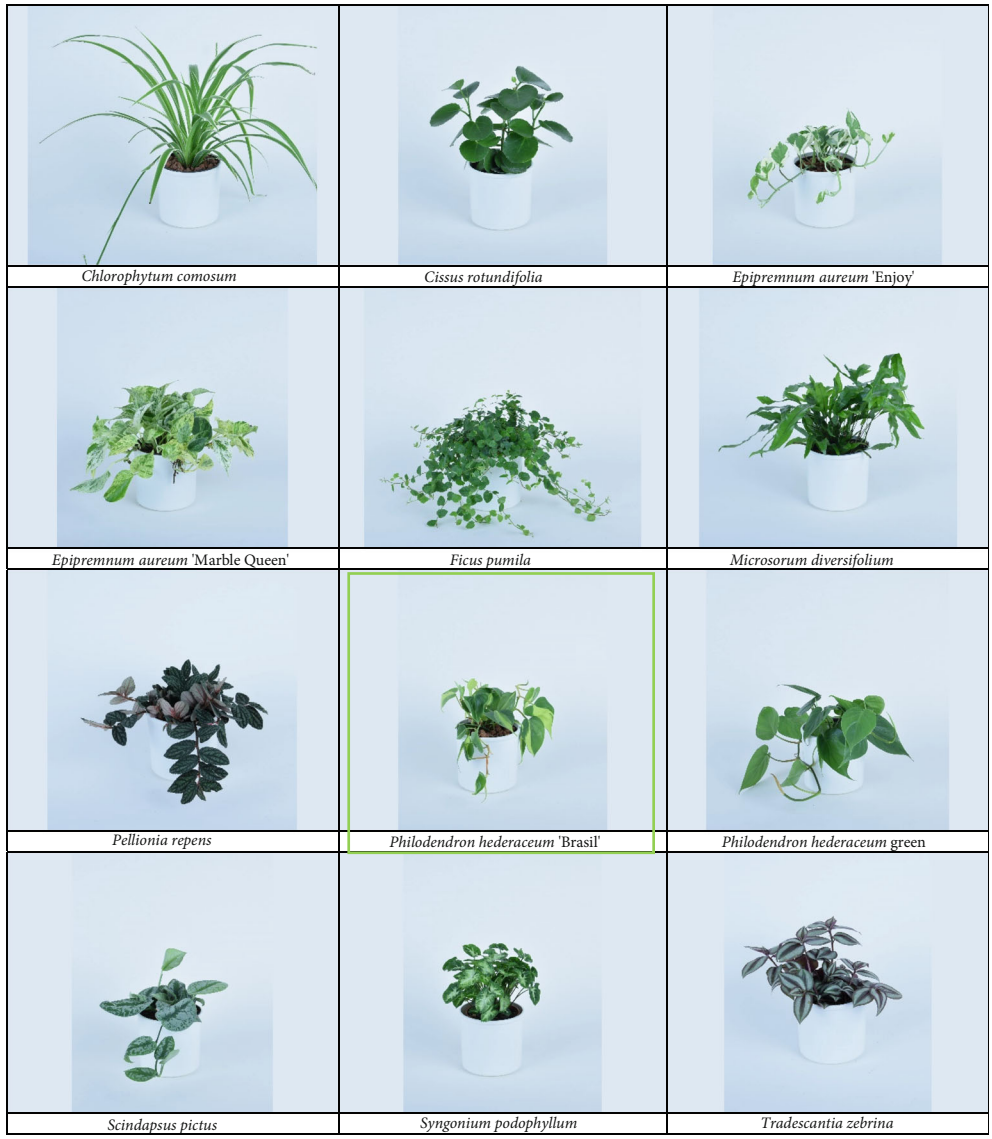


FIGURE 1: Plant species used for measuring the photosynthesis parameters (condition at the time of purchase 6/21). *Philodendron hederaceum* 'Brasil' (framed) was also used for greening the vertical systems.

[15 + 7 + 22 + 6 + trace elements] + 0.01 g L^{-1} Ferty 10 Special [trace elements]).

The plants for the fleece system were cultivated in pots over the same period and with the same treatment.

The vertical systems were equipped at the end of March 2022.

Rock wool system: mounting of vegetated, rooted rock wool slabs (total 66 plants).

Fleece system: bare root planting after removal of the growing medium by washing. Sixty-six plants were distributed in the pockets, which were closed tightly around the plants with a pneumatic stapler and watered (specification from the fleece system manufacturer).

2.2.3. Watering and Fertilizing the Vertical Systems. Both systems were equipped with a water tank at the base of the system, which in combination with a small water pump and perforated tubes running through the wall system allowed for even and easy irrigation of the plants. For the fleece system, the pump was controlled by a programmable timer switch, which allowed precise irrigation of the system. The pump for the rock wool system, due to the less frequent need for irrigation, was manually controlled.

Based on the manufacturer's recommendations (rock wool system: water every second day for 12–14 min; fleece system: water 3× daily for 6–8 min), the watering intervals and nutrient supply were continuously adapted to the plant growth and indoor climate conditions during the trial period. This resulted in the rock wool system being watered every 10–14 days for approx. 3 min, depending on requirements, and for the fleece system, in 3× daily for 3–5 min (0:00, 8:00, and 16:00).

Both systems were watered continuously with nutrient solution (0.2 g L^{-1} Ferty 1 Basis [0 + 14 + 38 + 5 + trace elements] + 0.35 g L^{-1} calcium nitrate tetrahydrate [12% N] in 100% deionized water). The nutrient solution was changed



(a) (b)

Figure 2: (a) Rock wool and (b) fleece greening systems before planting.

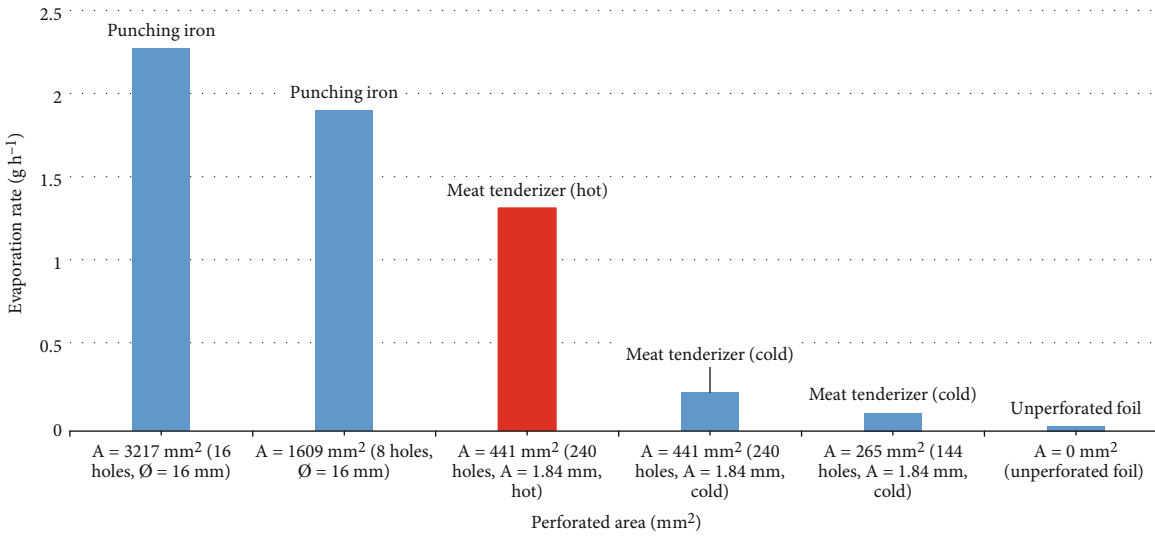
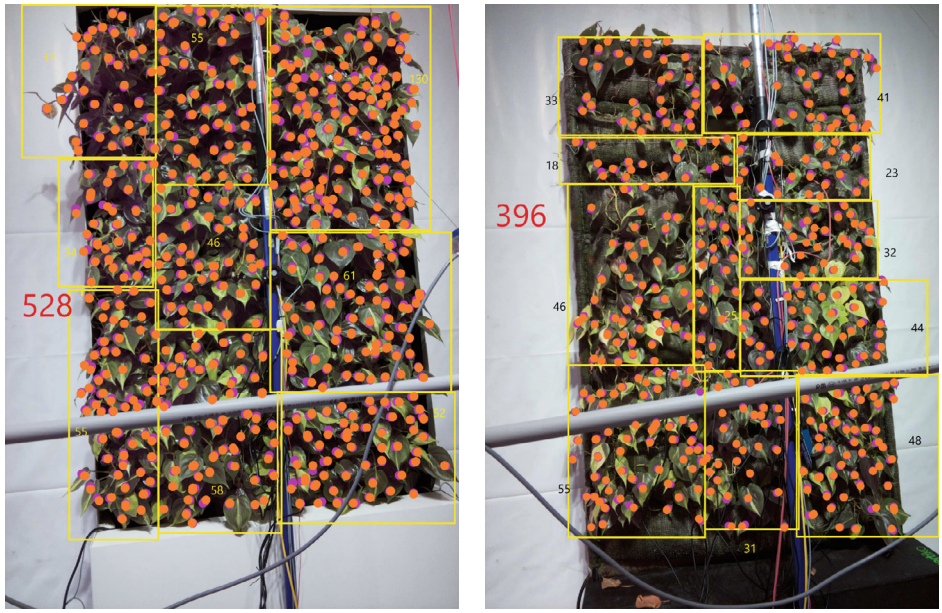


Figure 3: Comparison of different methods for perforating the HDPE foil of the rock wool system with respective evaporation rates, as well as the resulting hole sizes and total perforated areas.

in November 2022 to a more common variant: 0.233 g L^{-1} Peters Excel Hard Water Grow Special (18 + 10 + 18 + 2 + trace elements) in 75% tap water (water hardness of 38.6 dH) and 25% deionized water. The aim was to achieve pH values between 4.5 and 7.5. If the maximum value was exceeded, the pH was lowered by adding sulfuric acid. EC of the nutrient solution was set between 0.5 and 2.0 mS cm^{-1}. Values in excess were reduced by adding pure water.

