

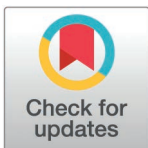
RESEARCH ARTICLE

Impact of green wall orientation on building energy performance in a tropical climate: An experimental assessment

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Abstract

Vertical Greenery Systems, also known as Green Walls have emerged as essential components of Green Infrastructure, offering promising outcomes for both the present and the distant future. This study aimed to establish correlations between orientation and the thermal performance of green walls. The research was conducted in a controlled climatic environment, featuring a bare wall as the control experiment and green walls with four different plant species, including *Xiphidium caeruleum*, *Asparagus aethiopicus*, *Ophiopogon japonicus*, and *Dianella ensifolia variegata*. The growth medium consisted of a consistent 1:1:1 ratio of coir dust, sand, and compost for all plant species. Data collection, which spanned from 9:00 a.m. to 6:00 p.m., included parameters: surface temperature, ambient temperature, relative humidity, and wind speed for the green wall's exterior and interior. The results of the study demonstrated that east-oriented green walls, particularly those featuring *Asparagus aethiopicus*, achieved significant influence on building energy conservation, with a maximum temperature reduction of 4.1 °C in both interior and exterior surface temperatures compared to the bare wall. The findings highlight the potential of optimally oriented green walls to reduce cooling energy consumption in buildings.

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1. Introduction

The global landscape is in a state of profound transformation, witnessing a shift from arable lands to expanding urban centers. This transition is significantly driven by the built environment, which now accounts for a staggering 75% of the world's annual greenhouse gas (GHG) emissions. Among these emissions, buildings stand out, contributing to 39% of the total, thereby exerting a substantial impact on both the environment and human health [1]. The rapid pace of urbanization over the past five decades, as projected by the United Nations (UN) World Urbanization Prospects, anticipates a surge in the global population to approximately 9.8 billion by 2050, with an estimated 68% residing in urban areas—a notable 14%

Data availability statement: The data supporting the findings of this study are openly available in the Open Data Science Framework Repository and can be accessed via the following link: https://osf.io/wm5sg/?view_only=443c73de260a438d839562057196d7f2.

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increase from 2016. This demographic shift is poised to exacerbate Urban Heat Island (UHI) effects, leading to heightened thermal discomfort. Consequently, the increased demand for air conditioning, recognized as a negative consequence of UHI [2], is anticipated to substantially escalate energy consumption for buildings by 2050.

In response to these projections, there is a growing emphasis on enhancing building comfort through the integration of green infrastructure during both the design and operational phases. Despite the recognized importance of trees and vegetation in mitigating environmental stressors, there is an urgent need to reassess strategies for incorporating natural elements into modern urban landscapes. One significant obstacle to achieving this goal is the limited availability of space within the built environment, particularly in areas characterized by high imperviousness in urban land use [3]. Architects and engineers propose a solution to this spatial constraint through the integration of green features into the building envelope.

In recent years, green walls have emerged as a prominent and dynamic method for infusing buildings with plant life, both internally and externally [4]. Green walls and green facades, whether internal or external components of a structure, involve partial or complete coverage by small plants. These plants, which may range from a few square meters to an entire building, can grow either directly from the ground soil or from vertically supported soil. Referred to interchangeably as 'Green walls,' 'bio-walls,' or 'vertical gardens,' these structures amalgamate vegetation, growing mediums, irrigation, and drainage components into a unified system [5]. The foliage of green wall plants serves to intercept solar radiation, creating a living facade that contributes to environmental sustainability in the built environment.

2. Background

The thermal performance of green walls is multifaceted, with several factors playing key roles, including climate, building skin type, and the density of plant coverage. By strategically incorporating shading, insulation, and vegetation, green walls can effectively mitigate heat, resulting in a reduction of indoor temperatures by up to 10 °C. Additionally, the presence of vegetation acts as a natural heat barrier, potentially lowering energy consumption by as much as 20% [6]. Crucially, the thermal effectiveness of green plants is closely tied to the evapotranspiration process, which relies on adequate water and sunlight. Consequently, regions characterized by high solar radiation and rainfall intensity are likely to experience optimal thermal performance [7]. It's important to note that varying climatic conditions yield distinct environmental characteristics, such as temperature, solar radiation, air humidity, wind speed, and rainfall, all of which significantly influence the thermal behavior of green walls.

2.1. Green wall plant selection

The performance of Green Walls is heavily influenced by the selection of plant species, which can be categorized based on four key groups: structural parameters, radiative properties, plant traits, and processes. Among these characteristics, Leaf Area Index (LAI) stands out as the most influential, with higher LAI values correlating with greater energy benefits. Interestingly, while plant height may not be a significant factor, species with lower height often offer superior cooling benefits and easier coverage of greenery.

Manipulating albedo and emissivity can effectively reduce leaf temperature, leading to increased energy benefits. Light-colored plants with longer hair lengths are particularly adept at generating a cooling effect. Additionally, plants with thinner leaves are advantageous due to their enhanced heat dissipation and reduced heat storage capacity. Species with higher stomatal conductance play a vital role in maintaining lower leaf temperatures, thereby amplifying

energy benefits. Careful consideration of these plant characteristics is essential for optimizing the energy performance of Green Walls [8].

2.2. Orientation effects

The thermal performance of Green walls is contingent upon a multitude of factors, including climate, building skin type, and the density of plant coverage. By meticulously integrating shading, insulation, and vegetation, Green walls have the potential to mitigate heat transfer, thereby decreasing indoor temperatures by up to 10 °C. Moreover, vegetation serves as a formidable heat barrier, capable of reducing energy consumption by as much as 20% [6]. Central to the thermal efficacy of green plants is the evapotranspiration process, reliant on adequate water and sunlight. Consequently, regions characterized by high solar radiation and rainfall intensity may experience heightened thermal optimization [7]. The varying climatic categories engender distinct environmental parameters, encompassing temperature, solar radiation, air humidity, wind speed, and rainfall, all of which are poised to influence the thermal behavior of Green walls.

The thermal effectiveness of Green walls is intricately linked to the plant species chosen for their construction, making the selection of plants a critical determinant of their success. The physiological and morphological traits of these plants play a significant role in shaping the energy benefits derived from Green walls [8]. Numerous factors contribute to the thermal performance of Green walls, including the type of vegetation and various plant characteristics such as leaf morphology, developmental stage, color, form, solar transmittance, vegetation coverage percentage, substrate type, and moisture content. Additionally, building characteristics and local climate conditions exert substantial influence. To comprehensively gauge the potential of each Green wall system to enhance building energy performance, previous analyses have typically considered several key factors, including the study period, plant species utilized, façade orientation, foliage thickness or coverage percentage, and substrate composition and thickness [9]. This holistic approach aids in understanding the contextual nuances and environmental conditions under which Green walls operate, facilitating informed decisions regarding their implementation.

2.3. Research gaps

When evaluating the potential of Green walls as a passive energy-saving solution, previous studies have acknowledged the significant influence of climatic conditions on their operation. Climate not only shapes the thermal performance of Green walls but also impacts various plant-related factors such as growth (foliage density, plant height, etc.) and physiological responses (transpiration, leaf positioning, etc.), consequently affecting the overall thermal behavior of the system. Key climatic parameters such as solar radiation, temperature, relative humidity, rainfall, and wind exert the most substantial influence [10]. While some researchers specify the location of their studies, others do not. Table 1 provides a summary of select previous studies illustrating the impact of climate on the thermal performance of various Green walls. It becomes evident from the table that different climatic categories engender diverse environmental characteristics, including temperature, air humidity, wind speed, and precipitation. These environmental factors distinctly influence the thermal performance of Green walls, underscoring the importance of considering climate in their design and implementation.

[11] conducted an analysis investigating the impact of façade orientation and the proportion of plant coverage on the thermal performance of a building zone within the Greek region during the summer months. Results indicated surface temperature reductions of 1.73/0.65 °C

Table 1. Influence of climate on the thermal performance of the green walls.

