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Article

An Experimental Study on the Thermal Performance of Intensive Green Walls and Green Roofs in Temperate Continental Climatic Zones

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Abstract: Green facades and roofs are prevalent in various building typologies across most climatic regions. In warm contexts with the presence of cooling needs, numerous empirical and theoretical studies showcase the effectiveness of these systems in regulating the internal thermal conditions of spaces. The research addresses a gap in the literature concerning experiences with living green roof and green wall systems in cold climatic conditions. Considering the climate in Quito, characterized as a 4C type climate according to ASHRAE, which entails combined heating and cooling needs, this research aims to assess and compare the thermal performance through an empirical methodology based on the construction of two physical prototypes—one with vegetated elements and one without. Throughout the investigation, a comprehensive database of temperature and relative humidity records was compiled from four experiments conducted during both dry and rainy seasons. The findings of the experimental study indicate that these systems not only help in lowering temperatures during the day but also possess the capability to maintain temperatures during the night and early morning and addresses that during periods of heavy rainfall, yet the vegetated prototype exhibited consistent thermal performance, indicating resilience to adverse weather conditions. These findings suggest that green walls and roofs can maintain their effectiveness even in challenging weather scenarios.

Keywords: green roof; green wall; relative humidity; living wall; thermal performance

1. Introduction

Green walls and roofs have become distinctive features in low-rise buildings, tall structures, and various facilities across hot, temperate or cold cities, are implemented by architects and specialized suppliers (Manso & Castro-Gomes, 2015). Despite their widespread use, these elements are often chosen for their aesthetic appeal rather than their functional, well-being, and health benefits (Fonseca et al., 2023; Villacis-Ormaza, 2023).

Given the current climate crisis and the rapid urbanization of various regions worldwide (Buhaug & Urdal, 2013; Chowdhury et al., 2021), it is crucial to recognize that buildings should not be designed merely as objects but rather as a process that generates positive impacts directly on the building itself and, similarly, on the environmental system it encompasses (Hes & du Plessis, 2014; Villacis-Ormaza & Moya-Vicuña, 2021). One of the main concerns is associated with climate change, leading to variations in the planet's temperature ranging from 1.1 °C to 6.1 °C as stated in the IPCC AR6 report and other studies (Calvin et al., 2023), which, in turn, is linked to global CO_2 emissions (Calvin et al., 2023; Friedlingstein et al., 2020; Villacis-Ormaza & Moya-Vicuña, 2021). In the field of construction and architecture, the production of CO_2 accounts for a quarter of the total global emissions (Friedlingstein et al., 2020), with a significant portion of this impact attributed to the implementation and operation of building air conditioning systems (HVAC) (Ghahramani et al., 2018; González-Torres et al., 2022; Rafsanjani et al., 2020).

The research addresses a gap in the literature concerning experiences with living green roof and green wall systems in cold climatic conditions (Bowler et al., 2010; Xing et al., 2019). While numerous studies have focused on warm climates (Morakinyo et al., 2019), there is limited documented information on the performance of green infrastructure in cold climates characterized by heating degree days (HDD). This research contributes valuable insights into the thermal performance of green walls and roofs in a temperate continental climatic zone, providing essential knowledge for architects, engineers, and urban planners in similar regions (Gao et al., 2023).

The use of vegetation in building envelopes in cities with cold conditions, such as Quito (ASHRAE Climate Zone 4C) (ANSI/ASHRAE, 2021), has been predominantly confined to the outdoor areas of structures. In many instances, it is only incorporated as furniture or decorative elements within interior spaces. The incorporation of vegetation as integral components of building facades and roofs has been and continues to be a subject of investigation in the fields of architecture and construction (Besir & Cuce, 2018b). This exploration aims to comprehend the contributions and limitations of these systems beyond their visual and spatial compositional qualities (Manso et al., 2021; Ormaza et al., 2022).