2.2.4. Determination of Total Leaf Area on Greening Systems. To estimate the contribution of plant transpiration to the total measured evapotranspiration, the number of leafs for every system was counted and used to estimate the total leaf area. A visual representation of the counting process can be seen in Figure 4a,b. With a mean leaf size of 36.42 cm^2 for *Philodendron hederaceum* 'Brasil', the total leaf surface area was calculated to be 1.92 and 1.44 m^2 for the rock wool and fleece systems, respectively.

2.3. Investigations in Measuring Rooms. The measurements with the vertical greening systems were carried out in two identical ("parallel") measurement rooms. While one of the rooms served as a reference room without any greening system, the other acted as the specimen room with a greening system. Prior to the experiment, both rooms were equipped with various sensors, as illustrated by Figure 5,



(a) (b)

Figure 4: Number of leaves for the (a) rock wool and (b) fleece systems. Spots mark the counted leaves.

validated in an empty state, and proved to exhibit similar thermal and hygric behavior within the limits of the measurement uncertainty. Thus, the direct comparison of both rooms showed the effects of the investigated prototypes.

The evaporation measurements were performed by gravimetric methods. The custom-made scale was large enough to carry the entire wall systems, including its water reservoir. The scale's load cells allowed for measurements with a relatively high resolution of 10 g—given the high total weight of up to 200 kg. The setup was designed in such a way that the evaporation measurement was fully independent of pump activity. Soil humidity sensors were also used. All measurements were conducted under the following conditions unless otherwise specified:

- active heating at room temperatures below 22°C,
- outdoor fans running from 8:00 to 18:00 for 10 h total run time per day to supply fresh air and to ensure the minimum air exchange, hence the room was ventilated with an air change rate of 50 $m^3\,h^{-1}$,
- plant exposure from 9:00 to 17:00 for 8 h total runtime per day with a light intensity of 90 $\mu mol\,m^{-2}\,s^{-1}$,
- manual irrigation system for the rock wool prototype used approximately every 10–14 days, and
- automatic irrigation system for the fleece system running three times daily (due to root rot that occurred in the fleece system, irrigation was subsequently reduced to three times per day instead of five times per day in the beginning).

Evapotranspiration rate of the rock wool and fleece systems was measured during periods of 3 weeks each.

In order to better control the evaporation rate of the system, a separate technical evaporation area was built for the project. The core of the evaporation device was made up of a rack with a frame, as seen in Figure 6a. A hydrophilic-coated glass surface (1 × 1.6 m) was clamped inside the frame, over which water could flow and evaporate. A pump lifted the water to the top of the frame, where it flowed along a tube and into sponges along the tube, from which it could flow onto the hydrophilic surface. Despite the coating, the water did not wet the surface evenly, creating trickles instead, as can be seen in Figure 6b.

2.4. Statistical Analyses

2.4.1. Measurement of Photosynthesis Parameters. All statistical analyses were performed using Minitab 21.1, applying one-way ANOVA and GLM for multifactorial analysis of variance, depending on the affecting factors. Mean value comparison was done with Tukey's test ($p < 0.05$). Vertical error indicators in the figures represent standard deviation. Mean values that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$).

2.4.2. Measurements of Greening System Performance. Numerical analysis of measured data at CAE was performed using Python 3 with library NumPy. For visualization purposes, values with high noise were smoothed using a Gaussian filter. The filter width σ is given in the figure caption, if applicable.

3. Results

3.1. Measurement of Photosynthesis Parameters in a Phytochamber. Since the transpiration rate (E) is determined by the stomatal opening, which is measured as stomatal conductance (GS), all factors that influence stomatal

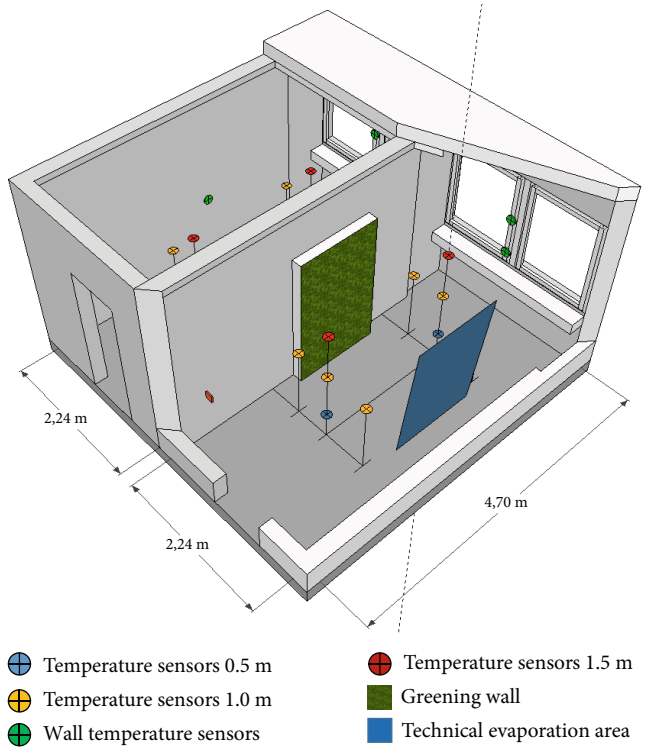
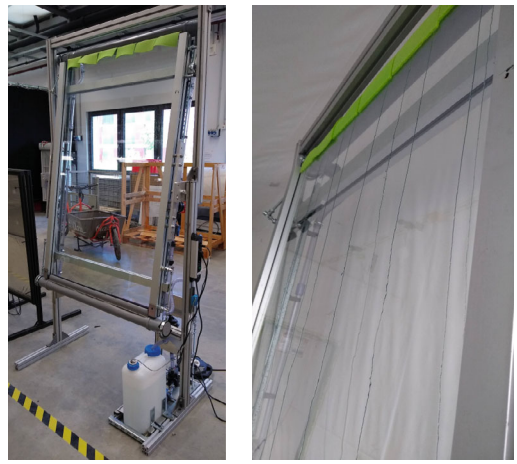


Figure 5: Schematic of the identically constructed measurement rooms, showing sensor placement with colored circles.



(a) (b)

Figure 6: (a) Technical evaporation device. (b) Close-up of the hydrophilic surface of the evaporation rack.

conductance have an impact on the transpiration rate of plants. Therefore, the influence of light intensity, air humidity, temperature, and water supply (growing media moisture) as well as plant species-specific differences was examined. The influence of CO_2 concentration and wind speed was not investigated due to limitations of experimental set-up and measuring equipment.