Study	Type of green wall	Type of study	Country	Region	Climate condition	Surface external building wall temperature reduction (°C)
[11]	Traditional green façade	Case study	Greece	Thessaloniki	–	5.7 (°C)
[13]	Traditional green façade	Simulation	USA	Chicago	Humid continental climate	7.9 (°C)
[14]	Traditional green façade	Experiment and simulation	England	Nottingham	–	6.1 (Sunny day)/4.0 (Cloudy day)
[15]	Double-skin green façade	Experiment	Spain	Lleida	Mediterranean continental	–
[16]	Double-skin green façade	Experiment	Japan	Chikusa	–	4.1–11.3–7.9–6.6–3.7 (°C)
[17]	Double-skin green façade	Experiment	Singapore		Tropical climate	4.36 (°C)
[17]	Green wall	Experiment	Singapore		Tropical climate	Day: 1 to 10.94 (°C)/Night 2 to 9 (°C)
[18]	Green wall	Experiment	Italy	(A) Lonigo (B) Venezia	Mediterranean climate- Summer	Day: (A)12–20 (°C); (B) 16/Night: (A) 2–3; (B)6 (°C)
[18]	Green wall	Experiment	Italy	(C) Pisa	Mediterranean climate- Autumn	Day: (C)12 (°C)/Night: 3 (°C)
[19]	Green wall	Experiment	China	Wuhan	Sub-Tropical climate- Summer	20.8 (°C)
[20]	Green wall	Experiment	Chile	Santiago	Semi-arid climate	Up to 30 (°C)

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for the North façade, 10.53/2.04 °C for the East façade, 6.46/1.06 °C for the South façade, and 16.85/3.27 °C for the West façade. These reductions translated to cooling load reductions of 4.65% for the North, 18.17% for the East, 7.60% for the South, and 20.08% for the West. In a study by [10], the influence of leaf area index (LAI) and façade orientation on the shading effect of a green façade was examined. The research found that energy savings of up to 34% were achieved with Boston Ivy plant species exhibiting an LAI of 3.5–4 during the summer period under a Mediterranean continental climate. Additionally, the study confirmed the significant role of façade orientation, with East and West orientations contributing substantially to the overall energy savings.

[12] conducted a study investigating the influence of leaf densities on the effectiveness of energy transfer in green façades. The experimental research was conducted in Indonesia during December, focusing on the East orientation and utilizing two different plant species. Three sets of data measurements were carried out, namely, experiments I, II, and III. Experiment I represented the model without a green façade (leaf density 0%), while experiment II and III represented models with green façades of 50% and 90% leaf densities, respectively. The temperature differentials between the bare wall and the two Green wall systems were measured at 6.8 °C and 7.8 °C for the exterior surface, and 6.7 °C and 7.3 °C for the interior surface. Heat flux profiles showed a correlation with surface temperature, with experiment III exhibiting the lowest heat flux profile. Across experiments I to III, the average heat fluxes were 22.35 Wm⁻², 8.76 Wm⁻², and 0.60 Wm⁻², respectively. The study highlighted a significant cooling effect of the green façade compared to the bare wall, with greater leaf densities resulting in more pronounced cooling effects. However, it is worth noting that the study exclusively considered the East orientation in its experimentation.

[21] carried out an experimental study in Hong Kong, China to assess the effect of Orientation on thermal and energy performance of Green walls. It was found that the highest reduction of 6.1 °C could be obtained from the West-oriented wall when compared to the other orientations. The study was conducted from July to August using the Green walls covered with *Schefflera octophylla*, a commonly used plant species for outdoor Green walls. However, the study has not studied the impact of the plant covered percentage for the thermal performance of the Green Walls.

Numerous studies worldwide have explored vertical greenery systems through experimental trials, simulations, and case studies to evaluate the thermal performance of Green

walls. Previous research overwhelmingly indicates a correlation between ambient conditions and the thermal behavior of Green walls, primarily due to prolonged exposure of the façade. Despite the abundance of research on Green walls, only a limited number of studies have systematically investigated all four major building orientations, particularly in hot, humid temperate climates where the year-round thermal benefits of Green walls could be highly advantageous. Therefore, this study aims to assess the orientation-specific impacts on the thermal performance of Green walls by analyzing heat exchanges and fluxes. This investigation is conducted through an experimental study in a controlled environment, providing valuable insights into how different orientations influence the thermal behavior of Green walls.

3. Materials and methods

This research employed an experimental approach, utilizing the rooftop of a 5-story building within the premises of the Faculty of Applied Sciences at the University of Sri Jayewardenepura in Colombo, Sri Lanka. This rooftop location was chosen for its open area, free from any shading caused by adjacent buildings or trees, ensuring minimal external disturbances during the research process.

3.1. Construction of experimental setups

Ten identical setups were carefully designed to be well insulated from all the sides apart from the wall. Moveable cubic structures were initially prepared from steel with the dimensions of $1\text{ m} \times 1\text{ m} \times 1\text{ m}$. A small platform was constructed to provide support in building the cement wall. A wooden pole at a length of 1m was used as the footing of the cement wall which had a surface area of $1\text{ m} \times 1\text{ m}$, was built to cover only a side of the cubical structure. Two bare walls were used as the control experiment. All the 10 walls were intended to simulate building walls. The planted side of the Green wall was compared with the bare wall. For the cement wall to be built, approximately 10 solid cement blocks with the dimensions of $100\text{ mm} \times 190\text{ mm} \times 390\text{ mm}$ were used for each structure as shown in Fig 1. All the cement walls were not plastered with cement.

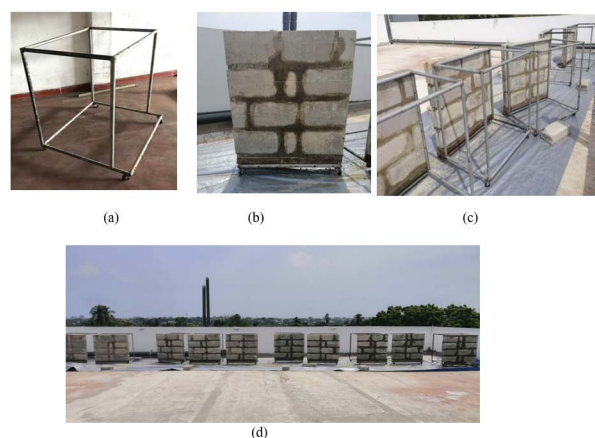


Fig 1. Cement wall that was built on the steel structure: (a) structure, (b) front view, (c) back view, (d) built walls on all setups.

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As all the other sides are exposed, to cover those five sides including the top, bottom and sides of the cubical structure, plywood sheets with the thickness of 0.5" were used. Two openings were made on the plywood sheets which were opposite to one another and adjacent to the built wall. Those two openings as shown in Fig 2 were used to insert the equipment to measure the temperature and relative humidity parameters inside the setup.

Since the research is designed for the green wall systems with geotextile felt, to insert the plant species, a white color geotextile felt with 36 pockets in each was made. White color geotextile felt was selected as it could absorb a lesser quantity of heat energy from the solar radiation than any other colored geotextile felts. As this was a small experimental setup compared to the commercially available Green walls, the felt was attached to the built cement wall as shown in Fig 3.

For the insulation of the setups, double-sided McFoil of 25 mm thickness was used. Edges of each setup were sealed with a sealant as the research was intended to measure the isolated impact of the heat transfer to the interior through a Green wall. Therefore, all other means of interior heat transfer were neutralized for every setup. Two openings from both sides were made as shown in Fig 4 to aid the measurement of interior data and were kept closed during the remaining period. Interior data was collected for the parameters of internal ambient temperature and internal relative humidity in order to check whether there are significant differences between the external ambient conditions and internal ambient conditions with respect to plant species and bare wall. To measure internal ambient temperature and internal relative humidity, Smart Sensor digital temperature and relative humidity meter AS-817 was used.

Each experimental setup consisted of two replicates, with a total of 36 plants installed on a single living wall. Two bare walls constructed with solid cement blocks served as control setups, while the living walls comprising geotextile felt and a growth medium were designated



Fig 2. The exposed sides covered with plywood sheets: (a) after covering, (b) after cutting the openings.

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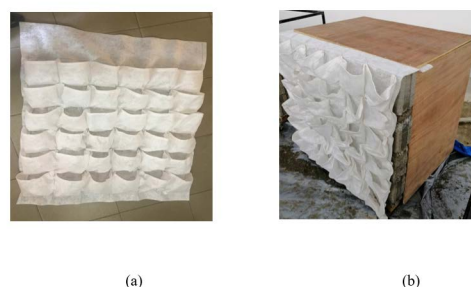


Fig 3. Installation of the geotextile felt: (a) prepared geotextile felt with the pockets, (b) after attaching the felt to the built wall.

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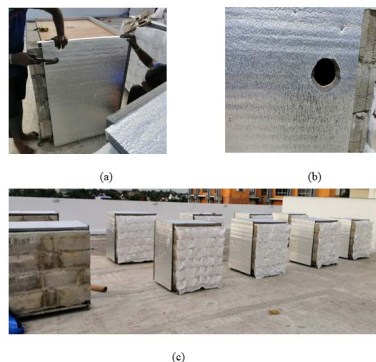


Fig 4. Insulation of the setups: (a) attaching the McFoil onto the plywood sheet, (b) cleared opening, (c) completed setups with the closed openings.

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as the treatment. To ensure uniform conditions for all plant species, a standardized growth medium was used, consisting of coir dust, sand, and compost mixed in equal proportions (1:1:1 ratio). This medium was chosen for its ability to retain moisture, provide adequate drainage, and support healthy plant growth in tropical climates. Following the installation of the plants into geotextile pockets, they were allowed a two-week acclimatization period to adjust to the environmental conditions before data collection began.

