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An experimental investigation of green wall bio-filter towards air temperature and humidity variation

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ABSTRACT

Green walls show promise in providing thermal comfort. Their benefits include the reduction of the temperature of air layers around them. They are classified as passive and active systems. Active systems are designed with ventilators that force air through the substrate and plant rooting system of the green wall. With a passive system, air is simply diffused through the green wall substrate and the plant foliage. The current work investigates the effect of green walls on the air temperature and humidity. Temperature and humidity are measured at different locations inside an acrylic chamber where different modules with different plant species are placed. The effect of changing the surrounding ambient conditions is also investigated. Experiments lasted at least 24 h to cover day and night time conditions. For the active modules, lower temperatures in the range of 1–3 °C, along with increased humidity levels have been observed when modules are saturated wet. Passive modules have also provided lower temperatures in the range of 0.5–2 °C. None of the plant species studied showed any preference, indicating that the moisture content of the substrate plays the major role affecting the temperature and humidity variations.

1. Introduction

The majority of the world's population now lives in cities, and urban areas are expanding faster than any other land-use type [1,2]. Urbanization has been linked with several negative environmental impacts, such as increased air pollution, increased storm water runoff, increased urban heat island effect and reduced biodiversity [3–5]. These impacts also have secondary effects, such as increased physical discomfort and health problems, and a greater demand for building cooling, leading to increased energy consumption [2,6,7]. Consequently, there is a requirement for sustainable practices to be integrated into new and existing developments to mitigate the detrimental effects of urbanization [8]. Green infrastructure integrated into building design is gaining in popularity as a means to not only ameliorate the issues related to urban expansion, but also to avoid the need for re-allocation of scarce land from other urban developments, as is the case with urban forestry or dedicated green space [9]. Research is thus needed to quantify how cities be improved by increasing their vegetation content, particularly in building façades, and to determine whether the use of green wall systems to reduce energy consumption and improve air quality and people's well-being is plausible.

A diverse range of benefits have been associated with green walls, including a reduction in the urban heat island effect [10–12], reductions in building energy consumption [13,14], enhanced air quality [15], and improved storm water management [16]. These benefits notwithstanding, most of the current work to date documenting the benefits of green infrastructure and green walls have been assessed on what is termed 'passive' bio-filtration [17,18]. The use of biological processes to clean contaminated air which is actively forced through a bioactive matrix is referred to as 'active bio-filtration' [17,19,20]. Active botanical systems (Breathing walls) use mechanical or other forms of ventilation to force air through a substrate or planting bed root system, rhizosphere and plant foliage, filtering and purifying the air and acting as a natural cooling system [21–23]. Passive bio-filtration in contrast occurs through the simple diffusion of polluted air to the green wall components, and is the method used in green roofs, potted plants and bio-covers [24]. It is well understood that plants and their associated microorganisms can purify air via passive biological filtration, acting as an air pollutant sink, trapping and converting various pollutants into non-toxic forms [17,25,26], however the efficiency, advantages and disadvantages of active bio-filtration are not yet well understood. Fig. 1 [27,28] shows a planted green wall module, *Schefflera arboricola*.

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Fig. 1. Green wall module with plant species, *Schefflera arboricola.* (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 2. Acrylic-sheets chamber with a green wall module (*Nephrolepis cordifolia*). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The green wall modules used in this study are developed for use both inside buildings and outdoors. The addition of assisted aeration through the plant's growing substrate was made with the primary function of filtering particulate matter and increasing removal of volatile organic compounds (VOCs). Preliminary work has demonstrated the system is capable of substantial reductions of PM_{10}, $PM_{2.5}$ (particulate matter with 10 μm and 2.5 μm in diameter and smaller respectively) [29] and VOCs within an enclosed environment [30]. The removal efficiency for PM_{10} is 53.5 ± 16.0% and is 48.2 ± 14.7% for $PM_{2.5}$ [19]. Breathing walls are able to clean up polluted cities as the filtered air will effectively contain lower concentrations of pollutants and particulate matters than the outdoor air [31]. The filter mechanism of the walls would last throughout the life time of the buildings, providing the energy savings and air filtration for more than 60 years without requiring replacement. The combined biological activities of the plant and substrate have been shown to be capable of reducing many types of urban air pollutants including volatile organic compounds [18], carbon dioxide [32] and particulate matter [29,33,34]. There has been a small number of studies related to VOC removal by green wall systems. Darlington et al. [35] and Wang et al. [36] both detected VOC removal from their green wall systems.

Green walls can produce changes in ambient temperature and humidity of the surrounding air [27,37], thus creating an interesting insulation effect [38,39]. Blanco et al. [40] developed a predictive model for the estimation of the difference of temperature between an uncovered wall and a vegetated wall. Their research concluded that the vegetated walls recorded surface temperatures lower than the uncovered wall up to 7.7 °C in summer time. Perez-Urrestarazu et al. [22] studied the performance of an active living wall on indoor air temperature and humidity, also demonstrating the ability of green walls to contribute to indoor air conditioning [28].

Plants are able to absorb a valuable amount of acoustic energy, with this effect particularly associated with the soil substrate, which is able to absorb up to 80% of acoustic incident energy [41]. Green walls demonstrate equivalent or better acoustic absorption coefficients compared to other common building materials [42], with particular effects on low frequencies. Davis et al. (2017) [43] tested the sound absorption properties of a vertical garden concluding that thicker substrates provide higher sound absorption coefficients in the lower frequencies. A thinner substrate can be used if lower frequencies are not important; in general they found that an 8–10 cm substrate thickness would result in a good sound absorption spectrum. Their study [43] also found that the weighted random incidence and absorption coefficient of modules densely planted with ferns equals 1.00 for mid and high frequencies, and 0.59–0.80 for low frequencies. This makes this type of substrate highly suitable for applications were sound attenuation is needed, paving the way for applying vertical garden systems for improving the acoustics indoor spaces or public areas.