These ecosystem services are known as urban green infrastructures, which enable architects and planners to achieve improvements such as energy savings, hygrothermal comfort, reduction of heat islands, treatment of rainwater, and enhancement of air quality, among other benefits (Jamei et al., 2023a; C. N. Nguyen et al., 2021; Raji et al., 2015; Vicuña & Ormaza, 2021). In the realm of temperature and humidity control or regulation, numerous published studies focus on warm climates (ASHRAE Climate Zones; CZ0, CZ1, CZ2, CZ3) (ANSI/ASHRAE, 2021; Detommaso et al., 2023) where there is a need for cooling or cooling degree days (CDD). The results highlight that various green roof systems (GRs) and green walls (GWs) can reduce the interior temperature of the building, prevent overheating from solar exposure, control indoor humidity, and decrease energy usage (Besir & Cuce, 2018a; Chen et al., 2013; Hunter et al., 2014; Perini et al., 2017; Ruiz-Valero et al., 2022; Tan et al., 2020; Vox et al., 2018; Xing et al., 2019).

However, there is limited documented information on experiences with green roof systems (GRs) and green wall (GW) systems in cold climatic conditions (Xing et al., 2019), where there is a need to meet heating requirements indicated by the quantity of heating degree days (HDD) (Bakhshoodeh et al., 2022). Similarly, there is a lack of information in contexts where there is a presence of both HDD and cooling degree days (CDD) requirements within short time periods (Nan et al., 2020). The objective of this research is to assess the thermal performance by analysing and comparing the internal temperature and relative humidity of prototypes consisting of green wall (GW) and green roof (GR) envelopes in a cold context (4C), characterized predominantly by HDD demands and partially by CDD.

The Heating Degree Days (HDD) and Cooling Degree Days (CDD) are essential metrics for assessing the energy demands of heating and cooling according to climate. The HDD measures the incremental temperature difference below a set base, usually 18 °C, indicating the need for heating. Conversely, the CDD calculates the difference accumulated by the end of that base, indicating the cooling demands. These metrics are essential for optimizing building design and energy systems (Corrales-Suastegui et al., 2021).

2. Materials and Methods

2.1. Methodology

The purpose of the methodology is to conduct a comparison of the internal and external thermal performance of two prototypes, differing solely in the incorporation of green walls and roofs.

The method employed resembles an applied experimental investigation, characterized by its quantitative approach and reliance on the use of prototypes. The procedure involves the design, execution, and monitoring of experimental prototypes, allowing the phenomena observed to be quantified and examined under controlled conditions. This method aims to identify cause-and-effect relationships between specific variables, such as the presence of vegetation, temperature, and humidity, and their impact on the thermal behaviour of the prototypes (Medl et al., 2017; Wang et al., 2024).

The primary goal of this method is to compare the thermal performance, both internal and external, of two modules designed with similar attributes, differing only in the inclusion of green walls and roofs. According to authors such as Polo and Francis (Francis & Jensen, 2017; Polo-Labarrios et al., 2020) this comparison is expected to facilitate an unbiased assessment of the impact of these vegetative solutions on environmental regulation and thermal comfort.

According to Camburn (Camburn et al., 2017), experimental prototyping methods are highlighted as a fundamental approach for investigating, evaluating, and improving the performance of complex systems under specific conditions. Their relevance in studies such as the present one is underscored by their ability to generate empirical knowledge through the iterative interaction between the design, implementation, and analysis of prototypes, as noted by Ascione in his review (Ascione et al., 2020).

In this context, the application of experimental prototyping is considered appropriate as it facilitates the identification of evident causal links between variables (Pozo Puértolas & Diaz Castañón, 2023), such as vegetation, internal temperature, and humidity, with the thermal behaviour of the analysed prototypes. Furthermore, these procedures not only provide precise quantitative data but also enable the validation of innovative solutions in controlled settings before scaling up, which is crucial for ensuring the effectiveness and sustainability of architectural interventions in real-world scenarios (de Asiain-Alberich et al., 2022). Thus, experimental prototyping is regarded as a robust scientific foundation that integrates theoretical design with empirical validation, thereby ensuring the accuracy and relevance of the results obtained.