Watering was a critical aspect of maintaining plant health, but it also posed a challenge due to its potential impact on temperature measurements. Watering the plants could significantly lower the surface temperature of the walls due to increased moisture, creating a disparity between the bare wall and living wall systems. To control for this, a consistent watering schedule was applied across all setups. Plants were watered daily in the early morning, prior to the start of data collection, ensuring uniform moisture levels across both experimental and control groups. Additionally, since all selected plant species exhibited similar water stress responses, the experimental design accounted for and neutralized any potential thermal effects caused by moisture. This approach ensured that temperature variations observed during the study were attributable to plant performance and wall orientation rather than discrepancies in hydration levels.

3.2. Selection of plant species

The selection of the four ornamental plant species for this study was driven by their compatibility with tropical climatic conditions. In regions where intense sunlight persists throughout the year, it is critical to choose species that can thrive under such conditions to ensure the long-term viability of the green wall. A key consideration in the selection process was the ability to visibly assess changes in plant characteristics, allowing for an evaluation of the potential impact of different species on the thermal performance of the green wall. Furthermore, the resilience of the plants to the local climate was prioritized, ensuring that they could withstand the environmental stresses typical of tropical regions. This approach not only supports plant survival but also enables a meaningful analysis of their contribution to building energy performance.

Four commonly used ornamental species were selected for the study as shown in Fig 5. Plant selection mainly depends on the suitability to the tropical climatic conditions. As sunlight is intense throughout the year, for the survival of the plants, they must be appropriate to the tropical climate. When selecting the plants, the ability to visibly assess the changes in plant characteristics was given special attention. The reason for this is to evaluate whether there are significant differences in the thermal performance of a green wall with respect to different

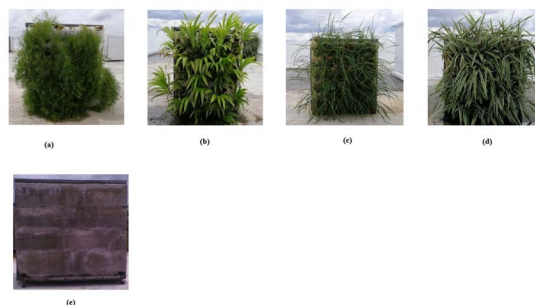


Fig 5. Installation of the plants: (a) green wall with *Asparagus aethiopicus*, (b) green wall with *Xiphidium caeruleum*, (c) green wall with *Ophiopogon japonicus*, (d) green wall with *Dianella ensifolia variegata*, (e) control experiment (bare wall).

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plant species. Similarly, the ability of the plants to withstand the local climatic conditions was considered in selecting the plants for the study. All selected plant species were perennial, and evergreen as shown in Table 2.

3.3. Data collection

In order to evaluate the thermal performance of the experimental wall setups, hourly data collection has been done from 9.00 a.m. to 6.00 p.m. during a day. Data has been collected for the following parameters as shown in Table 3. Before starting the data collection for the day, every morning the openings of each setup have been opened to release the hot air collected inside the setups in the previous day since it could affect the interior surface temperature as well as the interior ambient temperature for the sampling day. Four series of data measurements were carried out for 20 days on sunny days of clear sky with no precipitation as five days of data collection for each orientation. Data collection was carried out from June 2021 to February 2022. To analyze the impact from the orientation for the building energy performance, the direction of the walls was changed to four directions; North, West, East, and South. Interior data collection was carried out to measure the temperature reduction that can be achieved with a Green wall system when compared to a bare wall, as it is directly related to building energy performance. In order to measure the effect of leaves density on temperature reduction, leaves density has been calculated for each plant specie.

Table 2. Selected plant species.

Common name	Family	Scientific name
Soskia	Haemodoraceae	<i>Xiphidium caeruleum</i>
Asparagus	Asperagaceae	<i>Asparagus aethiopicus</i>
Chinese green grass	Asperagaceae	<i>Ophiopogon japonicus</i>
White ribbon plant	Asphodelaceae	<i>Dianella ensifolia variegata</i>

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Table 3. Parameters for the data collection.

Parameters	Unit
Surface temperature (Internal and external wall surface temperatures)	°C
Ambient temperature (Internal and external air temperature)	°C
Relative humidity (Internal and external relative humidity)	%
Wind speed	ms ⁻¹

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3.4. Heat flux estimation

The purpose of calculating heat flux is to quantify the amount of energy (q) passing through a material per unit area (m^2). This method has been applied in previous studies, such as the work by [18], which investigated three types of vertical greenery systems. However, in that study, the calculation did not account for variations in leaf density, which could have influenced the thermal performance of the greenery systems. From the heat flux calculation, the quantity of energy that is passing through a material per area is expressed [12]. According to Newton's cooling law, heat flux formula, q_c (Wm^{-2}) is obtained by the coefficient of convective heat transfer (h) and the temperature difference between the air and the surface ($T_w - T_a$) as:

$$q_c = h(T_w - T_a) \quad (1)$$

where T_a is the air temperature, $^{\circ}C$; T_w is the wall surface temperature, $^{\circ}C$. Based on the EN ISO 6946:2008 the convective heat transfer coefficient is calculated as the sum of the components from heat convective (h_c) and heat radiant (h_r) respectively as shown below.

$$h_c = 4 + 4v \quad (2)$$

$$h_r = \varepsilon 4\theta T_m^3 \quad (3)$$

where v is the wind velocity, ms^{-1} ; ε is the surface emissivity; θ is the Stefan Boltzmann constant and T_m is the mean thermodynamic temperature of the surrounding surfaces, $^{\circ}C$ [12]. According to [20], the emissivity for the Green wall is 0.94 while surface emissivity for a bare cement wall is 0.88.

3.5. Leaves density estimation

In this research, the leaves coverage area was considered to analyze the thermal performance with respect to the leaves density and it was compared without the living wall, which was the wall. Leaves density was calculated to provide recommendations on living wall design for optimum energy performance with respect to leaf density. Based on the domination theory by Odum, a simple calculation was done for the leaves density (LD) [12]

$$LD = \frac{L_1}{L_2} \times 100\% \quad (4)$$

where LD = Leaves Density, %; L_1 = The area that covered with green facade, m^2 ; L_2 = Entire area of object measurement, m^2 . The imageJ software which is a Java-based public domain software for image processing and analysis was used to calculate the pixels of the binary images, which represented the area covered by plants.

4. Results

Figs 6 and 7 shows the thermal images taken in the morning; 10.00 a.m. and in late afternoon; 4.00 p.m. to measure the exterior surface temperature of the bare walls and green walls, facing the South direction on a sunny day with no precipitation. Fig 8 shows the comparison of the average exterior surface temperature of the bare walls and green walls, carried out for the four orientations on a sunny day with no precipitation. The walls of the prepared setups receive direct heat from solar radiation. Although in the green walls, direct solar radiation is blocked by the plants of the greenery layer, in the bare wall all the heat is directly received by the exterior wall.