Pressure drop and air flow rate through green wall modules have been obtained in a previous work [28,44], and the air flow distribution has been investigated [28,45] to improve the design of the module and achieve more appropriate flow rate and flow distribution.

The aim of this experimental study is to investigate the effect of green wall modules on the surrounding air temperature and humidity. A closed chamber made of acrylic sheets is used to monitor the temperature and humidity variation caused by a green wall module placed at its center. The effect of both passive green walls and active (breathing) wall modules on temperature and humidity is investigated for different plant species and under varied ambient conditions.

2. Materials and methods

2.1. Active green wall bio-filter design

The green wall modules tested (Fig. 1) were composed of a rectangular plastic box (500 mm × 500 mm x 130 mm) holding a permeable polyethylene bag containing a plant-growing medium composed of coarse (~25 mm particle size) coconut husks and fibre. The front face of the module has 16 openings for plants, which protrude out from the bag inside. Plant roots are imbedded within the medium. A mechanical fan (constant-speed FANTECH TEF-100 16-W in-line axial fan) positioned at a central opening on the module's back-face, drives air through the medium and root system and then outward through the plants' canopy; all of which have functional value in removing both gaseous and particulate pollutants from the air. Drip-irrigation water was dispensed from a tube running along the open top-face of the module, with the excess drained through multiple small drainage holes on its bottom face. All front and rear ventilation openings are circular with diameter 100 mm. Fig. 1 shows a test green wall module.

2.2. Experimental design for active green walls (breathing wall)

A chamber made of 10 mm acrylic sheets is used to monitor the temperature and humidity variations caused by the green wall modules

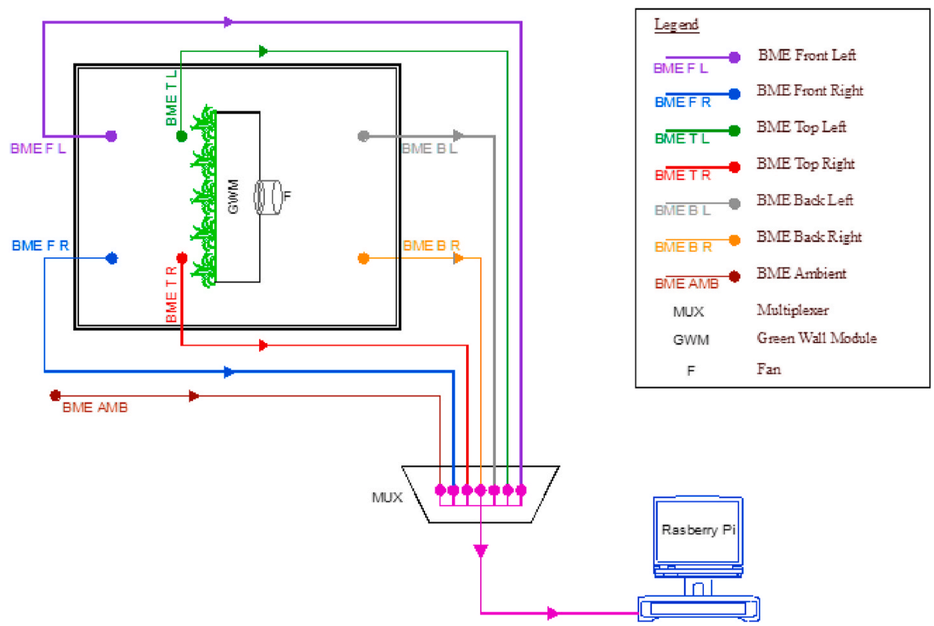

Fig. 3. Two dimensional schematic of the BME sensors location and their connection with the Raspberry Pi through the Multiplexer.

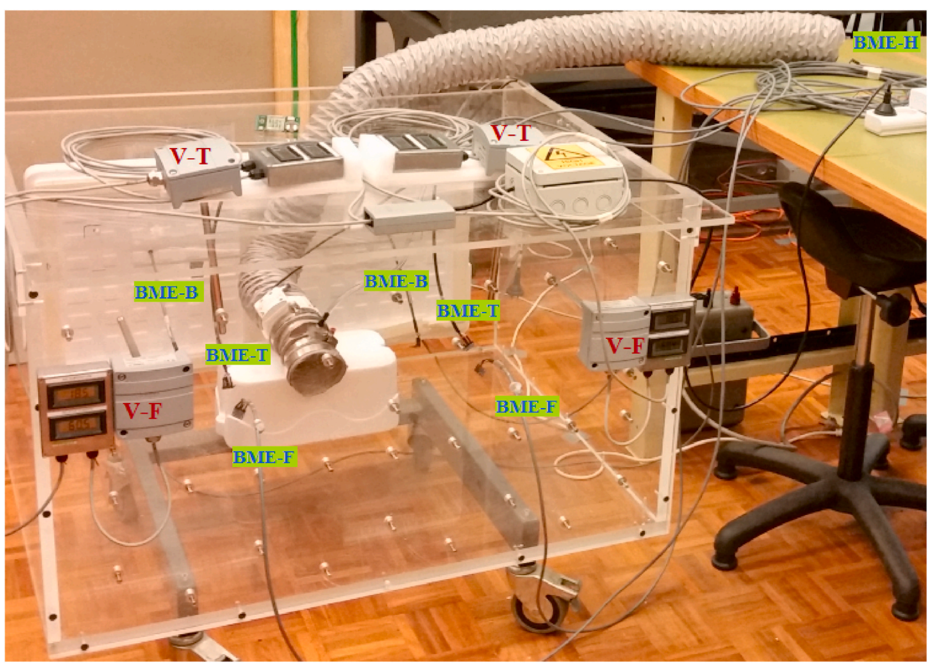

Fig. 4. Set up of the chamber indicating the locations of the sensors used. An opening can be seen on the chamber's top to allow for air circulation and insure no build-up of humidity.

placed at its center. The effect of heat transfer through the acrylic sheets has been considered insignificant in this study and thus ignored; the temperature difference between the internal and external sides of the acrylic sheet was measured to be less than 0.1 °C. The dimensions of the chamber are 960 x 780 × 590 mm^3. These dimensions of the scaled chamber are almost one fifth of those related to an actual room (5000 x 4000 × 3000 mm^3). Fig. 2 [27,37] shows the chamber with a green wall module (*Nephrolepis cordifolia)*.