3.1.1. Light (Photosynthetically Active Radiation = PAR in μmol m^{-2} s^{-1}). Stomatal conductance and transpiration rates were systematically measured for the plant species using combined sequences for air humidity and light intensity. Increasing the light intensity in the range of 40–260 μmol m^{-2} s^{-1} had a significant beneficial effect on the stomatal conductance and transpiration rate of *Philodendron hederaceum* 'Brasil', as can be seen in Figure 7a,b. This effect was particularly evident at low relative humidities of 15% and weakened with increasing humidity to 30% and 45%. The green form of *Philodendron hederaceum*, *Microsorum diversifolium*, and *Syngonium podophyllum* tended to behave in a similar way *to Philodendron hederaceum* 'Brasil'. In contrast, *Ficus pumila*, *Chlorophytum comosum*, *Pellionia repens*,

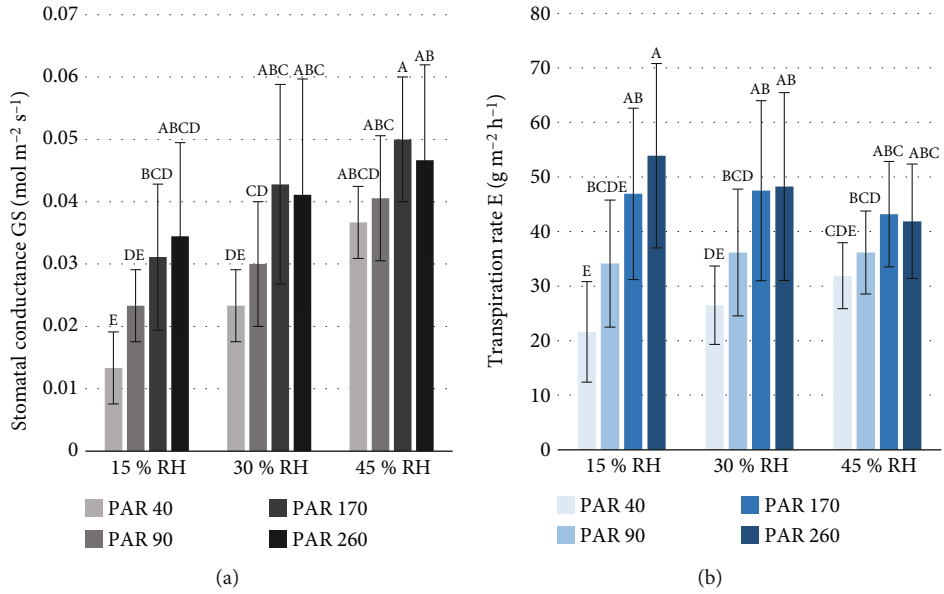


FIGURE 7: Comparison of (a) stomatal conductance or (b) transpiration rate of *Philodendron hederaceum* 'Brasil' at defined relative humidities (RH) and light intensities (PAR in μmol m^{-2} s^{-1}). Mean values (three replicates) that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$) related to RH x PAR. (GS: DF = 6; F-value = 0.66; p value = 0.686. E: DF = 6; F-value = 2.94; p value = 0.029).

Epipremnum aureum 'Enjoy', *Scindapsus pictus*, and *Tradescantia zebrina* showed no significant differences in stomatal conductance and transpiration rate as a function of light intensity (data not shown).

3.1.2. Relative Humidity. The stomatal conductance for the plant species *Philodendron hederaceum* 'Brasil' investigated with varying relative humidity can be seen in Figure 8a. All plant species tended to show a reduced stomatal conductance at lower air humidities, although the differences were only significant between 15% and 45% relative humidity for *Ficus pumila*, *Microsorum diversifolium*, *Pellionia repens*, *Philodendron hederaceum* 'Brasil' (H. and G.), *Philodendron hederaceum* green, and *Tradescantia zebrina*, respectively. For statistical data, see Table 1.

However, the reduced stomatal conductance at low relative humidity was predominantly not evident in reduced transpiration rates, which are shown in Figure 8b. Only with *Philodendron hederaceum* 'Brasil' in growing medium a significant influence of air humidity on the transpiration rate was shown, whereby the values differed only slightly from the nonsignificant differences in the hydro variant, as all standard deviations were comparatively large.

3.1.3. Temperature. Using the example of *Philodendron hederaceum* 'Brasil', Figure 9b shows that an increase in leaf temperature in the range from 18°C to 26°C led to a significant reduction in transpiration. This is caused by the significantly lower stomatal conductance at higher leaf temperatures as seen in Figure 9a. The stomatal conductance and transpiration rates of *Philodendron hederaceum* green and *Ficus pumila*, which were also examined, behaved in the same way.

3.1.4. Season and Growing Media Moisture. *Epipremnum aureum* 'Enjoy', *Ficus pumila*, *Philodendron hederaceum* 'Brasil' and green, *Scindapsus pictus*, and *Syngonium podophyllum* showed significantly lower stomatal conductance and transpiration rates in winter than in summer (data not shown). The values shown so far were determined during measurements in summer.

No significant influence of growing media moisture on stomatal conductance and transpiration rate of *Philodendron hederaceum* 'Brasil' was found when measured with varying relative humidity and irradiation (data not shown).

3.1.5. Plant Species. The comparison of stomatal conductance and transpiration rate of various plant species showed that there were significant differences: *Philodendron hederaceum* 'Brasil', *Philodendron hederaceum* green, and *Scindapsus* pictus, for example, displayed a significantly lower stomatal conductance than *Epipremnum aureum* 'Enjoy' and *Syngonium podophyllum*, as illustrated by Figure 10a. *Epipremnum aureum* 'Marble Queen', *Philodendron hederaceum* 'Brasil', *Philodendron hederaceum* green, and *Scindapsus pictus* showed a significantly lower transpiration rate than *Chlorophytum comosum*, *Epipremnum aureum* 'Enjoy', and *Syngonium podophyllum*, as seen in Figure 10b.

3.2. Measurements of Vertical Greening Systems in Measuring Rooms

3.2.1. Evapotranspiration. Evapotranspiration rates of the rock wool and fleece systems were measured gravimetrically during periods of 3 weeks each. The soil moisture sensors proved to be unreliable due to large variations in soil humidity across the walls.

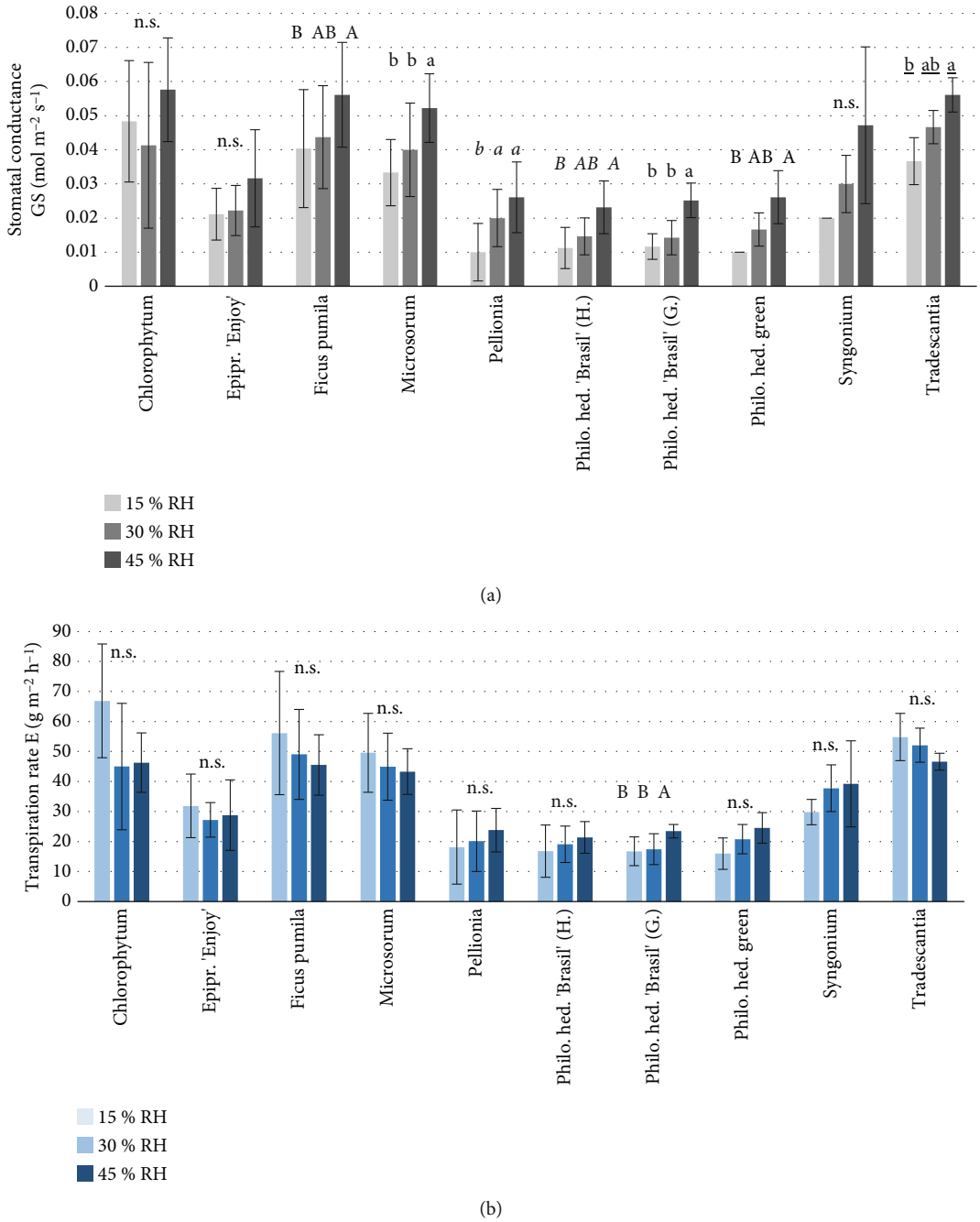


Figure 8: Comparison of (a) stomatal conductance or (b) transpiration rate of different plant species when measured in summer with defined relative humidities (RH). Mean values of one species (three plants with three leaves each = 9 repl.), which do not have a common grouping letter differ significantly in Tukey's test ($p < 0.05$).