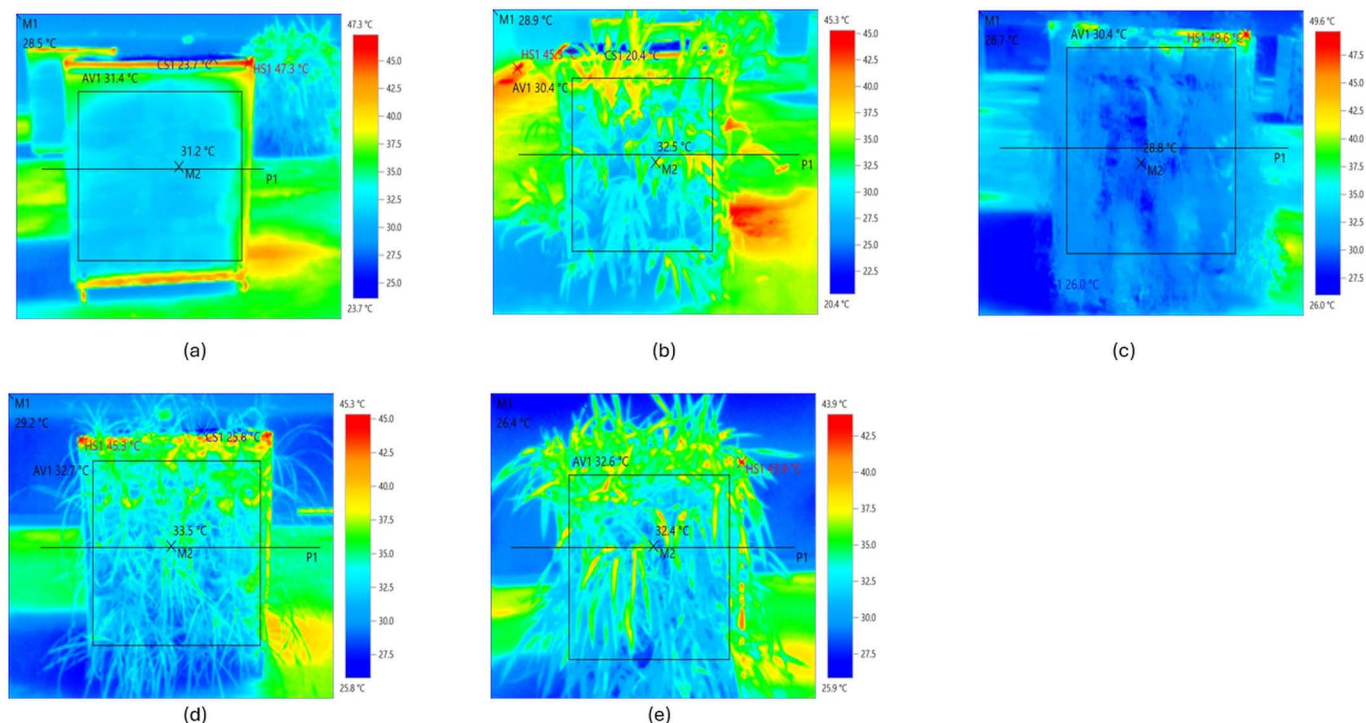


Fig 6. Thermal images of the experimental setups facing South direction, 27/09/2021, 10.00 a.m. (a) control experiment, (b) green wall with *Xiphidium caeruleum*, (c) green wall with *Asparagus aethiopicus*, (d) green wall with *Ophiopogon japonicas*, (e) green wall with *Dianella ensifolia variegata*.

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In the above four graphs, the exterior surface temperature of all the setups increases along the day and the time of walls reaching the peak value differs with the orientation. With the trend above, it is identifiable that the relative humidity fluctuates with the ambient temperature throughout the day similarly. It was also recognized that the ambient temperature also increases in the morning and again drops down in the evening after reaching its peak while the relative humidity falls in the middle of the day and again increases later in the evening. The ambient temperature tends to reach the peak value for the day between 12.00 p.m. to 2.00 p.m. for all four directions. However, the exterior surface of the bare wall which is the control of the experiment tends to get heated higher than the plant-covered surfaces when it is oriented to the South direction and East direction than other two orientations as the walls receive solar radiation for many hours of the day specifically than West-oriented walls.

However, the exterior temperature of the bare wall does not exceed the ambient temperature except in the evening when it is oriented to the West direction. Compared to the bare wall, significant temperature reductions can be achieved from the green walls particularly, for South and East orientation. For both orientations, the bare wall tends to get heated higher than the ambient temperature. The fluctuation of the exterior surface temperature of the green wall with *Dianella ensifolia variegata* plants is great than of other plant species. However, when considering the North orientation, the fluctuation of the exterior surface temperature of the green wall with *Ophiopogon japonicas* plants is great than of other plant species.

[Fig 9](#) shows the results of the comparison of the average interior surface temperature of the bare wall and green walls vs. time, carried out for South, East, West and North orientation.

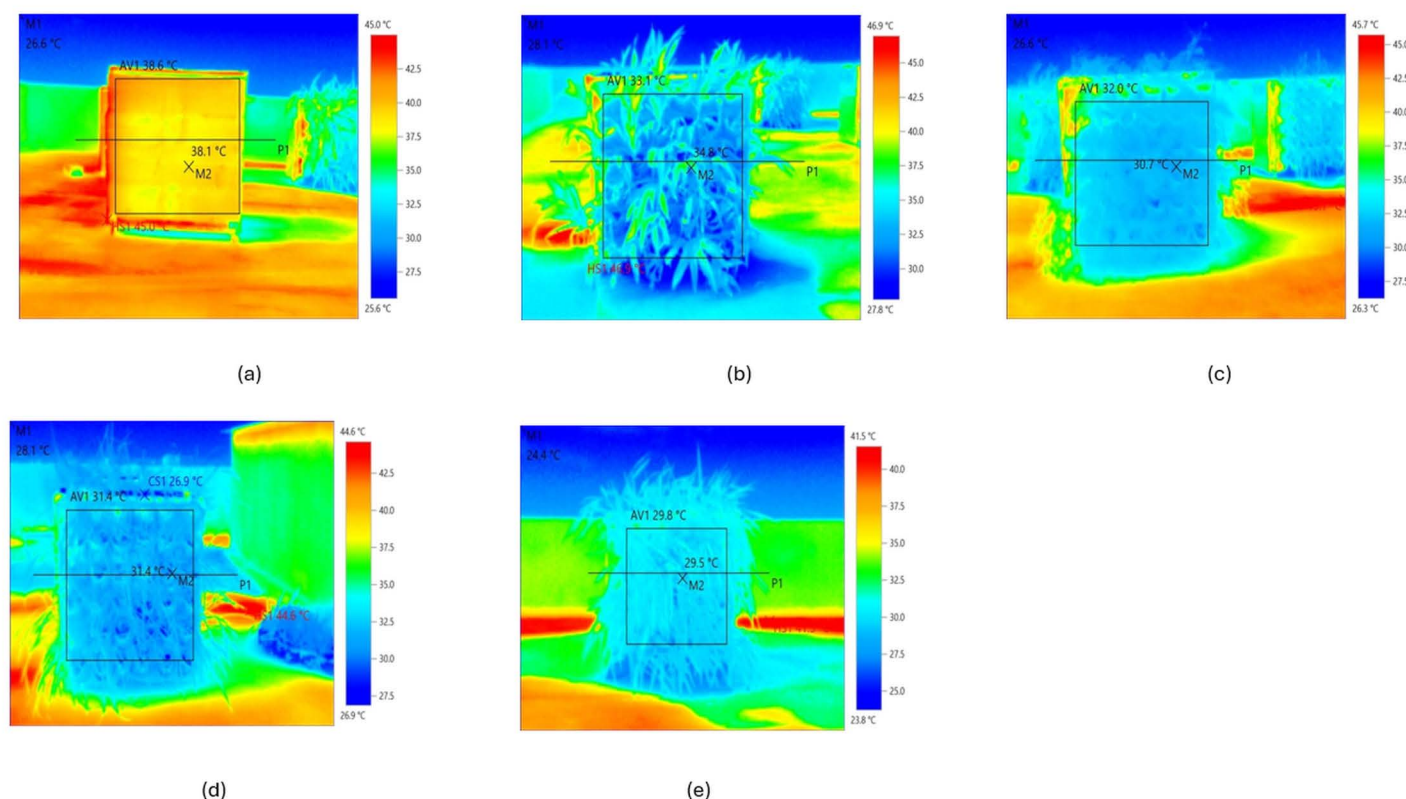


Fig 7. Thermal images of the experimental setups facing South direction, 27/09/2021, 4.00 p.m. (a) control experiment, (b) green wall with *Xiphidium caeruleum*, (c) green wall with *Asparagus aethiopicus*, (d) green wall with *Ophiopogon japonicas*, (e) green wall with *Dianella ensifolia variegata*.

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The interior surface temperature of the walls tends to increase throughout the day until it reaches a maximum level and then the temperature of the surfaces decreases while releasing the thermal energy from the wall to the interior ambient air.

The interior surface of the bare wall which is the control of the experiment tends to get heated higher than the Green walls with different plant species for all four orientations with a distinguishable temperature difference. However, the interior surface of the bare wall tends to get heated higher than the ambient temperature throughout the day, particularly when it is oriented to the East direction than the other three orientations. Unlike other orientations, the East-oriented bare wall reaches the peak interior surface temperature within the early hours as it receives more solar radiation since the sunrise. Contrasting to the bare wall, all the Green walls tend to reach their maximum interior surface temperature later in the day despite the orientation. The Green wall with *Asparagus aethiopicus* has gained maximum interior surface temperature among the Green walls when it is oriented to South and East while the West and North-oriented Green wall with *Ophiopogon japonicas* has gained maximum interior surface temperature among the Green walls experimented. Table 4 represents the mean surface temperature data of the experimental setups for all orientations.

Fig 10 shows the comparison between average interior ambient temperature and the exterior ambient temperature of the bare wall and green walls carried out for the four orientations, on a sunny day with no precipitation.