To monitor temperature and humidity variations six BME280 (Pressure, Temperature and Humidity) sensors were distributed in the chamber, two inserted from the front sheet through 10 mm holes, another two sensors were inserted form the top sheet and placed in front of the module. The last set of BME280 was placed behind the module at the lower right and left corners. A seventh BME280 sensor was used to monitor the ambient conditions in the lab room's air, outside the acrylic chamber. All the BME280 sensors were connected to a multiplexer and then to the computer (Raspberry Pi 2). The software was set to record temporal readings every 15 s and the data was exported to excel. Graphs showing the temperature and humidity measurement for the seven sensors are downloaded from the software as well. During a course of recording, temperature and humidity fluctuating temporal readings varied by less than 3% about an average value. Fig. 3 shows a two dimensional schematic of the BME sensors' locations and their connection with the Raspberry Pi through the multiplexer.

In addition, four Vaisala (Humidity and Temperature) sensors have been used to digitally record measurements of both temperature and

Table 1
Plant species used in this experiment.

Species name	Common name	Image
Nematanthus glabra	Goldfish plant	
Schefflera arboricola	Dwarf umbrella tree	
Nephropelis exaltata bostoniensis	Boston fern	
Nephrolepis cordifolia	Lemon button fern	

humidity. Two of these sensors are inserted into the chamber from the front sheet through 10 mm holes and the other two are placed on the top cover sheet and are at a closer proximity to the module as shown in Fig. 2. Readings of the Vaisala sensors were recorded manually and compared to the reading recorded by the BME280 sensors; the difference between the two kinds of sensors varied by less than 2%.

All experiments lasted at least 24 h to cover day and night time conditions. During the day, the temperature was controlled by air-conditioning, which was shut down during the night. This allowed for different ambient conditions in the lab, daytime and nighttime. The lights were on at all times in the lab. The air flow due to the air conditioning outside of the chamber was insignificant throughout the lab.

All modules were tested under the active mode with the fan pushing air at ambient conditions through a 100 mm duct into the module. During operation the lid of the chamber remained slightly open to insure no buildup of humidity and to provide proper circulation of air. This small opening can be seen in Fig. 4 on the chamber's top. This opening was used only during the active mode, since without it the humidity inside the chamber would reach 100% within minutes of operation as demonstrated by initial experiments. The presence of the opening may affect the measurements taken especially for humidity, however its effect on the temperature readings is considered insignificant especially at a distance close to the module. Real installations of green walls would take place in large open areas, rather than limited sized rooms, which may justify the use of the opening in our case.

Fig. 4 [27] shows the setup, but without the module in place in order to provide a clear representation of the locations of sensors. There are two BME-T, two BME-F and two BME-B sensors, each pair has one sensor on the right side and another sensor on the left side of the chamber. During the active mode, the BME sensor to monitor ambient conditions was placed outside of the acrylic chamber at the inlet of the duct connected to the fan; its location is indicated by BME-H at the top right corner of Fig. 4. The Vaisala sensors are indicated by V–F and V-T on their grey case which holds a stainless steel probe, connected to an electronic box with a screen for digital recordings.

The study has assessed four plant species shown in Table 1 [27,37], these species grow well in the vertical alignment which the present bio-filter module uses and they are widely used by the vertical gardening industry. These plants have been grown in a glass house for more than a year; they were all well grown and full of foliage. The modules were irrigated with sufficient water (approximately 4 L) to saturate them 24 h before the experiments were conducted. The differences in the moisture

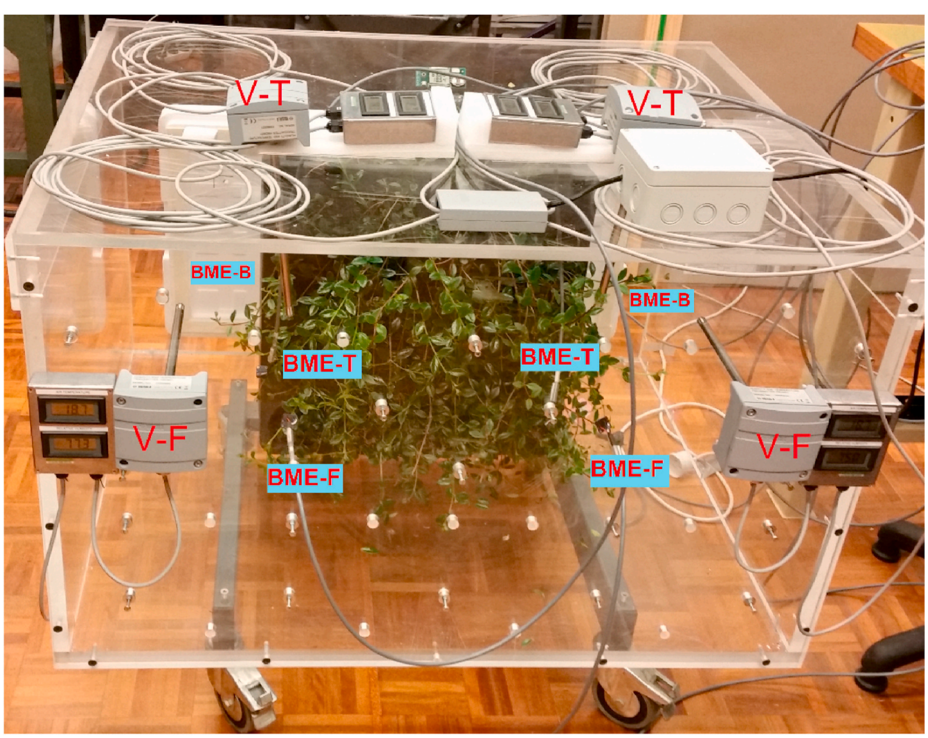

Fig. 5. Set up of the chamber during passive mode indicating the locations of the sensors used.