Various studies have demonstrated that multivariate analyses incorporating temperature and humidity provide a more detailed understanding of thermal regulation and energy savings in sustainable systems (Aparicio-Ruiz et al., 2023; Fanger, 1970; Fanger, 1986). These parameters and measurement criteria are not only grounded in a solid scientific foundation (Grimnes & Martinsen, 2015), but are also aligned with global best practices in experimental design for sustainable architecture and environmental performance assessment.

The mentioned parameters are widely supported in the scientific literature as key indicators for evaluating the energy efficiency and environmental performance of building systems. The selection of each indicator is justified below.

The parameter of indoor air temperature is considered crucial as it is directly related to thermal comfort, as noted by Langner, Fanger, and Seyam (Fanger, 1986; Gao et al., 2023; Langner et al., 2025; Seyam, 2019). This parameter is also standardized by ASHRAE Standard 55 (ASHRAE, 1992) and associated with energy demand for heating or cooling, as highlighted in the same Standard (ASHRAE, 1992) and thermo-technical research by Gonzalez-Torres, which mentions that HVAC systems consume up to 38% of a building's energy (González-Torres et al., 2022), or up to 40%, according to recent state-of-the-art studies by Ahmad (Ahmad et al., 2016). Various studies have demonstrated that monitoring indoor air temperature allows the quantification of heat retention and dissipation properties of diverse materials and construction systems (Santana et al., 2022), including vegetated systems (Arabi et al., 2015; Rosenzweig et al., 2006; Sun et al., 2012).

On the other hand, relative humidity is considered essential for evaluating occupant comfort and the moisture control properties of a building (J. L. Nguyen et al., 2014). Relative humidity refers to the amount of moisture expressed as a percentage of the saturation pressure at a given temperature (Alsmo & Alsmo, 2014). Excessive humidity or dryness levels are shown to affect both comfort perception and energy efficiency, as noted by authors such as Olgyay and Givoni (Ajibola, 2001; OLGYAY et al., 2015). Its inclusion is supported in the literature, as it interacts with temperature to influence cooling and heating needs (Benarie, 1984; Seyam, 2019), particularly in systems incorporating green roofs or walls, which impact evaporative cooling processes (Alsmo & Alsmo, 2014).

The decision to conduct four experiments at separate times ensures the robustness of the dataset and allows for a comprehensive analysis under diverse conditions, ensuring that observed variations are not the result of random factors but rather the inherent behaviour of the local climate. For instance, experiments in controlled environments provide valuable insights into the performance, potential, and challenges of vegetated systems during periods of peak heating or cooling demand, as highlighted in studies on dynamic living wall plants (Wang et al., 2024). Similarly, prototype experimentation is used to validate theoretical information regarding the performance of green walls and green roofs in cold environments (Safikhani & Baharvand, 2017).

2.2. Study Area and Climatology of the Region

This research was conducted in Quito, Ecuador (−0.120694, −78.498677), located in South America at an average altitude of 2850 meters above sea level. The city is situated on the eastern slopes of the active volcano Pichincha as seen on Figure 1. Its urban area spans over 370 km^2, and as of the last population census in 2010, it is home to two and a half million inhabitants (Instituto Nacional de Estadística y Censos INEC, 2014). The city's topography is characterized by rugged terrain due to its location in the Andean region. Additionally, the area faces a high seismic risk, posing a degree of vulnerability to buildings (Cunalata & Caiza, 2022).