For the rock wool system, the evapotranspiration rate was measured to be between 65 and 100 $g\,m^{-2}\,h^{-1}$ during daytime, which declined to roughly 25 $g\,m^{-2}\,h^{-1}$ during nighttime (data not shown).

The evapotranspiration rate of the fleece system was slightly lower and measured to be between 55 and 90 $g\,m^{-2}\,h^{-1}$ during daytime, which declined to roughly 18 $g\,m^{-2}\,h^{-1}$ during nighttime (data not shown).

For the additional technical evaporation area, the hydrophilic properties of the surface were not as good as expected, so instead of a thin water film, small water channels appeared. This reduction of the water surface is assumed to be directly proportional to the reduction of the evaporation of the system. The technical evaporation surface therefore only had an evaporation rate of 25–28 $g\,m^{-2}\,h^{-1}$. Although this evaporation rate is lower than in the greening systems, it is easier to regulate so that the evaporation rate of the system can be better controlled.

3.2.2. Contribution of Transpiration to Evapotranspiration. In order to estimate the contribution of the plants' transpiration to evapotranspiration of the greening system, the leaf

TABLE 1: Statistical data (DF, *F*-value, and *p* value) to Figure 8.

Species	GS			E			Species	GS			E		
	DF	*F*-value	*p* value	DF	*F*-value	*p* value		DF	*F*-value	*p* value	DF	*F*-value	*p* value
Chlorophytum	2	1.56	0.315	2	4.36	0.099	*Philo. hed.* 'Brasil' *(H.)*	2	9.41	0.031	2	2.38	0.208
Epipr. 'Enjoy'	2	2.06	0.243	2	0.48	0.652	*Philo. hed.* 'Brasil' *(G.)*	2	22.57	< 0.01	2	17.30	0.011
Ficus pumila	2	8.08	0.039	2	1.43	0.339	*Philo. hed.* green	2	9.10	0.032	2	5.73	0.067
Microsorum	2	25.13	< 0.01	2	1.99	0.252	*Syngonium*	2	2.88	0.168	2	1.84	0.272
Pellionia	2	20.74	< 0.01	2	2.33	0.214	*Tradescantia*	2	10.81	0.024	2	1.66	0.298

areas of 1.92 m^2 for the rock wool system and 1.44 m^2 for the fleece system were taken into account for the calculation of the leaf area per 1 m^2 of greened area. This enabled a direct comparison of the water releases of the plants (calculated from measured single plants) and the evaporation of the growing media in the greening systems (calculated from measured evapotranspiration), as illustrated by Figure 11 for a relative humidity of 45% and 90 $\mu mol\, m^{-2}\, s^{-1}$ PAR.

Combining the estimated leaf area size of 1.92 m^2 of the rock wool system with the photosynthesis measurements for *Philodendron hederaceum* 'Brasil', a transpiration rate of approx. 57 $g\, m^{-2}\, h^{-1}$ was attributed to the leafs. Therefore, the contribution of the plants' transpiration to the evapotranspiration rate was more than 50%.

Combining the estimated leaf area size of 1.44 m^2 of the fleece system with the photosynthesis measurements for *Philodendron hederaceum* 'Brasil', a transpiration rate of approx. 32 $g\, m^{-2}\, h^{-1}$ was attributed to the leafs, meaning that the contribution of the plants' transpiration to the evapotranspiration rate was less than 50%.

3.2.3. Humidity Control. Combining the technical evaporation area with a greening system enabled good control of the room's humidity level. In Figure 12, a typical day with this system in place is shown. The pump of the technical evaporation area was configured in such a way that it became active below a relative humidity level of 54%, and, with a hysteresis of 2%, inactive above 56%. The measurement was conducted on October 23, 2022. At roughly 8:30, the water pump of the technical evaporation surface was activated for the first time due to decreasing relative humidity levels. From there, it stayed active through most of the early day, until it was switched off automatically for two periods during the afternoon, from 13:50 to 14:15 and from 14:50 to 15:50. At 16:40, the pump switched off for the remaining time.

3.2.4. Physiological Comfort. Physiological comfort can be measured through various methods. A comfort surface suitable for office conditions (sitting activity and low airflow) is described in [30] and takes only air temperature and relative humidity into account, allowing for a simple comfort classification of measured values in the form of a two-dimensional plot.

To evaluate the effect of the greening systems on comfort levels of tenants, the air temperature–humidity curves were plotted for the measurement and reference room over two measurement periods. For the rock wool system, 18 days in May 2022 were evaluated, as shown in Figure 13a,b, while for the fleece system, the measurement period lasted 18 days during February and March 2023, as shown in Figure 14a,b. Additionally, the amount of time spent in comfortable, still comfortable, and uncomfortable parameter areas was calculated (Tables 2 and 3).

For the rock wool system, a large variation in temperatures was observed over the measurement period, owing to varying degrees of sunlight throughout the day. Nevertheless, it is clear to see that the relative humidity in the specimen room was increased compared to the humidity in the reference room. Due to high solar radiation and from the fact that the rooms have no window blinds, the temperatures were often too high for adequate comfort levels in both rooms during the day. The increase in relative humidity was especially noticeable at night, when mechanical ventilation was turned off. At high temperatures, an increase in air humidity quickly led to a decrease in comfort level, as the heat is more effectively transported towards inhabitants (see shape of the comfort areas which are not rectangular but indented in the high temperature–high humidity quadrant). Therefore, for the rock wool system, the measurement room overall was less comfortable than the reference room (Table 2). With additional external cooling capabilities, this would not have been the case, as the discomfort was primarily caused by the high temperatures.

For the fleece system, which was measured during February and March, the temperatures were lower, so that the heating control (set to 22°C) was active during most of the measurement period. Under these conditions with low humidity in the reference room, the greening system was able to show its capability, keeping the measurement room in the comfortable parameter window for most of the measurement period.

3.2.5. Cooling Effect. For both systems, an effort was made to estimate the cooling effect due to the evapotranspiration of the systems. However, because the thermal mass of the greening systems cannot be disregarded in relation to the thermal mass of the otherwise empty measurement rooms as a whole, both the increase in thermal mass and the evapotranspiration contribute to the observed temperature difference between the two rooms. In a representative 3-day period, daily temperature extrema for both rooms were identified to quantify the combined effect. The differences between the daytime extrema for the rooms are marked in Figure 15a,b, which shows the temperature profiles during these measurement periods. Considerable efforts were made

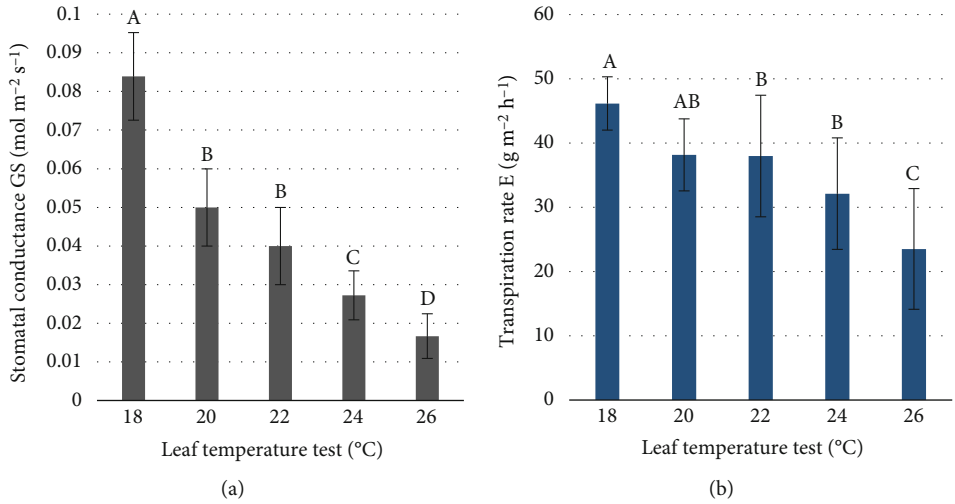


Figure 9: Comparison of (a) stomatal conductance or (b) transpiration rate of *Philodendron hederaceum* 'Brasil' at defined leaf temperatures. Mean values (three replicates) that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$). (GS: DF = 4; F-value = 148.68; p value < 0.01. E: DF = 4; F-value = 26.18; p value < 0.01).