Table 2
Average temperature values recorded by BME sensors for different plant species.

Plant type	Time	Temperature (°C)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Nematanthus glabra	Day	17.8	17.5	16.7	16.7	17.1	17.0	18.2	17.2
	Night	21.4	21.1	20.0	20.2	20.3	20.3	22.8	20.5
Schefflera arboricola	Day	16.9	16.4	16.8	16.1	16.6	16.5	18.3	16.5
	Night	20.3	20.2	20.1	19.7	20.0	19.9	22.3	20.0
Nephropelis exaltata bostoniensis	Day	17.0	16.4	16.8	16.8	17.2	17.1	18.2	16.9
	Night	19.8	19.3	19.6	19.6	19.8	19.7	22.6	19.6
Nephrolepis cordifolia	Day	17.7	15.8	17.4	17.1	17.3	16.7	18.6	17.0
	Night	20.5	18.4	20.1	19.7	19.7	19.3	22.2	19.6

Table 3
Average humidity values recorded by BME sensors for different plant species.

Plant type	Time	Humidity (%)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Nematanthus glabra	Day	76.1	71.6	82.9	87.4	85.2	80.8	62.3	80.7
	Night	82.9	80.3	91.5	97.8	92.6	89.4	65.7	89.1
Schefflera arboricola	Day	83.6	82.3	82.1	95.9	89.7	88.5	62.9	87.0
	Night	94.3	90.2	93.4	99.0	96.5	96.6	72.0	95.0
Nephropelis exaltata bostoniensis	Day	92.6	88.8	91.9	94.9	90.7	90.4	63.4	91.5
	Night	97.4	95.3	97.0	99.0	96.1	96.5	68.7	96.9
Nephrolepis cordifolia	Day	81.2	93.1	81.5	92.3	87.7	90.1	64.4	87.7
	Night	85.9	96.1	86.4	99.2	92.6	95.0	67.6	92.5

content between the different modules at the time of the experiment have been considered insignificant.

In addition, one unplanted module with growing medium only was tested. This unplanted module was experimented dry first in its initial condition, and then experimented saturated wet after irrigation 24 h before the experiment.

Pressure difference across the module has been measured using a Sensirion digital-sensor SDP610 – 125Pa. It is 0.1-Pa accurate for low differential air-pressure up to 125 Pa. Values have been recorded every second and the average value was then calculated from a data logger. When air exits from the module, it exits to the ambient. Thus readings from the digital sensor for (gauge) pressure at the module's back-opening are also the pressure difference across the module. During a course of recording which typically lasts several minutes, pressure readings varied by less than 10% about an average value [44].

2.3. Experimental design for passive green walls

The setup of the experiment using the passive modules was very similar to the setup used for the active ones. As the passive green walls modules do not utilize a fan for operation, during the time of the experiment the lid of the chamber remained closed. To ensure no excessive buildup of humidity some openings of 10 mm diameter were kept open. Fig. 5 [37] shows the setup, with a tested green wall module (*Nematanthus glabra*) inside the chamber. The locations of the inside BME sensors are indicated by BME-T, BME-F and BME-B. The BME sensor to monitor ambient conditions was placed outside of the acrylic chamber, on a nearby table at the top right corner of Fig. 5. The Vaisala sensors are indicated by V–F and V-T on their grey case.

Under the passive mode the study has assessed three plant species shown in Table 1 (*Nematanthus glabra, Schefflera arboricola,* and *Nephrolepis cordifolia*). The modules were irrigated with sufficient water to saturate them 24 h before the experiments were conducted.

3. Results and discussion

For the plant species studied, time-dependent temperature and humidity inside the acrylic chamber have been monitored and recorded. Similarly, the ambient conditions (temperature and humidity) were also recorded. Experiments were held during day time and during night time. Various averages have also been obtained such as the averages from all sensors inside the acrylic chamber at any particular time and the average from a particular sensor over a time period (day or night). Comparisons have been made especially between averages of the ambient and inside the chamber.

Readings of the Vaisala sensors were recorded manually and compared to the readings recorded by the BME280 sensors for both temperature and humidity, the values compared varied by less than 2%.

3.1. Results for active green walls (breathing wall)

The ambient temperature during day time was approximately 18–18.5 °C while at night it was approximately 21.5–22.5 °C. The ambient humidity during the day was approximately 62–65% while during the night it was 65–70%.

Table 2 [27] shows the average temperature values recorded by the BME sensors during the day and night time; refer to Fig. 3 for the location of the sensors inside the chamber. The average of the six sensors was also obtained and shown in Table 2 to indicate the temperature of the chamber. All of the sensors recorded lower temperatures than the ambient temperature and the average difference was in the range of 1–1.5 °C during the day and in the range of 2.5–3 °C during the night.

Table 3 [27] shows the average humidity values recorded by the BME sensors during the day and night time. The average of the six sensors was also obtained and shown in Table 3 to indicate the average humidity inside the chamber.