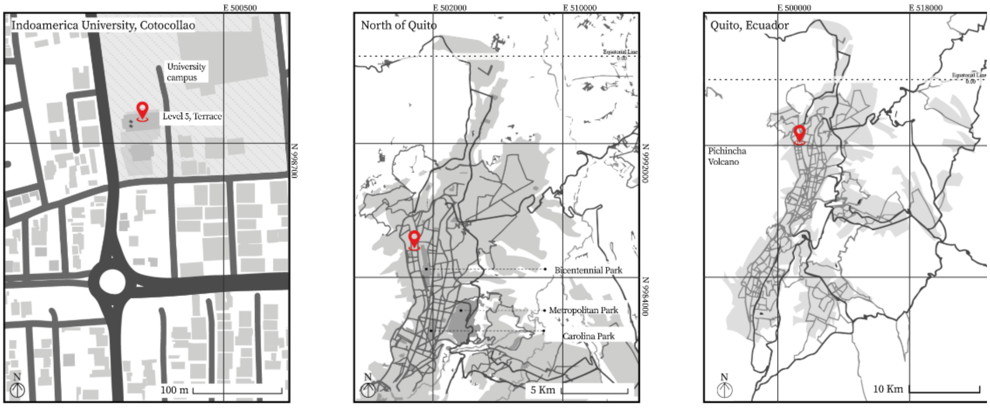


Figure 1. Site location of experiment.

According to ASHRAE (ANSI/ASHRAE, 2021) and the Ecuadorian construction standard issued by MIDUVI(MIDUVI, 2018), the Andean region of Ecuador experiences a rainy and cold season as well as a dry season, placing Quito in a rainy continental climatic zone (4C). This is characterized by a thermal criterion of CDD10 °C ≤ 2500 and HDD18 °C ≤ 2000 (MIDUVI, 2018). In addition to these conditions, a thermal and energy analysis variable is considered, such as solar radiation, maintaining an average insolation of 4574.99 Wh/m^2/day (Consejo nacional de electricidad (CONELEC), 2008).

According to the information collected from the EPW file of the 840710 WMO station at the National Institute of Meteorology and Hydrology of Ecuador, as shown in Figure 3, we can determine that, in order to enhance the habitability and comfort conditions in the 4C climatic zone, there is a need for heating, and to a slightly lesser extent, a need for cooling as noticed in Figure 3 (MIDUVI, 2018). This requirement exists within the same day-night cycle, considering that the region also receives substantial amounts of rainfall.

In this region, aiming to achieve a level of climatic-habitational comfort, INER recommends the use of passive strategies such as thermal inertia, natural ventilation, solar protection, and enhancing building insulation to minimize heat losses (Godoy et al., 2017). In the Building Bioclimatic Chart by Givoni or the Psychrometric Chart for the city of Quito generated by INER as seen on Figure 2, it is evident that by minimizing heat losses, we can improve the comfort conditions of interior spaces by 58.8%. This proves to be the most relevant and effective strategy according to the chart.