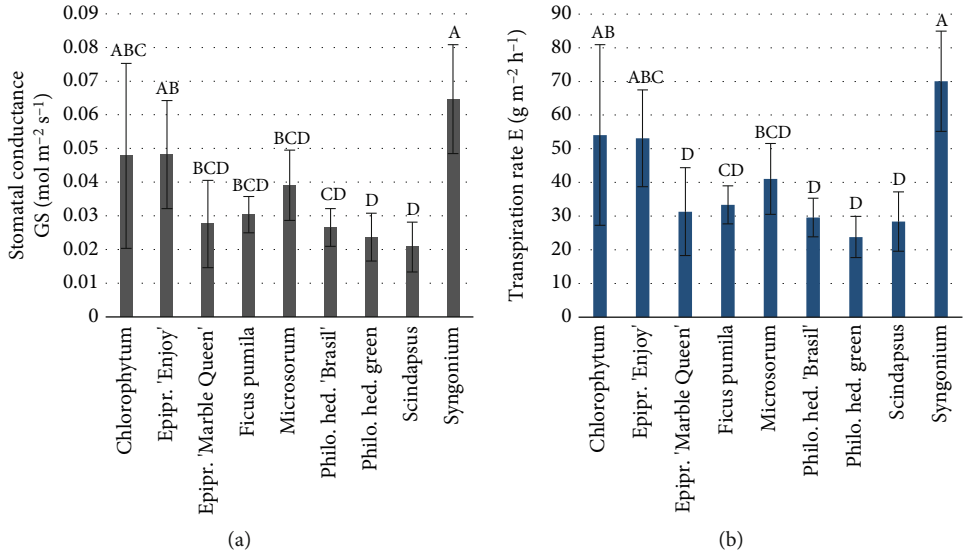


Figure 10: Comparison of (a) stomatal conductance and (b) transpiration rate of different plant species when measured in summer. Mean values (three leaves of three plants each = 9 repl.) that do not have a common grouping letter are significantly different by Tukey's test ($p < 0.05$). (GS: DF = 8; F-value = 9.59; p value < 0.01. E: DF = 8; F-value = 11.64; p value < 0.01).

to separate these two effects by simulating both rooms with the measured temperature data. However, these efforts ultimately proved unsuccessful as the impact of certain factors that were not measured in the experiments, such as air exchange rates with the exterior, had too great an influence compared to the effects to be quantified.

While the cooling effect of the greening systems cannot be precisely quantified in terms of temperature difference, the gravimetrically measured evapotranspiration can be used to calculate the cooling power provided during the times of active illumination from 9 a.m. to 5 p.m.

$$E_{\text{evap}} = m_{\text{evap}} * l_{\text{evap}}, \quad (1)$$

where E_{evap} is the energy evapotranspiration, m_{evap} is the evapotranspirated mass, and l_{evap} is the latent heat of evaporation.

For the rock wool system, the total average cooling energy by evapotranspiration was 0.41 and 0.52 kWh d^{-1} m^{-2} for the fleece system. For comparison, with measurements taken at a close-by location, the average heat energy delivered to the measurement rooms by solar irradiation during the same timeframes was calculated to be 3.6 and 6.3 kWh for the rock wool and fleece systems, respectively.

4. Discussion

4.1. Measurement of Photosynthesis Parameters in a Phytochamber

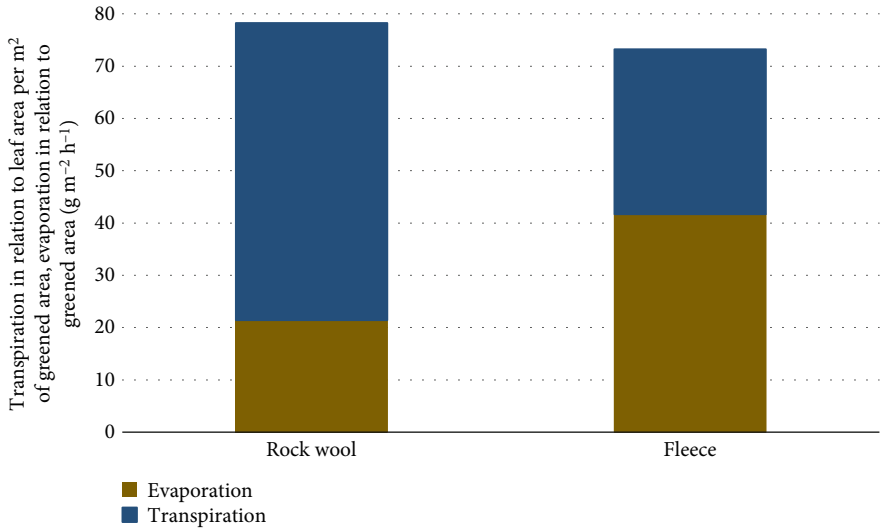


Figure 11: Comparison of the transpiration rate of *Philodendron hederaceum* 'Brasil' in relation to the leaf area per square meter of greened area at 45% RH and 90 μmol m^{-2} s^{-1} PAR with the evaporation rate of the greening system growing media.

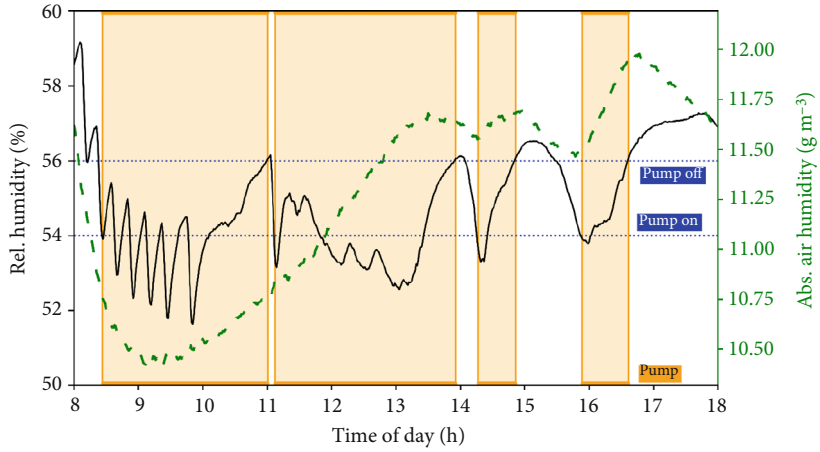


Figure 12: Fine control of humidity levels via the evaporation surface. Shown are the relative (solid line) and absolute (dashed line) humidity levels, as well as the active periods of the evaporation surface (marked areas). The control boundaries for the pump of the evaporation surface are shown as dotted lines.

4.1.1. Light (Photosynthetically Active Radiation = PAR in μmol m^{-2} s^{-1}). According to Damour et al. [31] light intensity is the most fluctuating factor that modulates stomatal aperture, and they refer to a nonlinear asymptotic relationship between stomatal conductance and light intensity.

In indoor greening, minimum light intensities of around 20 μmol m^{-2} s^{-1} are aimed for in order to ensure maintenance growth. In contrast, the given 260 μmol m^{-2} s^{-1} correspond approximately to the lower limit for growth conditions of Araceae in production [32].

However, the low light intensity of 40 μmol m^{-2} s^{-1} did not lead to optimal transpiration performance in *Philodendron hederaceum* 'Brasil' or in the green form *of Philodendron hederaceum*, *Microsorum diversifolium*, and *Syngonium podophyllum*, respectively. This is in accordance with findings of Gubb et al. [33] who report for most of their investigated potted ornamentals that increasing indoor light levels up to 300 μmol m^{-2} s^{-1} has a significant impact on CO_2 assimilation and results in an increase of relative humidity. On the other hand, lower light compensation points being in the typical indoor light range were observed for *Spathiphyllum wallisii* 'Verdi' and *Hedera helix* [33].

Optimal for use in rooms with low light intensity are those species that showed no significant differences in stomatal conductance and transpiration rate as a function of light intensity and thus can maintain a high performance even at low light intensities. This was the case for *Ficus pumila*, *Chlorophytum comosum*, *Pellionia repens*, *Epipremnum aureum* 'Enjoy', *Scindapsus pictus*, and *Tradescantia zebrina*, respectively. Hence, in terms of transpiration, increased energy input for lighting had no benefit using these species. Wu et al. [34] also report for *Epipremnum aureum* that the