All of the sensors has recorded higher humidity readings compared to the ambient and the average difference was approximately 25% during both day and night times. Higher humidity level has been expected due to the moisture content of the substrate, which has been saturated 24 h before the experiments. It is noted that none of the plant species had any preference except for some slight differences in the temperature and humidity, which is probably due to the different moisture content of the substrate. In most of the cases, the sensors closest to the mod-

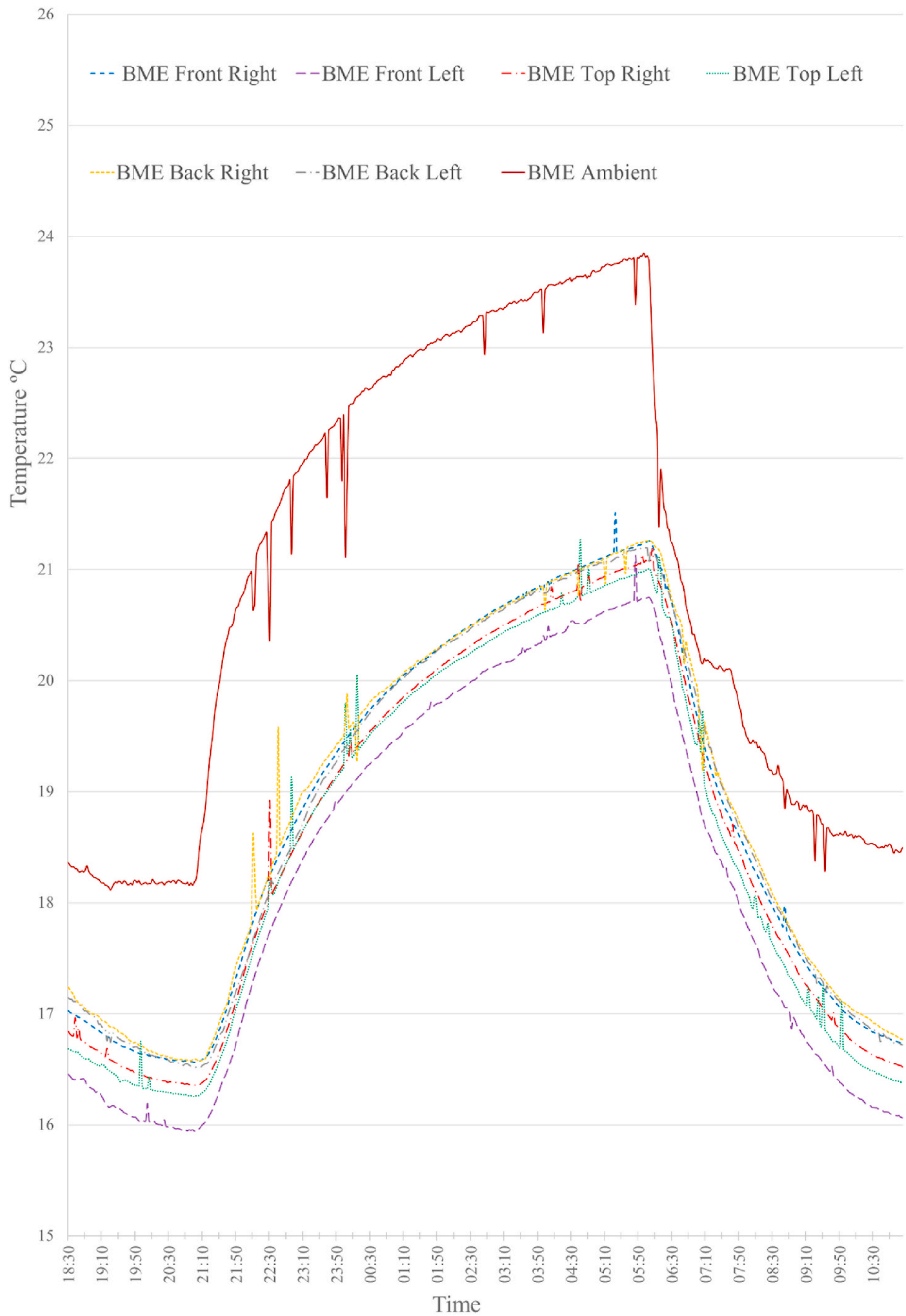

Fig. 6. Graph showing temperature readings for Nephropelis exaltata bostoniensis between 6:30 p.m. and 11:00 a.m. The highest trace is the ambient temperature; the other lower traces are from sensors inside the acrylic chamber.

Table 4
Average temperature values recorded by BME sensors for unplanted module.

Module Type	Time	Temperature (°C)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Dry Unplanted	Day	18.4	17.8	18.2	18.6	18.6	18.3	18.1	18.3
	Night	21.0	20.8	20.8	21.3	20.6	20.5	21.6	20.8
Wet Unplanted	Day	17.4	16.4	16.0	16.1	16.8	16.4	17.8	16.5
	Night	20.4	19.5	19.1	19.4	19.8	19.4	21.7	19.6

ule (BME-T), has recorded higher humidity levels compared to other sensors.

Fig. 6 shows the graph of the time-dependent temperatures for *Nephropelis exaltata bostoniensis* between 6:30 p.m. till 11:00 a.m. next

Table 5
Average humidity values recorded by BME sensors for unplanted module.