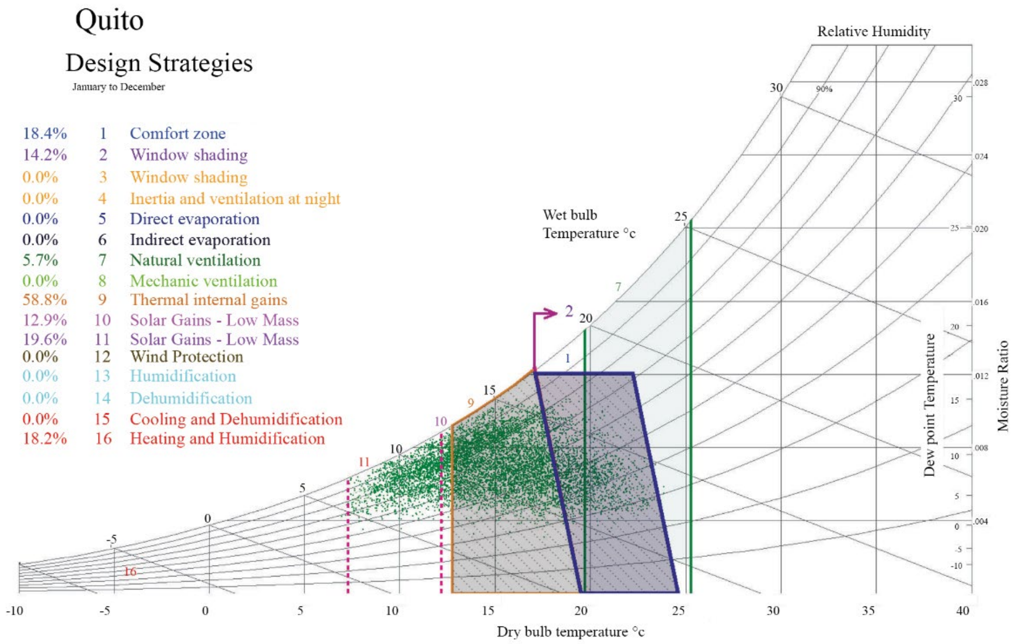


Figure 2. Quito´s psychrometric chart. Original source: INER.

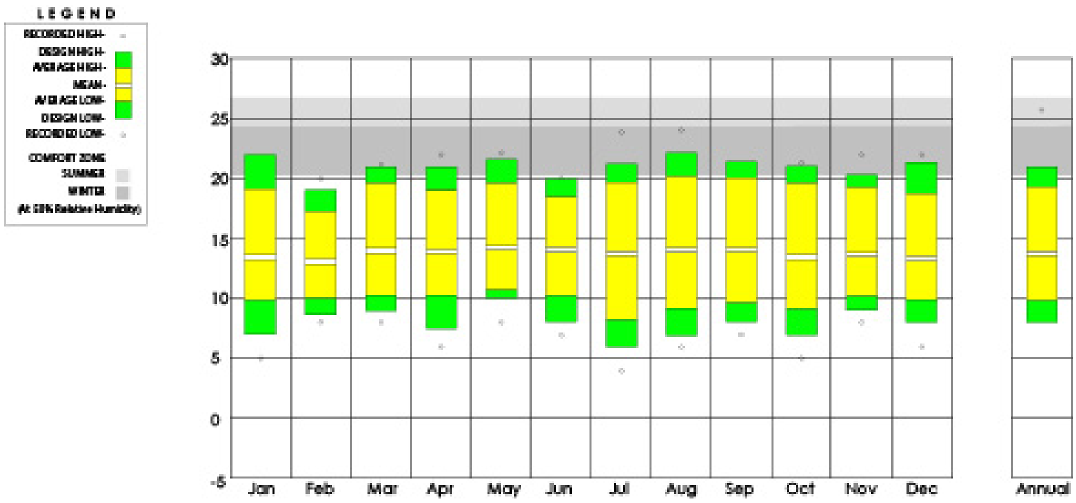


Figure 3. Quito´s annual temperature range. Software source: Climate consultant. Data Source: Station Number 840710 WMO.

2.3. Design and Setup of Experimental Prototypes for Data Collection

Two prototypes with identical characteristics were created as seen on Figure 4 and Figure 5, simulating the envelopes of common buildings in the urban areas of Quito as stated by Brito-Peña et al (Brito-Peña et al., 2022). As part of these conditions, the aim was to maintain thermal insulation in the envelope through a thermal conductivity similar to the construction system of 190 mm thick cement block masonry (λ: 0.312 W/mK) (Martínez Gómez & Macias, 2018). This was achieved by using 8mm thick recycled Tetra Pak (polyaluminum) panels as the envelope material (λ: 0.220 W/mK) (Ecuaplastic, 2022).