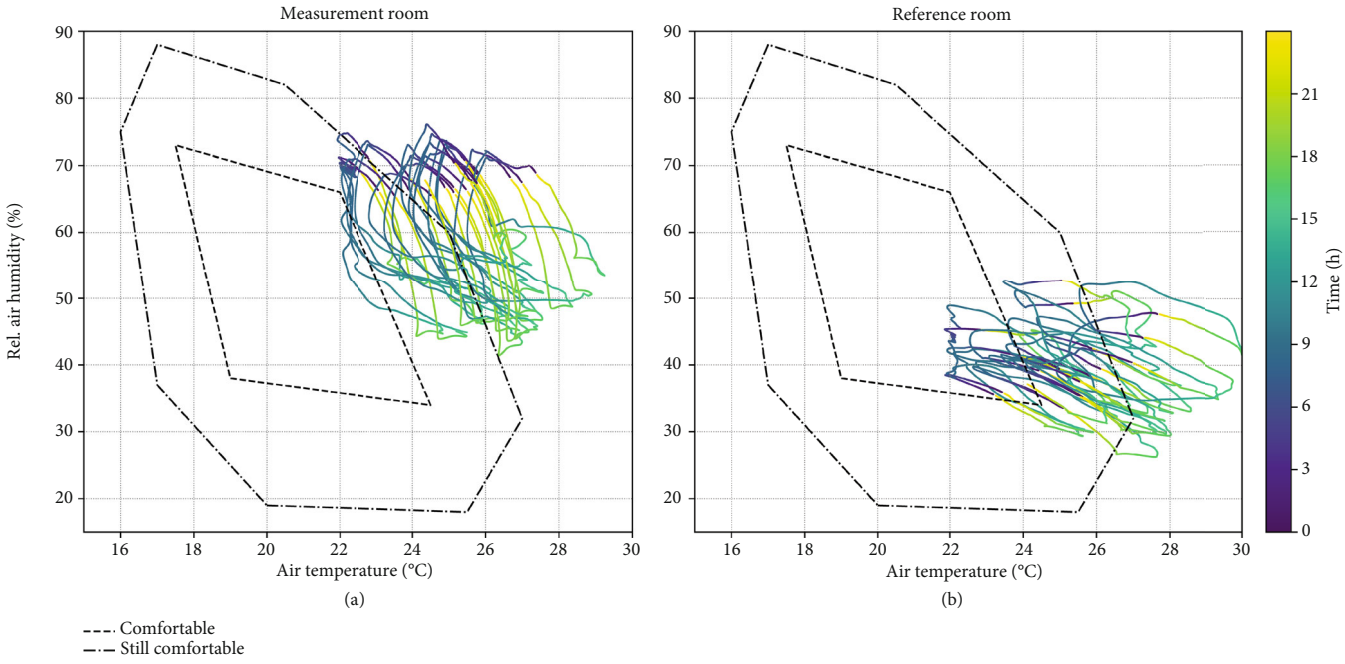


Figure 13: Comfort levels (a) with and (b) without vertical greening rock wool system, measured over a period of 18 days during May 2022. All values were smoothed with a Gaussian filter ($\sigma = 10$ min).

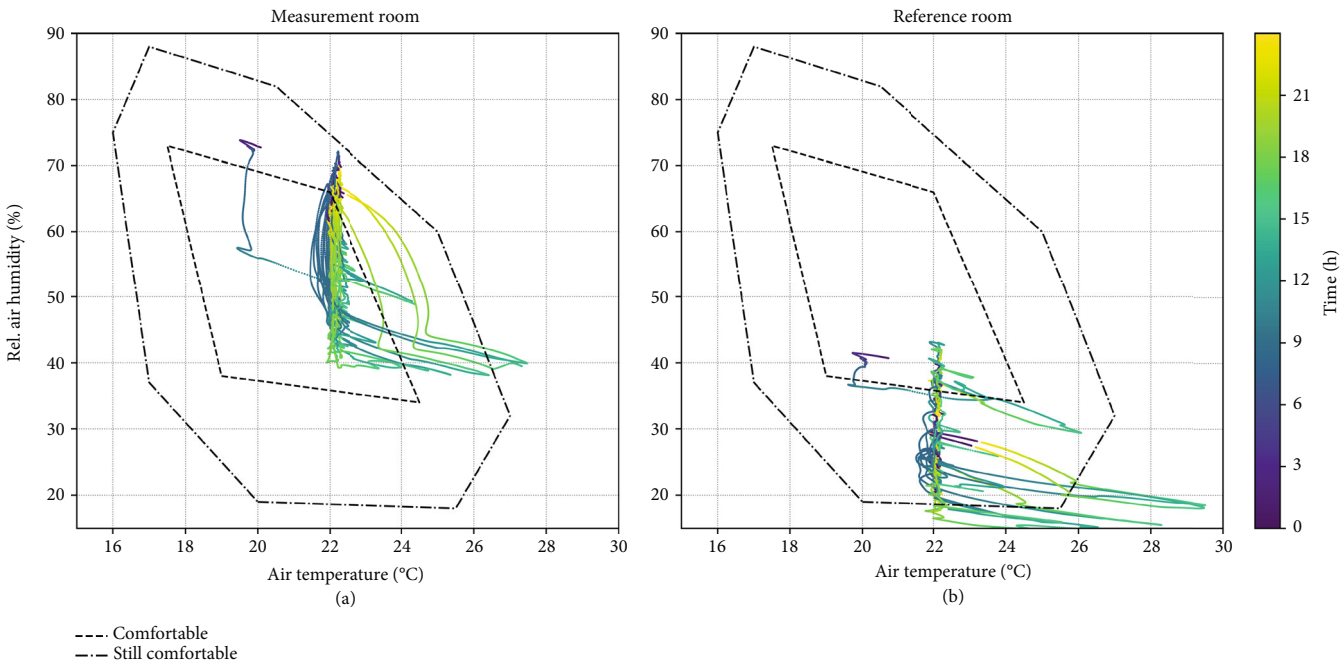


Figure 14: Comfort levels (a) with and (b) without vertical greening fleece system, measured over a period of 18 days during February and March 2023. All values were smoothed with a Gaussian filter ($\sigma = 10$ min).

transpiration rate in the PAR range of 50–200 μmol m^{-2} s^{-1} was not affected by light intensity, with transpiration rates of a similar order of magnitude as reported here.

In comparison, for *Philodendron hederaceum* 'Brasil' as well as in the green form of *Philodendron hederaceum*, *Microsorum diversifolium*, and *Syngonium podophyllum*, an increase in light intensity at low humidity of 15% had a stronger promoting effect on stomatal conductance and transpiration rate. At a higher humidity of 45%, no significant increase in transpiration could be achieved by increasing the light intensity.

These findings indicate distinct differences between plant species' response to increased light intensities and

TABLE 2: Relative amount of time spent in the comfortable, still comfortable, and uncomfortable parameter ranges for the measurement room with the rock wool greening system and the reference room over a period of 18 days during May 2022. Values for only the time periods between 09:00 and 17:00 are listed separately.

	Rock wool system	Comfortable (%)	Still comfortable (%)	Uncomfortable (%)
Total time	Measurement room	1.60	28.0	70.5
	Reference room	21.0	52.9	26.1
09:00–17:00	Measurement room	3.65	39.6	56.7
	Reference room	10.4	49.7	40.0

TABLE 3: Relative amount of time spent in the comfortable, still comfortable, and uncomfortable parameter ranges for the measurement room with the fleece greening system and the reference room over a period of 18 days during February and March 2023. Values for only the time periods between 09:00 and 17:00 are listed separately.

	Fleece system	Comfortable (%)	Still comfortable (%)	Uncomfortable (%)
Total time	Measurement room	63.7	34.9	1.41
	Reference room	16.9	74.2	8.86
09:00–17:00	Measurement room	84.1	11.7	4.23
	Reference room	15.8	63.8	20.4

hence their suitability to increase relative humidity under office conditions as discussed in the plant species section below.

4.1.2. Relative Humidity. Most of the plant species examined showed no reaction of the transpiration rate to the relative humidity in the measuring cuvette. In contrast, the stomatal conductivity reacted more sensitively to the reduced humidity. When assessing these results, it should be taken into account that only the relative humidity in the measuring cuvette was set during the measurements. Room air humidity could not be set, but may have had an influence on the physiology of the entire plant.

The question of whether there are plants that keep their stomata open at low air humidity (office conditions) and thus maintain a high transpiration rate must therefore be answered in a differentiated manner, as the stomatal opening of the species studied appears to react more sensitively to the reduced air humidity than the transpiration rate.

One possible explanation for this observation might be the following: With low relative humidity, stomatal conductance is reduced, but transpiration stays high because of the increasing leaf-to-air vapor pressure deficit, which results in a faster water conduct through the smaller pore and thus maintains transpiration in spite of reduced stomatal conductance. This suggestion can be supported by the findings of Gomes et al. [35] and El-Sharkawy et al. [36] showing stomata closure as a response to an increase in the leaf-to-air vapor pressure difference and of Damour et al. [31] reporting that stomata also close with decreasing air humidity in accordance with their role in water loss regulation. However, Monteith [37] concluded that stomata respond to the rate of transpiration rather than to humidity per se. Jalakas et al. [38] indicate an increase in vapor pressure deficit to cause high transpiration followed by stomatal closure to reduce excessive water loss.

4.1.3. Temperature. Whereas according to Li et al. [39], leaf temperature had no significant effect on stomatal conductance, Damour et al. [31] found more or less linear or optimum curves representing the response of stomatal conductance to temperature. Hence, the observed decrease of stomatal conductance and transpiration with increasing temperature from 18°C to 26°C might be the decreasing branch of the optimum curve for *Philodendron hederaceum* and *Ficus pumila*, indicating best transpiration performance at 18°C.