Module Type	Time	Humidity (%)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Dry Unplanted	Day	69.1	69.4	68.3	68.7	68.8	67.7	63.7	68.7
	Night	81.7	78.5	80.5	80.7	84.1	81.7	70.2	81.2
Wet Unplanted	Day	82.0	84.5	91.2	99.2	89.4	90.4	68.9	89.5
	Night	87.8	90.9	96.1	99.0	94.3	95.4	70.9	93.9

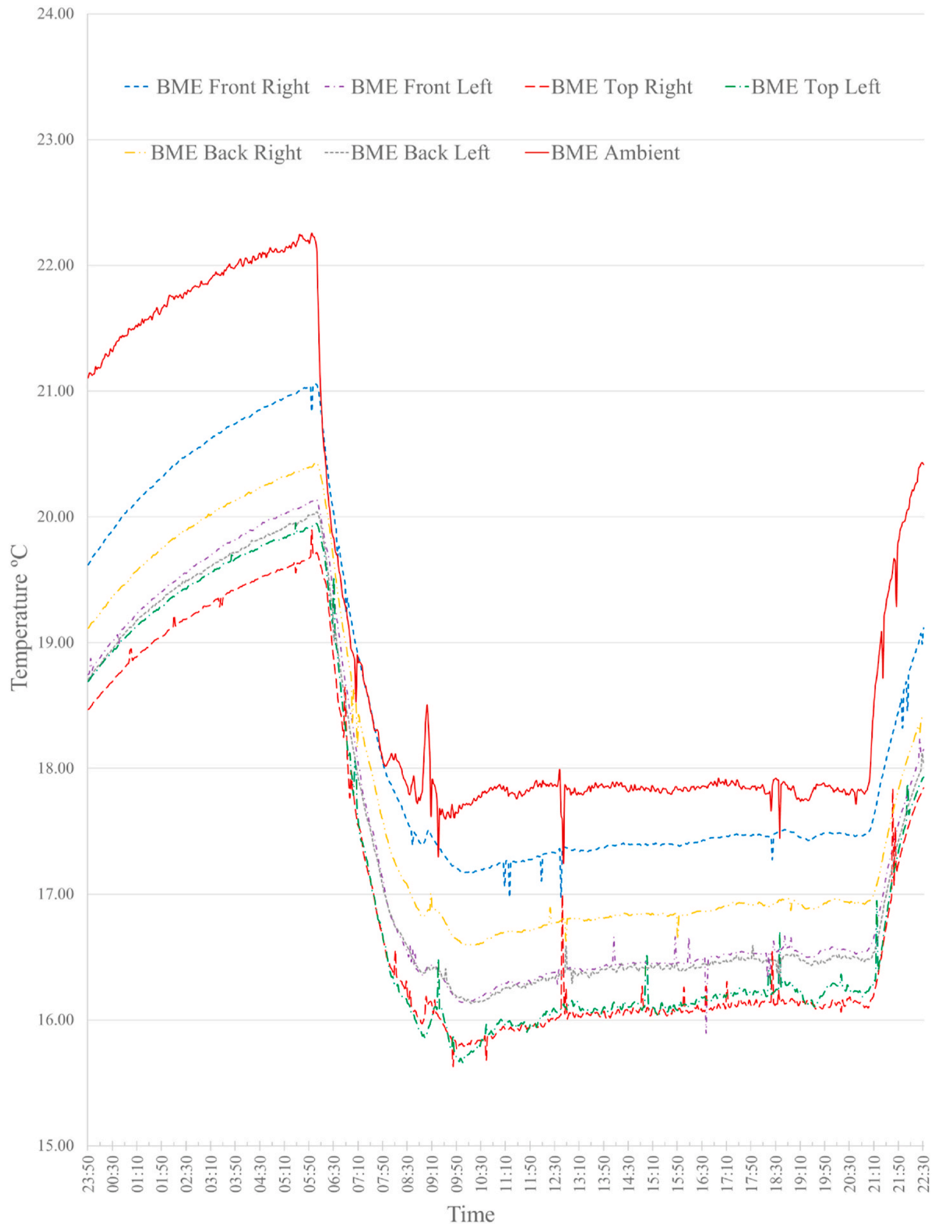

Fig. 7. Graph showing temperature readings for the unplanted module between midnight and 10:00 p.m. The highest trace is the ambient temperature; the other lower traces are the temperatures from sensors inside the chamber.

day. As mentioned the difference is approximately 3 °C during night time between the ambient temperature (higher) and the temperature inside the chamber while this difference is about 1 °C during the day.

As for the unplanted module with growing medium only, it was tested dry and then saturated wet. When dry there was no significant change recorded in temperature as it only differed by less than 1 °C during the night and by less than 0.5 °C during the day. Humidity variation was also low, about 5% during the day and 10% during the night. When saturated wet, the variation in temperature and humidity has been similar to the other modules with plant species. This indicates that the moisture content plays a major role in the temperature and humidity variations and that the transpiration of the different plant species do not have a significant role. Tables 4 and 5 [27] show the average temperature and humidity recorded by the BME sensors for the unplanted module when dry and when saturated wet. The temperature and hu-

Table 6
Pressure difference across the modules and corresponding total air flow rate.

Module Type	Pressure Difference (Pa)	Total Flow Rate (L/s)
Nematanthus glabra	23.8	16.0
Schefflera arboricola	25.7	15.3
Nephropelis exaltata bostoniensis	35.3	12.8
Nephrolepis cordifolia	28.2	14.5
Dry Unplanted	20.1	9.1
Wet Unplanted	24.5	15.8

midity variations are primarily due to the evaporation of the water available in the module's substrate during operation.

Fig. 7 shows the graph of the temperatures for the unplanted module when saturated wet from midnight till 10:00 p.m. The difference is approximately 1.5 °C during day time between the ambient temperature (higher) and the temperature inside the chamber, while this difference is about 2 °C during the night.

The results obtained agree with the results concluded by Perez-Urrestarazu et al. [22] who also studied the performance of an active living wall on indoor air temperature and humidity. Their work has

Table 7
Average temperature values recorded by BME sensors for different plant species.