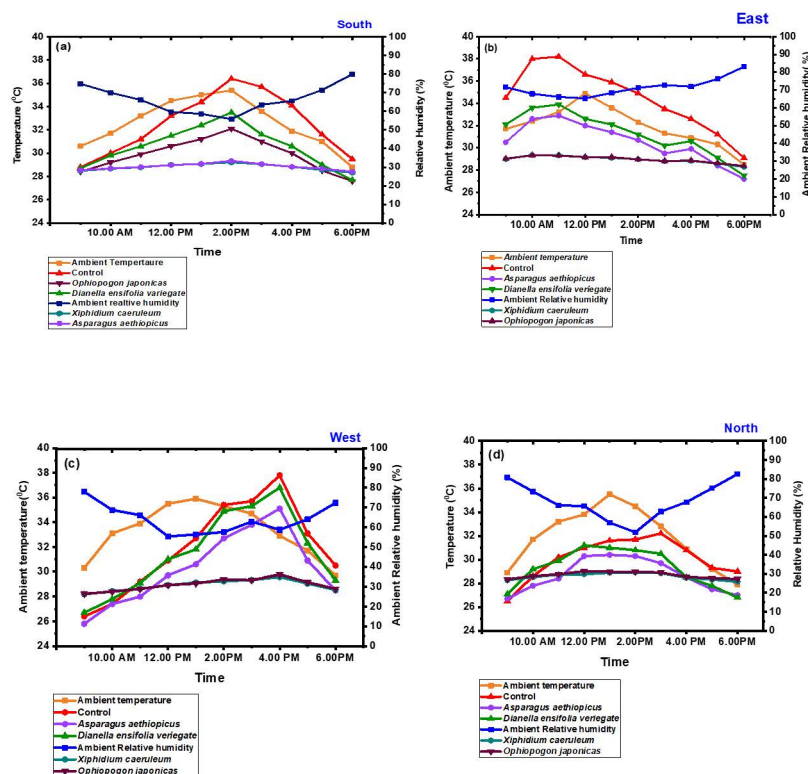


Fig 8. Comparison of the average exterior surface temperature of the bare wall and green walls vs. time (a) South orientation (b) East orientation (c) West orientation (d) North orientation.

<https://doi.org/10.1371/journal.pstr.0000156.g008>

According to the graphs in [Fig 10](#), it could be identified that the interior ambient temperature tends to get fluctuated when the ambient temperature changes along the day. Distinguishable changes of interior ambient temperature cannot be detected between the bare wall and the Green walls despite their orientation. Interior ambient temperature of all the experimental setups for South, East and North orientation reaches their maximum interior ambient temperature around the same time whilst the ambient temperature reaches its maximum. Interior ambient temperature is lower than the ambient temperature whilst the ambient temperature reaches its maximum. When the ambient temperature decreases in the evening, the interior ambient temperature of all the experimental setups also decreases.

4.1. Calculating heat flux values for the experimental setups

The quantity of energy that is passing through a material per area, which is expressed as the heat flux, was calculated to quantify the impacts of Green walls in building energy performance. The calculated heat flux provides the heat energy that transits the experimental walls to the inside of the experimental setups. The values quantify the impact on building energy performance with the use of Green walls in the present study. [Fig 11](#) shows the results of calculated heat flux of the bare wall and green walls vs. time, carried out for South, East, West

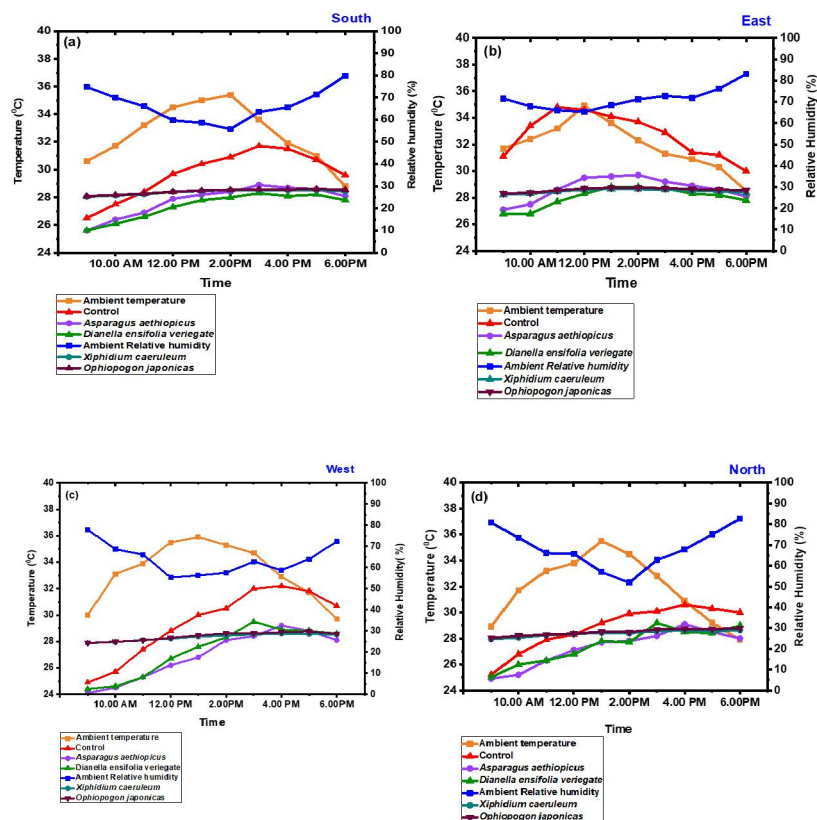


Fig 9. Comparison of the average interior surface temperature of the bare wall and green walls vs. time (a) South orientation (b) East orientation (c) West orientation (d) North orientation.

<https://doi.org/10.1371/journal.pstr.0000156.g009>

Table 4. Comparison of average surface temperature data of bare wall and green walls for South, East, West and North orientation.

	Exterior (°C)				Interior (°C)			
	South	East	West	North	South	East	West	North
Control (bare wall)	32.5	34.4	31.9	30.1	29.7	32.7	29.4	28.8
<i>Xiphidium caeruleum</i>	30.0	30.9	30.7	28.7	27.4	28.1	27.0	27.4
<i>Asparagus aethiopicus</i>	29.8	30.5	30.3	28.6	27.8	28.7	26.9	27.3
<i>Ophiopogon japonicus</i>	30.3	31.0	30.9	29.3	27.7	28.7	27.5	28.0
<i>Dianella ensifolia variegata</i>	30.5	31.3	31.5	29.3	27.4	28.0	27.3	27.5

<https://doi.org/10.1371/journal.pstr.0000156.t004>

and North orientation. Heat flux analysis was conducted on the exterior surface of the experimental walls, in correspondence of both Green walls and the bare wall. In the above four graphs, similar thermal behavior can be seen within Green walls for each orientation and also the heat flux of the bare wall seems to be higher than the Green wall. According to Equation 2, the heat flux direction was considered as the heat flux from the exterior wall to the ambient temperature. The heat flux results have been determined as either incoming heat flux, which is negative or the outgoing heat flux which is positive in the below.

When considering the South orientation, the maximum incoming heat flux has been recorded around 1.00 p.m. for the bare wall and at the same time, a higher negative heat flux

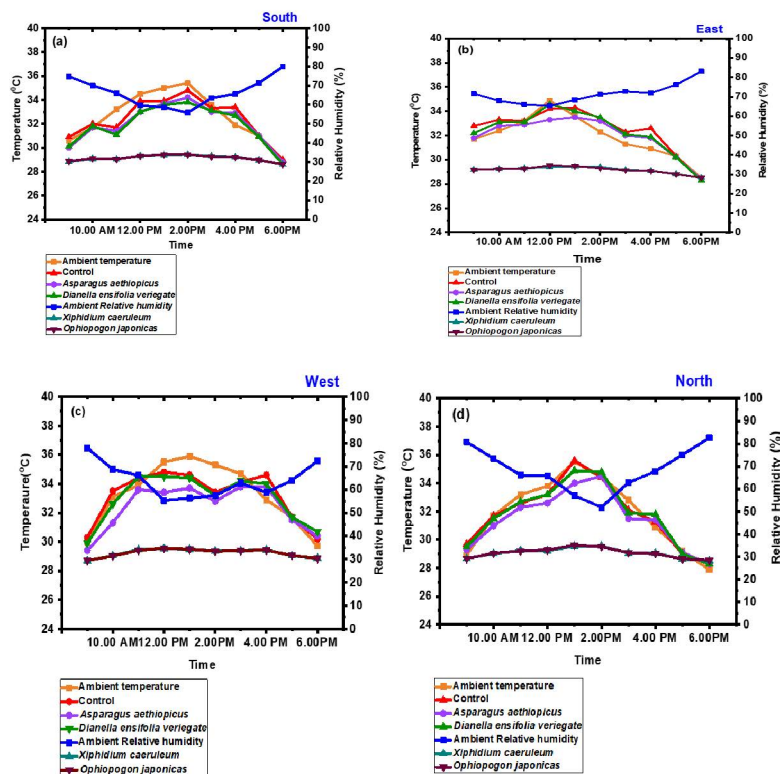


Fig 10. Comparison of the average interior ambient temperature of the bare wall and green walls and exterior ambient temperature vs. time (a) South orientation (b) East orientation (c) West orientation (d) North orientation.

<https://doi.org/10.1371/journal.pstr.0000156.g010>

has been recorded for the Green walls. Although the value was higher, the heat is flowing from the surrounding atmosphere to the Green wall indicating a cooling effect in the surrounding environment. The heat flux of all the experimental setups tends to be positive in the evening. However, for the East orientation, a peak outgoing heat flux has been recorded for the bare wall around 11.00 p.m. and during that time all the Green walls show a substantially lower heat flux difference when compared to the bare wall. During the experimental time period, the heat flux for all the setups was positive indicating an outgoing heat flux from the walls.