4.1.4. Season and Growing Medium Moisture. In winter, with reduced photosynthetic activity, transpiration rates became negligible. A significant reduction in the evaporation rate in winter compared to summer is also reported for *Ficus benjamina* and *Epipremnum aureum*, for example [40]. Hence, the expected contribution of the plants to the evapotranspiration of the greening systems was significantly lower in winter than in summer and counteracts the higher humidification requirements of the rooms in winter.

No influence of growing media moisture on stomatal conductance and transpiration rate was found in the here reported trials, which is in accordance with the findings of Gubb et al. [33]. They report negligible differences in net CO_2 assimilation between dry or wet conditions of potted ornamentals. In contrast, Damour et al. [31] describe a coupling between the availability of soil water and transpiration, whereas stomatal conductance remains independent of soil water content until it is very dry. It is possible that the drying time selected in the reported experiments and thus the degree of drying achieved was not sufficient to have an effect on the stomatal opening and transpiration rate.

4.1.5. Plant Species. There is little information in the literature on transpiration rates of tropical ornamental plants. For example, Yungstein and Helman [11] report transpiration

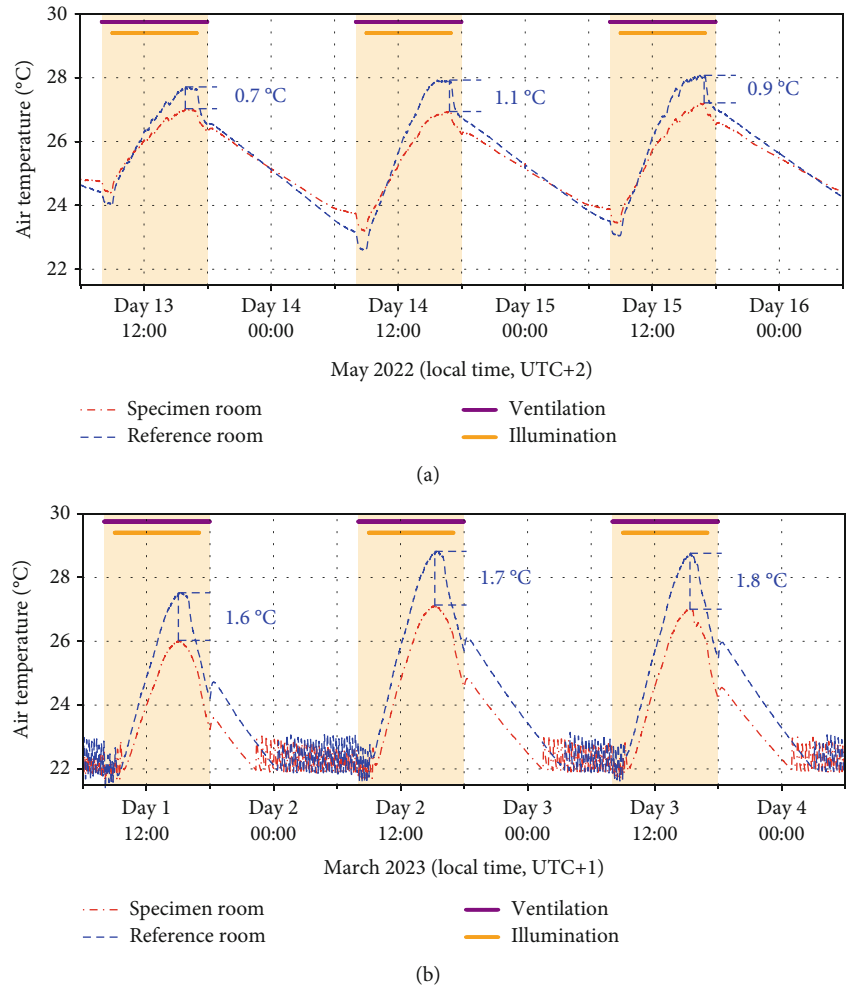


Figure 15: Measured air temperatures for the (a) rock wool and (b) fleece system from a 3-day period in May 2022 and March 2023, respectively. Marked are the periods between 8:00 and 18:00 where the ventilation was active and the periods of additional illumination. The differences in the daytime extrema, defined by the plant lamp schedule, are marked for comparison between the reference and specimen rooms.

rates of *Chlorophytum comosum* and *Philodendron hederaceum*. Their referred values of 0.03–0.38 mmol $m^{-2} s^{-1}$ for *Chlorophytum comosum* are slightly lower than the here measured values of, on average, 0.8 mmol $m^{-2} s^{-1}$ (= 54 g $m^{-2} h^{-1}$ in Figure 10). For *Philodendron hederaceum*, Yungstein and Helman [11] measured almost no transpiration (−0.18 to 0.05 mmol $m^{-2} s^{-1}$) in contrast to the here reported findings of a transpiration rate in the range of other species, that is, 0.37–0.46 mmol $m^{-2} s^{-1}$ (= 24–30 g $m^{-2} h^{-1}$ in Figure 10 for *P. h.* 'green' and *P. h.* 'Brasil', respectively). For *Epipremnum aureum*, transpiration rates of 0.3–1.6 mmol $m^{-2} s^{-1}$ are reported by Wu et al. [34]. This is slightly higher than the measured values of 0.5–0.8 mmol $m^{-2} s^{-1}$ (= 31–53 g $m^{-2} h^{-1}$ in Figure 10 for *Epipremnum* 'Marble Queen' and 'Enjoy', respectively).

In a comparison of the species, *Chlorophytum comosum* and *Epipremnum aureum* 'Enjoy' have high stomatal conductance and transpiration rates that are less affected by low light intensities and humidity levels. At first glance, these species seem particularly suitable for increasing the humidity in a room, but neither species is well suited for growing in vertical greenings.

Jeong et al. [41] report on a comparison of 27 species, including *Epipremnum aureum*, *Syngonium podophyllum*, and *Chlorophytum comosum*. They observe large differences between the species in increasing relative humidity (5%–30%) due to transpiration in a closed chamber. They link the differences in transpiration rates to the morphology of the plants and assume that plant species with thicker leaves have a higher transpiration rate.

Further research is therefore needed to systematically record the reasons for higher transpiration rates of tropical ornamental plants. Morphological and physiological differences as well as room climate and horticultural practices should be taken into account in this research. Recommendations can then be made for plant species that are particularly suitable for increasing humidity under indoor conditions.

4.2. Measurements of Vertical Greening Systems in Measuring Rooms

4.2.1. Evapotranspiration. In a study of the University of Seville [9], an average of 4°C lower temperatures as well as 15% higher relative air humidity near the studied vertical greenings are stated. Investigating a greening wall (as part of an HVAC system) by measuring air parameters before and after passing over the greening wall, a temperature decrease of 2°C–2.5°C and an increase in relative humidity by 1%–7% are reported by Purdue University [42].

The increases in relative humidity found in the experiments reported in this study were even greater, up to 20% and more. However, this discrepancy shows why an increase in relative air humidity on its own is not a good parameter for quantifying evapotranspiration or comparing it across studies, as it is highly dependent on other factors such as room size, occupation, air exchange rates, and size of the greening wall. Instead, the gravimetrically determined evapotranspiration rate gives an accurate measure of how much water is released, allowing the calculation of the increase in air humidity according to the individual parameters mentioned before for any given application. Nevertheless, other studies using gravimetrically determined evapotranspiration rates of indoor greenings are not available for the discussion.

When comparing against other systems such as electric humidifiers, which depending on size can reach evaporation rates of $1000\,g\,h^{-1}$, it is clear that the greening walls rates of $60–100\,g\,h^{-1}$ are lower. However, these maximum evaporation rates come at the price of high power consumption in the range of 60 W and more, which results in energy costs accordingly, whereas the greening walls have almost no power consumption outside of the weekly or daily water pump activation, given that natural lighting is available and sufficient.

4.2.2. Contribution of Transpiration to Evapotranspiration. The higher evaporation of the fleece system compared to the rock wool system can be explained by the wetter growing medium. On the one hand, this system was watered much more frequently (three times a day) than the rock wool system, which was only watered every 10–14 days. Secondly, the fleece material was not covered by a film and was therefore able to evaporate water freely. Despite the perforation of the HDPE foil on the rock wool system, evaporation was limited compared to the fleece system.

Due to interim problems with a root fungus infestation, the plants had not developed as well on the fleece system as on the rock wool system, which was also expressed in a lower number of leaves per square meter and therefore a smaller leaf area per square meter. This explained the lower transpiration rate of the fleece system compared to the rock wool system.

Despite the different proportions of evaporation and transpiration, the total evapotranspiration of $1\,m^2$ of vegetated area was only slightly different for the two systems studied. It can be assumed that evapotranspiration could have been significantly increased in the fleece system if plant development had been as good as in the rock wool system, and thus the transpiration rate was at the same level as there.

4.2.3. Humidity Control. While a good control over the relative humidity could be demonstrated with the technical evaporation area, the evaporation rate of the device itself was rather low in comparison to the evapotranspiration rates of the vertical greening systems. This is well explained by the lacking hydrophilic property of the glass surface, despite its coating. However, since the evapotranspiration rates of the greening walls were sufficient, the combined effect of both systems was able to provide the necessary humidity.