Plant type	Time	Temperature (°C)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Nematanthus glabra	Day	18.6	18.3	18.4	18.3	18.8	18.7	19.1	18.5
	Night	20.9	20.6	20.5	20.5	20.7	20.4	22.2	20.6
Schefflera arboricola	Day	16.9	16.4	16.8	16.0	16.6	16.5	18.3	16.5
	Night	20.7	20.5	20.5	20.5	20.2	20.0	22.5	20.4
Nephrolepis cordifolia	Day	18.5	18.1	18.2	18.3	18.5	18.3	18.8	18.3
	Night	20.5	20.1	20.3	19.9	19.8	20.5	22.1	20.2

Table 8
Average humidity values recorded by BME sensors for different plant species.

Plant type	Time	Humidity (%)							
		BME-F (Right)	BME-F (Left)	BME-T (Right)	BME-T (Left)	BME-B (Right)	BME-B (Left)	Ambient	Average Chamber
Nematanthus glabra	Day	79.5	73.5	79.6	82.8	76.7	68.9	58.1	76.8
	Night	94.9	92.8	95.5	99.9	94.6	94.3	68.4	95.3
Schefflera arboricola	Day	85.7	83.6	84.5	96.5	88.5	88.6	61.6	87.9
	Night	92.0	89.3	91.2	98.9	95.2	95.4	71.3	93.7
Nephrolepis cordifolia	Day	89.7	88.3	90.7	97.4	90.4	91.6	61.0	91.4
	Night	89.6	94.5	89.0	96.5	91.5	93.0	66.7	92.4

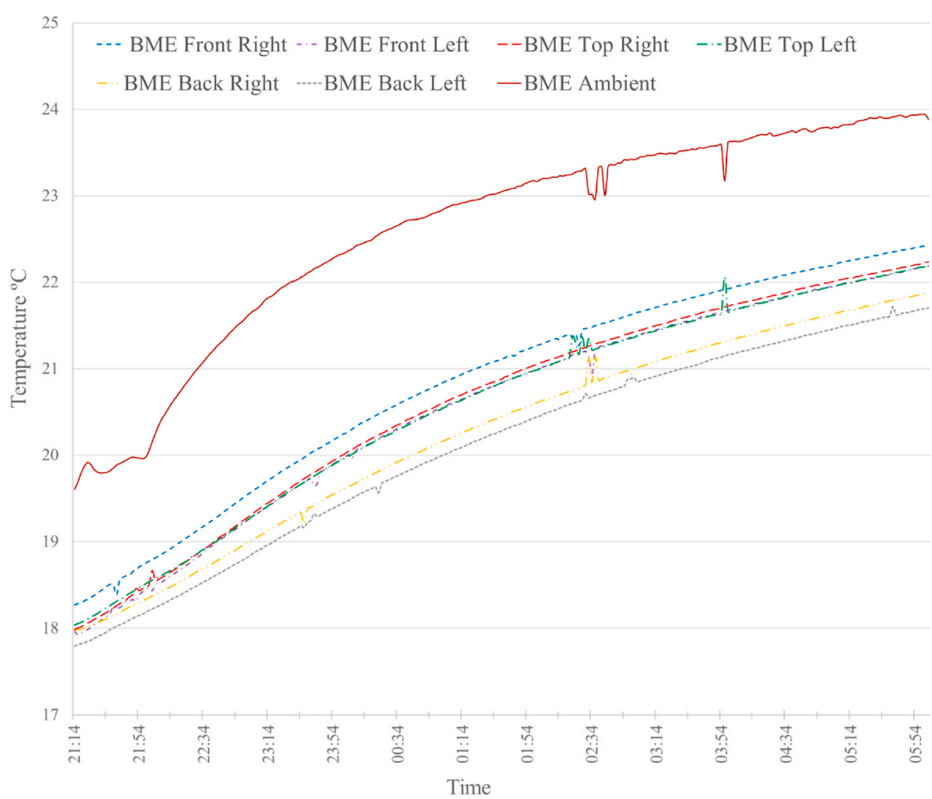

Fig. 8. Graph showing temperature readings for *Schefflera arboricola* between 9:30 p.m. and 6:00 a.m. The highest trace is the ambient temperature; the other lower traces are from sensors inside the acrylic chamber.