Each prototype has a surface area of 1.44 m^2 and an air volume of 2.88 m^3, composed of a perimeter steel structure (100 mm × 100 mm × 4 mm) covered and sealed on all sides with 8mm thick recycled tetrapak (polyaluminum) panels. The prototypes used in the experiment were positioned in such a way as to avoid creating shadow zones or blocking solar incidence between them. Both prototypes were oriented with an azimuth angle of 45° relative to the north (refer to Figure 3) (Gao et al., 2023). This positioning was chosen to ensure that in the morning, both the vegetated and non-vegetated facades receive solar exposure, and similarly, in the afternoon, the vegetated facade and the remaining non-vegetated facade also receive direct solar exposure.

2.3.1. Prototype 1

Prototype 1 (P1), or the improved case, has its northwest and southeast facades covered by a hydroponic vegetation system fed through automatic dripping. This system consists of four layers: the first layer comprises a framework of aluminium profiles mechanically anchored to the prototype structure using self-tapping 1 inch screws; the second layer consists of an impermeable panel made of 8mm thick recycled Tetra Pak (polyaluminum) panels; the third layer is formed by two 3 mm thick phytoregenerative poly-felt panels, each attached to the previous layer with metal staples; the fourth layer corresponds to the bare-root vegetation cover consisting of native and introduced species, as shown in Figures 6 and 8.

At the top of the northwest and southeast facades, an irrigation system was incorporated, fed by two 25-gallon reservoirs. One reservoir contains water, while the second holds a solution of nutrients dissolved in water, such as nitrogen, phosphorus, potassium, and in smaller quantities micronutrients like calcium, sulphur, iron, magnesium, boron, manganese, zinc, molybdenum, copper, and cobalt. The irrigation system is controlled by solenoid valves with a flow rate of 0.6 litres/minute, programmed to activate for one minute at 30-minute intervals under normal conditions, and for one minute at 15-minute intervals during high-temperature conditions or plant adaptation periods.

Prototype 1 (P1), on its upper face or roof, consists of a semi-intensive green roof with a soil substrate on a Ø50 mm stone drainage layer with sand. These layers are enclosed by geotextile and plastic sheets, which, in turn, are bounded along their entire perimeter by a wooden container, as shown in Figures 7, 8 and 9. The green roof is installed on a double-layer roof composed of two sheets of impermeable panels made of 8 mm thick recycled Tetra Pak (polyaluminum) panels, with a naturally ventilated intermediate space of 200 mm.

The vegetation layer of the facades and roof was composed of different types of native and introduced plants adapted to the climatic conditions as shown in Figures 8 and 9, readily available in local municipal and private nurseries. In the plant selection process, those were chosen that exhibited a quick adaptation after transplantation, had a short root system, and could be sustained without soil substrate but with hydroponic systems (see Figures 8, 9 and 10).

This prototype integrates both vegetated solutions, combining a green roof and a green wall within a single structure, with the objective of evaluating their combined performance. The focus is placed on analyzing the synergy between both systems to maximize benefits in thermal regulation, indoor comfort improvement, and energy efficiency. This vegetated system is designed to mitigate thermal peaks and enhance thermal comfort, particularly under conditions of high solar radiation and during periods of the lowest temperatures.

2.3.2. Prototype 2

Prototype 2 (P2), or the base case, has all four facades without any type of protection or artificial or natural shading elements. The roof of the prototype consists of a double-layer system composed of two sheets of impermeable panels made of 8 mm thick recycled Tetra Pak (polyaluminum) panels, with a naturally ventilated intermediate space of 200 mm.

This prototype is used as a baseline reference for the research, representing a conventional structure without vegetated systems. Its primary objective is to provide comparative data on interior temperature, interior relative humidity, and exterior surface temperature, allowing for the identification of differences in thermal and environmental behaviour between traditional solutions and vegetated proposals.