When considering the West orientation, the bare wall shows a maximum incoming heat flux around 11.00 p.m. while a higher negative heat flux has been recorded for the Green walls. The bare wall shows the highest outgoing heat flux around 4.00 p.m. while the Green walls show a positive yet lower heat flux than the bare wall. Moreover, for the North orientation, a peak outgoing heat flux has been recorded for the bare wall around 3.00 p.m. and during that time all the Green walls show a substantially lower heat flux difference when compared to the bare wall.

Table 5 shows the mean heat flux values that have been calculated considering both incoming and outgoing heat flux of the walls. The obtained results greatly depended on the ambient climatic conditions at the time of data collection.

From the analysis of bare wall heat fluxes along all orientations, East-oriented bare wall records the highest outgoing heat flux of 44.245 Wm^{-2} , while other bare walls show an incoming heat flux. The above result shows that the East-oriented bare wall receives more heat than the ambient temperature, giving an outgoing heat flux from the exposed wall. The wall is oriented to the East direction and it receives the most of the incident solar radiation from the time of the sunrise than the other orientations providing the opportunity to heat up for

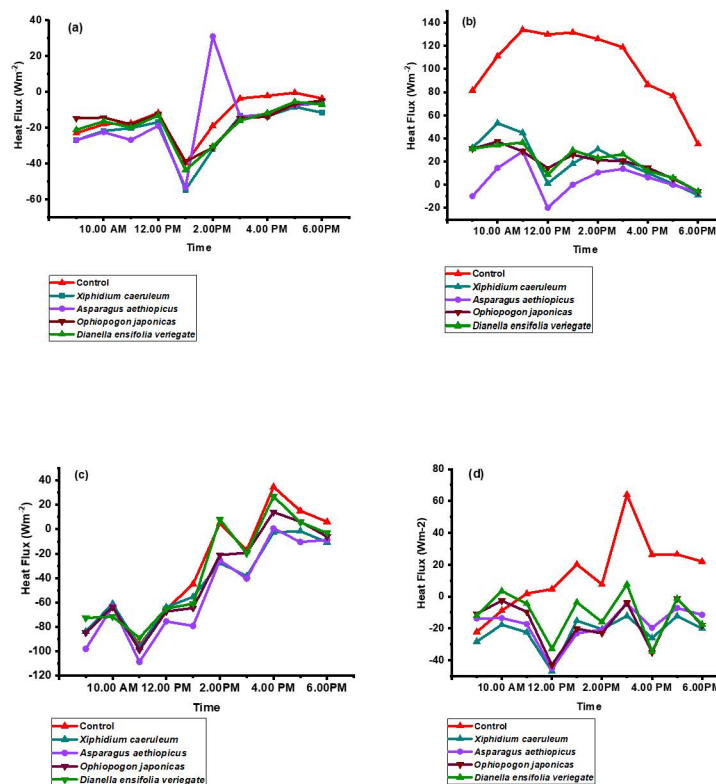


Fig 11. Comparison of calculated heat flux of bare wall and green walls vs. time (a) South orientation, 27/09/2021 (b) East orientation, 07/11/2021 (c) West orientation, 06/12/2021 (d) North orientation, 02/12/2021.

<https://doi.org/10.1371/journal.pstr.0000156.g011>

Table 5. Comparison of mean heat flux values of the bare wall and green walls for South, East, West and North orientation.

Orientation	Control (Wm^{-2})	<i>Xiphidium caeruleum</i> (Wm^{-2})	<i>Asparagus aethiopicus</i> (Wm^{-2})	<i>Ophiopogon japonicus</i> (Wm^{-2})	<i>Dianella ensifolia variegata</i> (Wm^{-2})
South	-3.005	-29.370	-32.410	-25.361	-23.759
East	44.245	-16.619	-23.724	-15.706	-10.026
West	-18.343	-31.472	-37.459	-27.912	-24.311
North	-11.654	-30.007	-28.277	-23.209	-23.092

<https://doi.org/10.1371/journal.pstr.0000156.t005>

longer hours. Therefore, the bare wall heats up to a higher temperature than the walls facing other orientations and the heated up bare wall cools down slowly during the evening giving a positive average exterior surface temperature value for the East orientation. When considering the bare wall, the highest incoming heat flux of -18.343 Wm^{-2} has been recorded for the West orientation. Since the West-oriented bare wall is able to receive more solar radiation during the late afternoon, it does not heat up to a higher temperature exceeding the ambient temperature. Minimum incoming heat flux for the bare wall has been recorded for the South orientation, as it receives solar radiation considerably throughout the day the exterior surface of the bare wall heats up to a substantial value. Even though the average exterior surface temperature for the South-oriented wall is noticeable, it does not exceed the ambient climatic conditions.

When reviewing the Green walls for all four orientations, the highest incoming heat flux has been recorded for the West orientation by the Green wall with *Asparagus aethiopicus* while the minimum incoming heat flux has been recorded for the East-oriented Green wall with *Dianella ensifolia variegata*. Considering the outcomes, all the Green walls have given incoming heat flux, indicating a lower exterior surface temperature of the Green walls than the ambient climatic conditions. Higher the negative heat flux, the higher the cooling down of the wall compared to the ambient conditions. As the rise in exterior surface temperature leads to higher interior surface temperature, the cooling down of the exterior surface of the wall is important for the energy performance of the building. Lesser the interior surface heats up, the lesser the cooling energy consumptions of the building. Therefore, the Green wall with *Asparagus aethiopicus* performs well for South, East and West orientations while the Green wall with *Xiphidium caeruleum* performs well when it is oriented to North direction. The results obtained for the living walls denote the importance of considering the effect of the leaves density on the energy performance of the building.

In the present study, the effect of leaves density of the living walls has been observed for the building energy performance. Leaves density has been calculated using Equation 4, and the results have been compared with the obtained heat flux results. Fig 12 shows the generated binary images using the imageJ software which is a Java-based public domain software for image processing and analysis to calculate the pixels of the binary images, which represented the area covered by plants.

Even though the leaves density differs among the four orientations, the living wall with *Dianella ensifolia variegata* shows the maximum coverage of the bare wall for all orientations while recording the minimum incoming heat flux for all four orientations. The leaves density of other living walls has been fluctuated due to differences in the growth of the plant species and external factors. Since the leaves density fluctuated for the four orientations, leaves density has been qualitatively compared with the heat flux to identify the relationship between the leaves density and heat flux. When considering the South orientation, minimum leaves density is for the living wall with *Ophiopogon japonicas* and the incoming heat flux is comparatively lower than the other species. However, the maximum incoming heat flux is for the living wall with *Asparagus aethiopicus* which has the second-highest leaves density for South orientation. When considering the East orientation, minimum leaves density is for the living

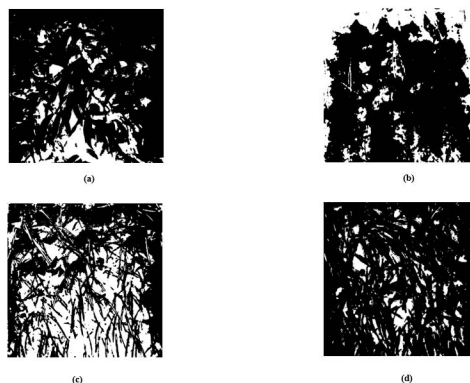


Fig 12. Leaves coverage of the green walls for East orientation, 07/11/2021 (a) living wall with *Xiphidium caeruleum*, (b) living wall with *Asparagus aethiopicus*, (c) living wall with *Ophiopogon japonicas*, (d) living wall with *Dianella ensifolia variegata*.

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wall with *Ophiopogon japonicas*. The above-mentioned pattern between the leaves density and incoming heat flux of living wall with *Ophiopogon japonicas* is similar for both South and East orientation. When considering the West orientation, minimum leaves density is for the living wall with *Asparagus aethiopicus* while recording the maximum incoming heat flux value for West orientation. When considering the North orientation, minimum leaves density is for the living wall with *Asparagus aethiopicus*. Despite having a higher leaves density, unlike the living wall with *Dianella ensifolia variegata*, the maximum heat flux is recorded by the living wall with *Xiphidium caeruleum*. For both East and West orientations, the trend between the leaves density and incoming heat flux is similar for the living wall with *Xiphidium caeruleum*.

Despite having a varied leaves density, the living wall with *Asparagus aethiopicus* performs effectively for South, East and West orientations. For North orientation, the living wall with *Xiphidium caeruleum* with a higher leaves density is able to reduce the energy consumption of a building (Table 6). Since the above mentioned two plant species belong to two different plant families while having different plant properties, further studies are needed to consider the impact of the plant species for the building energy performance.