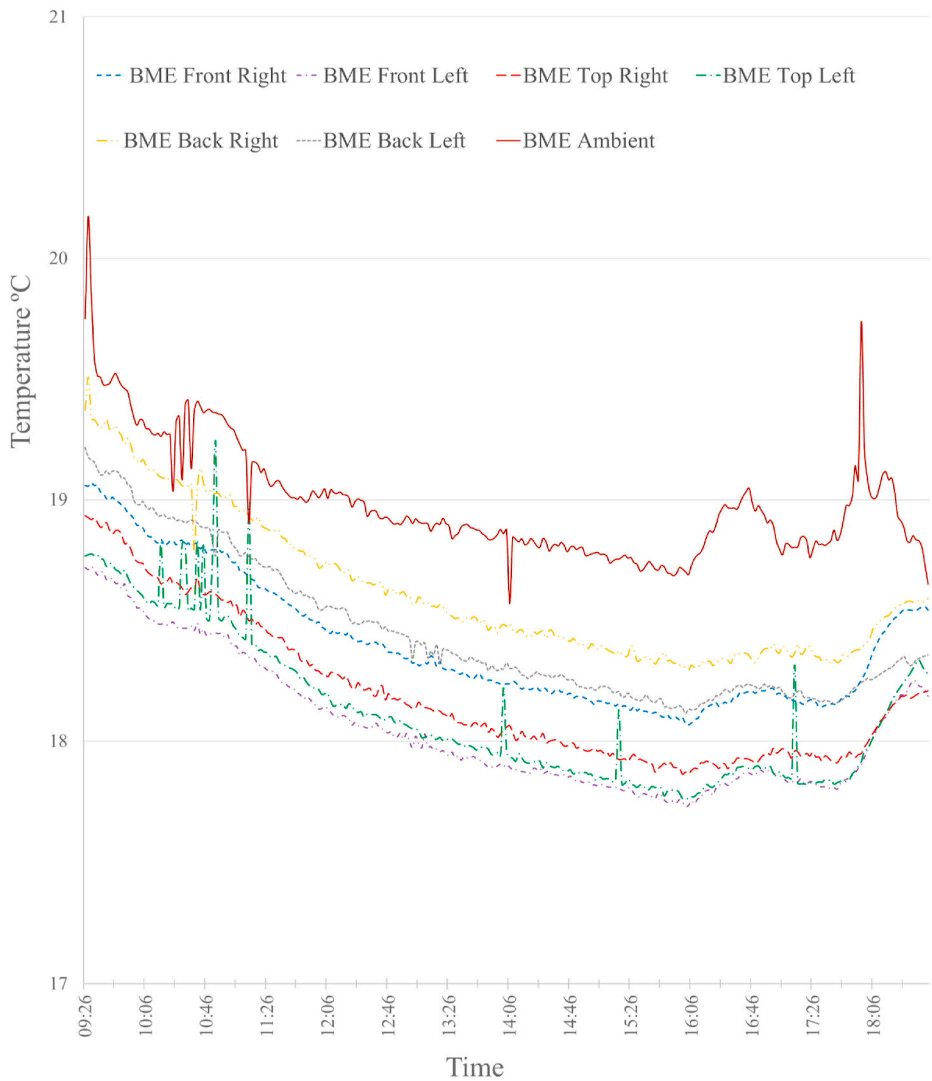

Fig. 9. Graph showing temperature readings for *Nematanthus glabra* between 9:30 a.m. and 6:00 p.m. The highest trace is the ambient temperature; the other lower traces are from sensors inside the acrylic chamber.

Fig. 10. In situ vertical green wall comprised of modules tested in the current study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

demonstrated that green walls contribute to indoor air conditioning, with temperature reductions of 0.8–4.8 °C observed at different distances from the green wall. It is noted that the conditions of the experiments are not identical since Perez-Urrestarazu et al. have used an actual exist9ing green wall to conduct their experiment.

Pressure difference (P) across the different modules studied have been obtained and recorded in Table 6 [27]. The total flow rate (Q) is estimated based on the method described in previous research [28,44,45]. It has been noted that much more air would pass through the modules when wet than when they are dry which would contribute more to the variation in temperatures and humidity.

The Q-P relationship in all cases has trends agreeing with typical fan performance curves', namely as Q increases, P decreases [44,45]. But it should also be noted that there is much back flow in all the cases considered.

3.2. Results for passive green walls

The ambient temperature during day time was approximately 18–19 °C while at night it was approximately 22–22.5 °C. The ambient humidity during the day was approximately 58–62% while during the night it was 66–72%. Table 7 [37] shows the average temperature values recorded by the BME sensors during the day and night time; refer to Fig. 4 for the location of the sensors inside the chamber. The average of the six sensors was also obtained and shown in Table 7 to indicate the temperature of the chamber. All of the sensors recorded lower temperatures than the ambient temperature and the average difference was in the range of 0.5–1.5 °C during the day and in the range of 2–2.5 °C during the night.

Table 8 [37] shows the average humidity values recorded by the BME sensors during the day and night time. The average of the six sensors was also obtained and shown in Table 8 to indicate the average humidity inside the chamber.

All of the sensors have recorded higher humidity readings compared to the ambient and the average difference was approximately 20–25% during both day and night times. Higher humidity level has been expected due to the moisture content of the substrate which has been saturated 24 h before the experiments.

It is noted that none of the plant species had any preference except for some slight differences in the temperature and humidity which is probably due to the different moisture content of the substrate. In most of the cases, the sensors closest to the module (BME-T), has recorded higher humidity levels compared to other sensors.

Fig. 8 shows the graph of the time-dependent temperatures for *Schefflera arboricola* between 9:30 p.m. till 6:00 a.m. next day. As mentioned the difference is approximately 2 °C during night time between the ambient temperature (higher) and the temperature inside the chamber while this difference is about 1 °C during the day as shown in Fig. 9 for *Nematanthus glabra* between 9:30 a.m. and 6:00 p.m.

4. Conclusion

The effect of active and passive green wall bio-filters on the air temperature and humidity has been investigated. Cases for dry and wet (saturated) unplanted module, as well as saturated planted modules with different plant species have been considered. The effect of different surrounding ambient conditions is also investigated. Fig. 10 shows a vertical green wall comprised of modules tested in the current study.

Following are the conclusions noted in this study for the active green wall modules:

- Lower temperatures in the range of 1–3 °C, along with increased humidity levels have been noted when modules are saturated wet for cases of unplanted as well as planted modules with different plant species.
- While any of the plant species studied did not show any preference, an unplanted module with dry substrate did not cause any significant temperature variation indicating that the moisture content plays the major role in the temperature as well as humidity variations.
- The temperature and humidity variations are primarily due to the evaporation of the water available in the module's substrate during operation. On the other hand, transpiration of the plants has an insignificant effect.
- With all the cases investigated Q-P relationship agrees with the typical fan performance curves', namely as Q increases, P decreases.

As for the passive green wall modules, lower temperatures in the range of 0.5–2 °C, along with increased humidity levels have been noted when modules are saturated wet for planted modules with different plant species. Similar to the active green walls, none of the modules studied showed any preference indicating that the transpiration of the plants has an insignificant effect.

Future work is planned to conduct an experiment using an actual green wall installation with several modules to measure its effect on the temperature and humidity of its surrounding.

Declaration of competing interest

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

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