4.2.4. Cooling Effect. In this study, it was possible to calculate a cooling power due to the evapotranspiration that was measured gravimetrically. Despite the results of previous studies suggesting that a fairly significant cooling effect could be achieved with such a setup, it was found that the absolute cooling capacity from evapotranspiration is rather low compared to the potential heating from solar radiation and not sufficient to cool an entire room by several degrees Celsius. However, it was also observed that the thermal mass of the system, with its main contributor being the large amount of water in the tanks used for irrigating the plants, played a rather significant role in the total cooling effect of the greening system. Although the contribution of these two effects could not be precisely separated, it was shown that their combination led to more significant cooling than evapotranspiration alone. Even in the case where only the evapotranspiration is considered, a significant energy saving can be achieved in the cooling demands, as the cooling effect generated by this evapotranspiration in the range of 0.41 and $0.52\,kWh\,d^{-1}\,m^{-2}$ still is a significant contribution to cooling requirements, requiring little energy once the system is in place. Still, for most cases, additional cooling by conventional methods seems necessary to maintain thermal comfort levels.

Airflow provisions in buildings are largely determined by the cooling and humidification demands of individual rooms. Accurately calculating specific airflow requirements depends on numerous variables, such as outdoor humidity, occupancy levels, the sizes of the greening walls, and internal heating rates. As the simulations required for such detailed calculations are beyond the scope of this study, they were not conducted. Nevertheless, it is evident that the cooling and humidifying effects provided by the greening walls would, under many conditions, contribute to a reduction in the required airflow provision.

4.2.5. Physiological Comfort. In regard to the effect of the vertical greenings on physiological comfort levels, the parallel room measurements illustrated the strengths as well as the weaknesses of such a system with greening walls. The system alone was not able to keep a room in comfortable room parameter ranges during warmer days, mainly due to the lack of cooling capabilities. This is in accordance with previous studies that suggested that indoor living walls could create energy savings, but would not be sufficient to cool a room on their own in hot environments [11]. A dedicated temperature control system seems necessary for temperatures to stay comfortable during the warmer months, due to the limited cooling power

provided. For future studies concerning the cooling effect of vertical greenings on indoor climate, it would be recommended to have a similar thermal mass in the reference room in order to better quantify the effect of the evapotranspiration alone on room temperatures.

During winter, when the effect of cold outside air being heated and thereby having low humidity comes into play, it becomes evident that the system is capable of ensuring comfortable indoor climatic conditions. This is achieved by the high evapotranspiration rates that significantly increase relative humidity levels, even taking into account the relatively lower transpiration rates of the plants during winter. This is in contrast to previous studies such as from Berger et al. [40], who investigated the impact of plants on indoor climate and concluded that there is only a fairly small impact. This discrepancy is due to the greening walls used in our present study achieving a much higher evapotranspiration rate than individual plants, such as the one used by Berger et al. could achieve and matches the expectation provided by Gubb et al. [33] that plants in excess of 10 per room can raise indoor humidity significantly.

At night, when the ventilation to the outside was switched off in the measurement rooms, the humidity levels even rose above comfortable values for both greening systems. This underlines the need to coordinate the effect of vertical greening with the existing air conditioning systems to ensure that the evapotranspiration caused by the greening does not lead to uncomfortable humidity levels. For this purpose, the evapotranspiration performance of the installed systems should be measured against the air exchange rates of the building.

4.2.6. Use Cases and Scalability of the System. Since the main contribution of a vertical greening to indoor climate is to increase relative humidity rather than cooling, some conclusions can be drawn about the applications for which such a system is most suitable. For example, the comfort zones as seen in the results section of this paper are not perfectly round, but flattened in the warm-humid area, which means that a combination of high humidity and high temperature is not perceived as comfortable. Therefore, indoor greening walls may be better suited to cooler, continental climates where humidity tends to be lower and an increase in humidity does not risk reaching the hot-humid zone.

It is also best suited to buildings such as offices or similar where there is a central air conditioning system that can regulate humidity by adapting ventilation to the outside if it gets too high. In general, the system is easily scalable as it only requires a suitable space and good lighting for the plants and minimal maintenance if set up correctly. Therefore, it can and should be adapted to the individual building size and typical air exchange rates so that the additional moisture from evaporation results in a comfortable humidity level. Theoretically, the number of greening walls could be maximized to increase the cooling effect, but the additional humidity would likely increase so much that air exchange would need to be increased quite a bit, which would likely negate the benefits of increased cooling.

4.3. Outlook for Further Research Needs. The controllability of room air conditioning was demonstrated in the project. However, an accurate and reliable long-term control of the air humidity based on the values of growing media moisture sensors has not yet proven feasible due to the high uncertainty of the measured values, even when using different sensors. Hence, there is a need for further research into the selection and further development of suitable growing media moisture sensors.

Room simulation models could be used to simulate the effects of greening systems in different building designs with variable climatic situations based on the reported values for the humidifying and cooling effect and thus gain further insights into their targeted use. To this end, it could be beneficial to evaluate the impact of evapotranspiration and thermal mass of the system on the observed cooling effect and to collect more data at different seasons and during a more extended measurement period to increase the accuracy of the model results.

For large greening installations, plant monitoring might need to be automated through the use of methods such as PolInSAR or measuring the polarization of light by the plants [43, 44].

The energy and economic benefits of indoor greening have been scarcely examined to date. For this reason, the quantification of energy savings and a cost-benefit analysis are being targeted in a further project. For a holistic view, a life cycle analysis is planned in order to evaluate the efficiency of indoor greening over the entire period, that is, "from cradle to grave."

Additionally, a systemic investigation may be necessary to investigate how a greening system can be incorporated into an energy efficient climate control system that maintains physiological parameters year-round. Specifically, it is to be shown that suitable humidity levels can be sustained even in situations where the relative humidity is naturally high and is increased further by evapotranspiration of the vertical greening system.

5. Conclusions

Transpiration rate and stomatal conductance of 12 tropical ornamentals often used as indoor greenings were characterized. Optimal for use in rooms with low light intensity are those species that maintain a high photosynthesis performance even at low light intensities. This was the case for *Ficus pumila*, *Chlorophytum comosum*, *Pellionia repens*, *Epipremnum aureum* 'Enjoy', *Scindapsus pictus*, and *Tradescantia zebrina*, respectively. Most of the plants examined are capable of maintaining a high transpiration rate even under low relative humidities and therefore are suitable for indoor room conditions.

The indoor rock wool and fleece greening systems as well as an additional evaporation area were examined concerning their performance and limits regarding evapotranspiration and cooling capacity. For the rock wool system, the evapotranspiration rate was measured to be between 65 and $100\,g\,m^{-2}\,h^{-1}$ and for the fleece system between 55 and $90\,g\,m^{-2}\,h^{-1}$ during daytime. The technical evaporation

surface had a lower evaporation rate of 25–28 $g\,m^{-2}\,h^{-1}$ but is easier to regulate. Since the evapotranspiration rates of the greening walls were sufficient, the combination with the technical area was satisfactory to provide the necessary humidity and enabled a good control.

The contribution of the plants to evapotranspiration was more than 50% for the rock wool system and less than 50% for the fleece system. Despite the different proportions of evaporation and transpiration, the total evapotranspiration of 1 m^2 of vegetated area was only slightly different for the two systems.

Relative humidity in the specimen room was increased compared to the humidity in the reference room by the rock wool system as well as by the fleece system, resulting in the comfortable parameter window for most of the measurement period.

The total average cooling energy by evapotranspiration was 0.41 $kWh\,d^{-1}\,m^{-2}$ for the rock wool system and 0.52 $kWh\,d^{-1}\,m^{-2}$ for the fleece system. Nevertheless, the absolute cooling capacity from evapotranspiration of the greening systems was rather low compared to the potential heating from solar radiation. Hence, especially for the summer, additional cooling by conventional methods seems necessary to maintain thermal comfort levels. During winter, with low relative humidity and low heat input due to solar radiation, the greening systems seemed to be capable of ensuring comfortable indoor climatic conditions.

The soil moisture sensors proved to be unreliable due to large variations in soil humidity across the walls. They were therefore not suitable as a basis for developing a control strategy. Hence, further research is needed concerning reliable soil moisture sensors and a control strategy.

Data Availability Statement

The data presented in this study are available on request from the corresponding author, E.W., M.R., or C.W. for the vertical greening system measurements and A.B. for the photosynthesis measurements.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: A.B. and M.R.; formal analysis: A.B., C. W., and E.W.; funding acquisition: A.B., M.R., and S.W.; investigation: A.B. and M.R.; methodology: A.B., M.R., and C.W.; project administration: A.B. and M.R.; visualization: A.B., C.W., and E.W.; writing—original draft: A.B. and E. W.; writing—review and editing: A.B., M.R., C.W., E.W., and S.W.

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