5. Discussion

In Green walls, direct solar radiation is mitigated by the plants in the greenery layer, whereas in bare walls, the exterior surface absorbs all incoming heat directly. As ambient temperatures decrease, all walls gradually cool down from their peak temperatures. Notably, the exterior surfaces of South and East-oriented bare walls tend to reach elevated temperatures, peaking at 32.5 °C and 34.4 °C, respectively. These temperatures exceed those recorded for South and East-oriented plant-covered walls. The prolonged exposure to solar radiation characterizing South and East orientations, typical of Sri Lanka's proximity to the equator in the northern hemisphere, contributes to this disparity. During the experiment, conducted at a time when daytime hours in Sri Lanka were 3% longer than average [22], East-oriented walls received more horizontal solar radiation in the morning, while South-oriented walls experienced prolonged solar exposure spanning from sunrise to sunset. Conversely, North and West orientations received lower solar intensity due to the sun's position south of the equator during data collection. Consequently, average exterior surface temperatures for West and North orientations were 31.9 °C and 30.1 °C, respectively, reflecting the diminished solar radiation received compared to East and South orientations.

The findings of this study exhibit a comparable pattern to those observed in the research conducted by [19], where surface temperatures were analyzed for two distinct orientations: East and West. Notably, Chen et al.'s study bears resemblance to the present experiment as it was also conducted in a hot and humid climate, specifically on the rooftop of a 3-story

Table 6. Comparison of mean heat flux values and leaves density of bare wall and green walls for South, East, West and North orientation.

Orientation		<i>Xiphidium caeruleum</i> (Wm ⁻²)	<i>Asparagus aethiopicus</i> (Wm ⁻²)	<i>Ophiopogon japonicas</i> (Wm ⁻²)	<i>Dianella ensifolia variegata</i> (Wm ⁻²)
South	Heat flux	-29.370	-32.410	-25.361	-23.759
	Leaves density	59.35%	68.58%	45.14%	80.01%
East	Heat flux	-16.619	-23.724	-15.706	-10.026
	Leaves density	78.27%	70.11%	61.73%	86.18%
West	Heat flux	-31.472	-37.459	-27.912	-24.311
	Leaves density	83.94%	44.81%	75.97%	85.54%
North	Heat flux	-30.007	-28.277	-23.292	-23.092
	Leaves density	84.18%	50.75%	74.57%	84.30%

<https://doi.org/10.1371/journal.pstr.0000156.t006>

building. [19] conducted their experimental study during the summer season in Wuhan, China, reporting that West-oriented bare walls reached a maximum exterior surface temperature of 37.2 °C, while the mixed-species Green wall system recorded a maximum of 33.0 °C. This aligns with the observations made in the current study, further validating the influence of orientation on surface temperatures in hot and humid climates. While in the present study, the average exterior surface temperature, 31.5 °C was recorded by the West-oriented Green wall with *Dianella ensifolia variegata*. Furthermore, [19] reported the difference in exterior surface temperatures between the bare wall and Green wall was 4.20 °C while the interior surface temperature between the bare wall and the Green wall was 0.40 °C. The difference in exterior surface temperatures between the bare wall and Green wall with *Dianella ensifolia variegata* is 0.4 °C. For the interior surface, the difference between the bare wall and Green wall with *Asparagus aethiopicus* is 2.1 °C. From an experimental study carried out by Pan et al. (2018) in Hong Kong, China it was found that the highest reduction of 6.1 °C could be obtained from the West-oriented wall when compared to the other orientations. The study was conducted from July to August using the Green walls covered with *Schefflera octophylla*, a commonly used plant species for outdoor Green walls.

Across all orientations, interior relative humidity exhibited a consistent trend mirroring ambient relative humidity levels. The presence of greenery foliage on the walls facilitated an increase in water vapor content, with denser foliage obstructing air circulation to a greater extent. Consequently, Green walls with higher leaf density tended to display elevated relative humidity levels. While the sealed air layer within Green wall systems can augment the cooling effect, it simultaneously elevates indoor humidity levels significantly. The accumulation of humidity within the air layer of Green walls poses challenges, as excessive humidity can introduce latent heat into indoor spaces. To address this issue, careful consideration and proper design of natural ventilation systems are imperative. This observation aligns with findings from studies by [19] and [12].

Regarding heat flux, the South-oriented bare wall recorded the minimum incoming heat flux due to prolonged exposure to solar radiation throughout the day. Conversely, the West-oriented bare wall exhibited the highest incoming heat flux, as it received solar radiation predominantly during the late afternoon. Despite this, the West-oriented bare wall did not surpass ambient temperature due to its ability to dissipate heat effectively. Control walls, exposed to direct solar radiation, acted as heat sinks, accumulating substantial heat energy during midday hours. Although South, West, and North-oriented bare walls displayed incoming heat flux compared to East-oriented bare walls, the values were lower compared to Green walls for the same orientations. This underscores the superior thermal performance of Green walls across various orientations.

Considering the Green walls for all four orientations, the maximum incoming heat flux has been recorded for the West orientation Green wall with *Asparagus aethiopicus* while the minimum incoming heat flux has been recorded for the East-oriented Green wall with *Dianella ensifolia variegata*. Therefore, the Green wall with *Asparagus aethiopicus* performs well for South, East and West orientations while the Green wall with *Xiphidium caeruleum* performs well when it is oriented to North direction. The experimental study conducted by Pan et al. (2018) in Hong Kong, to determine the effect of orientation effect on thermal and energy performance of vertical greenery systems also found that the North- and East-facing walls with green walls had greater reductions in cooling load than the walls oriented to other orientations.

The Green wall with *Dianella ensifolia variegata* showed the maximum coverage of the bare wall for all orientations while recording the minimum incoming heat flux for all four orientations. Despite having a varied leaves density, the Green wall with *Asparagus aethiopicus*

performed effectively for South, East and West orientations. Therefore, it was evident that the Green wall with *Asparagus aethiopicus* can perform successfully in terms of energy savings with a higher leaves density in a tropical climate. The Green wall with *Xiphidium caeruleum* with a higher leaves density was able to reduce the energy consumption of a building for North orientation. Therefore, using a Green wall with *Xiphidium caeruleum*, with a higher leaves density more energy savings can be expected particularly for North orientation. The Green wall with *Ophiopogon japonicus* had a similar trend for South and East orientations, obtaining a lesser incoming heat flux with a lesser leaves density. Therefore, a Green wall with *Ophiopogon japonicus* with higher leaves density can be promising to obtain an effective energy performance for South and East orientations in a tropical climate. This bears out the importance of foliage density and the need for the healthy growth of plants for the effective energy performance of the Green walls. The Green wall with *Dianella ensifolia variegata* had the highest leaves density for all the four orientations. Therefore, it can be concluded that, for a Green wall with *Dianella ensifolia variegata*, the higher the leaves density, the lower it can contribute to the building energy savings. As the incoming heat flux of the Green wall with *Dianella ensifolia variegata* was lower compared to the other Green walls, the higher the cooling load requirement inside the building. However, the relationship between the leaves density and energy performance for the Green wall with *Dianella ensifolia variegata* has deviated from the other Green walls. The other plant traits such as vegetation color can be a possible explanation for such variations in obtained results [17].

The results of the present study align with findings from previous research conducted by [17] in Singapore and [12] in Indonesia, both of which demonstrated a correlation between leaf density and temperature reduction. These studies suggest that higher leaf density is effective in achieving greater energy savings. While our study also identified a similar relationship between leaf density and energy performance, it is important to note that different plant species were used across the studies. Although a generalized relationship between leaf density and thermal performance can explain the results, the observed deviations in the living wall with *Dianella ensifolia variegata* highlight the need to consider plant species alongside leaf density in future studies on building energy performance.

Additionally, the study suggests that instead of maintaining similar water content to a bare wall, using a wall with a geotextile layer and planting media inside pockets could mitigate the cooling effects of irrigation. It is important to note that this study only evaluated the impact of living walls during daytime (morning to evening), and future research should extend data collection to 24-hour periods to assess nighttime thermal performance, which may differ significantly from daytime results. Another key parameter for future analysis is the thickness of the foliage, as it plays a critical role in heat transfer [23]. While vegetation thickness is important, the percentage of surface coverage is crucial, as areas lacking adequate coverage are more susceptible to overheating [11]. Thus, leaf density is a vital factor in determining the shading and cooling effects of living walls. To further enhance the understanding of thermal performance, future studies should investigate the direct relationship between indoor and outdoor temperatures and plant leaf density.

Although the present study provides insights into suitable orientations for achieving optimal thermal performance, several limitations must be addressed for more robust conclusions. Firstly, the limited data collection timeframe, restricted to daytime hours, may not fully capture the diurnal cycle, potentially affecting the accuracy of thermal performance assessments over a 24-hour period. Additionally, the sample size—data collected for only five days per orientation—may be insufficient to account for variations in weather conditions, thereby limiting the reliability of the statistical analyses. Future studies should aim to expand the sample size and extend the duration of data collection to enhance the robustness of results.

Furthermore, the controlled environment in which the experiments were conducted may not reflect real-world conditions, where factors such as wind, solar radiation, and humidity can vary significantly. To draw more definitive conclusions, additional research is required to investigate seasonal temperature variations and solar intensity for specific geographic locations. Moreover, it is essential to explore the appropriate leaf density ratios necessary to create an effective green façade. Addressing these areas will contribute to a more comprehensive understanding of thermal performance in green wall systems.

6. Conclusions

East-oriented bare wall recorded the highest outgoing heat flux of while other bare walls showed an incoming heat flux indicating that the exterior wall could be acting as the primary source for the higher interior surface temperature of the East-oriented bare wall. Therefore, it was evident that the East-oriented bare walls required a higher energy consumption for the cooling of the building. The Green walls showed a higher incoming heat flux due to the canopy evapotranspiration effect. From the findings of the present study, it was evident that the Green walls reduced the heat energy that flowing into the interior, avoiding the overheat of the interior spaces particularly during the warmest hours of the day. Through absorbing a significant amount of heat energy, the Green walls affected the energy performance of the building. As there was a significant difference in the results obtained for the interior surface temperature for the Green walls with the interior surface temperature of the bare wall indicated the reduction of heat flow through conduction from the exterior surface of the Green walls than the bare wall. Therefore, from the results obtained, the contribution of Green walls was prominent in reducing the cooling loads and consequently reducing building energy consumption in the wet zone of a tropical climate. Considering the Green walls for all four orientations, the minimum incoming heat flux has been recorded for the East-oriented Green wall with *Dianella ensifolia variegata*. However, the maximum incoming heat flux is for the Green wall with *Asparagus aethiopicus* performs well for South, East and West orientations while the Green wall with *Xiphidium caeruleum* performs well when it is oriented to North direction.

The variations in the heat flux due to the influence of the leaves density were observed in the present study, to determine the building energy performance. Despite having a varied leaves density, it was evident that the Green wall with *Asparagus aethiopicus* can perform successfully in terms of energy savings with a higher leaves density in the wet zone of a tropical climate particularly for South, East and West orientations. For North orientation, it was evident that using a Green wall with *Xiphidium caeruleum* with a higher leaves density can result in more energy savings. Since the Green wall with *Xiphidium caeruleum* showed a higher incoming heat flux with a higher leaves density for East orientation, promising results for building energy performance can be expected from an East-oriented Green wall with *Xiphidium caeruleum*. For South and East orientations, a Green wall with *Ophiopogon japonicus* with higher leaves density can be encouraging to obtain an effective energy performance in the wet zone of a tropical climate. The Green wall with *Dianella ensifolia variegata* showed the maximum vegetation coverage for all orientations while recording the minimum incoming heat flux for all four orientations. It can be concluded that for a Green wall with *Dianella ensifolia variegata*, the higher the leaves density the lower it can contribute to the building energy savings. However, the relationship between the leaves density and energy performance for the Green wall with *Dianella ensifolia variegata* has deviated from the other Green walls, the other plant traits such as vegetation color can be a possible explanation for the variations in the obtained results. The results of this study show potential trends in the energy performance of a building with the orientation and leaves density of the Green walls. The findings of this study can be used when designing and allocating Green walls in the wet zone of a tropical climate.

However different results can be expected depending on the location and the surrounding environment of the building. Although this study focuses primarily on the thermal and energy performance of green walls under different orientations, it is important to acknowledge potential secondary consequences that may arise during real-world implementation. Factors such as increased mosquito habitats, the use of pesticides, and other ecological impacts, while beyond the scope of the present study, could present significant challenges if not managed appropriately. Future research should address these potential side effects to ensure that the deployment of green walls remains both effective and environmentally sustainable. Highlighting these considerations underscores the importance of a holistic approach when integrating green infrastructure into urban environments.

Author contributions

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References

1. Teng Y, Li K, Pan W, Ng T. Reducing building life cycle carbon emissions through prefabrication: evidence from and gaps in empirical studies. *Build Environ*. 2018;132:125–36. <https://doi.org/10.1016/j.buildenv.2018.01.026>
2. Wahba SM, Kamel BA, Nassar KM, Abdelsalam AS. Effectiveness of green roofs and green walls on energy consumption and indoor comfort in arid climates. *Civil Eng J*. 2018;4(10):2284. <https://doi.org/10.28991/cej-03091158>
3. Feltynowski M, Kronenberg J, Bergier T, Kabisch N, Łaszkiwicz E, Strohbach MW. Challenges of urban green space management in the face of using inadequate data. *Urban For Urban Green*. 2018;31:56–66. <https://doi.org/10.1016/j.ufug.2017.12.003>
4. Collins R, Schaafsma M, Hudson MD. The value of green walls to urban biodiversity. *Land Use Policy*. 2017;64:114–23. <https://doi.org/10.1016/j.landusepol.2017.02.025>
5. Sadeghian MM. A review on green wall, classification and function. *Int J Sci Res Sci Technol*. 2016;2(2):47–51.
6. Haggag MA. The use of green walls in sustainable urban context: with reference to Dubai, UAE. *WIT Trans Ecol Environ*. 2010;1:261–70. <https://doi.org/10.2495/arc100221>
7. Sari AA. Thermal performance of vertical greening system on the building façade: a review. In *AIP Conference Proceedings*. AIP Publishing; 2017.
8. Dahanayake KC, Chow CL, Long Hou G. Selection of suitable plant species for energy efficient Vertical Greenery Systems (VGS). *Energy Procedia*. 2017;142:2473–8. <https://doi.org/10.1016/j.egypro.2017.12.185>
9. Manso M, Castro-Gomes JP. Thermal analysis of a new modular system for green walls. *J Build Eng*. 2016;7:53–62. <https://doi.org/10.1016/j.job.2016.03.006>

10. Pérez G, Coma J, Sol S, Cabeza LF. Green facade for energy savings in buildings: the influence of leaf area index and facade orientation on the shadow effect. *Appl Energy*. 2017;187:424–37. <https://doi.org/10.1016/j.apenergy.2016.11.055>
11. Kontoleon KJ, Eumorfopoulou EA. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Build Environ*. 2010;45(5):1287–303. <https://doi.org/10.1016/j.buildenv.2009.11.013>
12. Widiastuti R, Caesarendra W, Prianto E, Budi WS. Study on the leaves densities as parameter for effectiveness of energy transfer on the green facade. *Buildings*. 2018;8(10):138. <https://doi.org/10.3390/buildings8100138>
13. Susorova I, Angulo M, Bahrami P, Brent S. A model of vegetated exterior facades for evaluation of wall thermal performance. *Build Environ*. 2013;67:1–13. <https://doi.org/10.1016/j.buildenv.2013.04.027>
14. Cuce E. Thermal regulation impact of green walls: an experimental and numerical investigation. *Appl Energy*. 2017;194:247–54. <https://doi.org/10.1016/j.apenergy.2016.09.079>
15. Pérez G, Rincón L, Vila A, González JM, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. *Appl Energy*. 2011;88(12):4854–9. <https://doi.org/10.1016/j.apenergy.2011.06.032>
16. Koyama T, Yoshinaga M, Hayashi H, Maeda K-i, Yamauchi A. Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. *Build Environ*. 2013;66:96–103. <https://doi.org/10.1016/j.buildenv.2013.04.020>
17. Wong NH, Kwang Tan AY, Chen Y, Sekar K, Tan PY, Chan D, et al. Thermal evaluation of vertical greenery systems for building walls. *Build Environ*. 2010;45(3):663–72. <https://doi.org/10.1016/j.buildenv.2009.08.005>
18. Mazzali U, Peron F, Romagnoni P, Pulselli RM, Bastianoni S. Experimental investigation on the energy performance of Living Walls in a temperate climate. *Build Environ*. 2013;64:57–66. <https://doi.org/10.1016/j.buildenv.2013.03.005>
19. Chen Q, Li B, Liu X. An experimental evaluation of the living wall system in hot and humid climate. *Build Environ*. 2013;61:298–307. <https://doi.org/10.1016/j.enbuild.2013.02.030>
20. Victorero F, Vera S, Bustamante W, Tori F, Bonilla C, Gironás J, et al. Experimental study of the thermal performance of living walls under semiarid climatic conditions. *Energy Procedia*. 2015;78:3416–21. <https://doi.org/10.1016/j.egypro.2015.12.160>
21. Pan L, Chu LM. Energy saving potential and life cycle environmental impacts of a vertical greenery system in Hong Kong: a case study. *Build Environ*. 2016;96:293–300. <https://doi.org/10.1016/j.buildenv.2015.06.033>
22. Sendanayake S. Development of an optimized integrated rainwater harvesting model for multistorey houses. 2010.
23. Olivieri F, Grifoni RC, Redondas D, Sánchez-Reséndiz JA, Tascini S. An experimental method to quantitatively analyse the effect of thermal insulation thickness on the summer performance of a vertical green wall. *Energy Build*. 2017;150:132–48. <https://doi.org/10.1016/j.enbuild.2017.05.068>