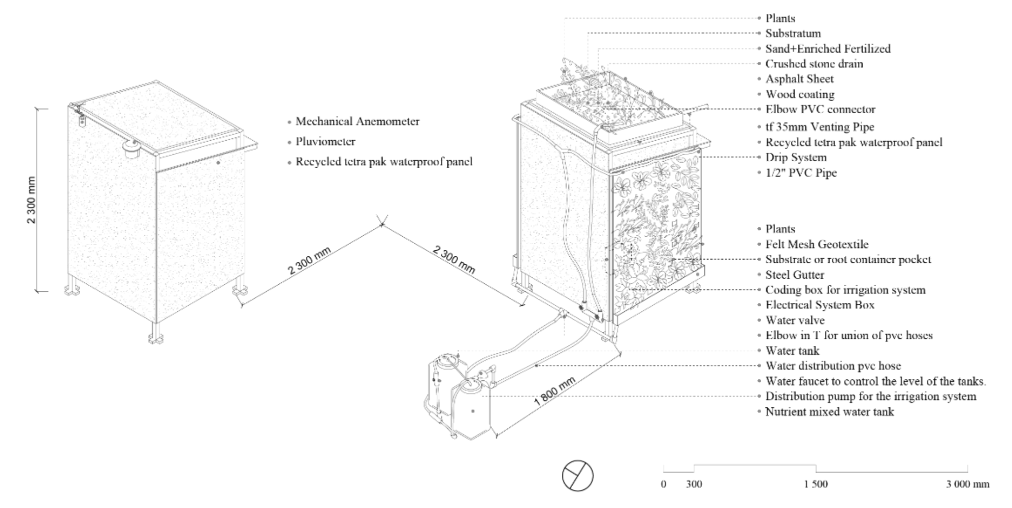


Figure 4. Axonometric drawing of prototype 1 (**right**) and prototype 2 (**left**). Drawing by Kamila Ramirez & Kristopher Buitron.

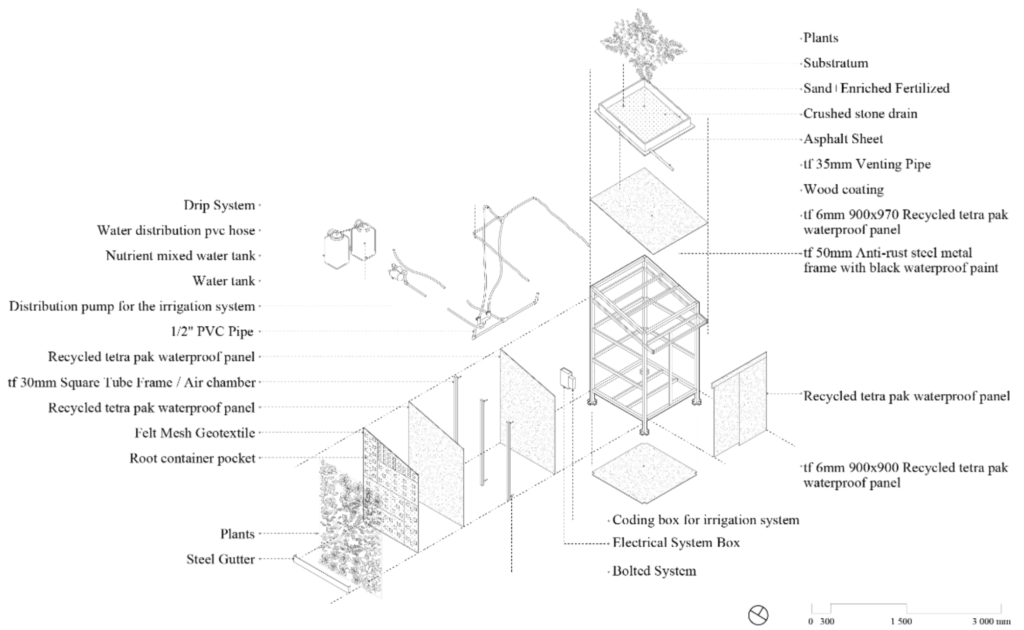


Figure 5. Exploded axonometric drawing of prototype 1. Drawing by Kamila Ramirez & Kristopher Buitron.

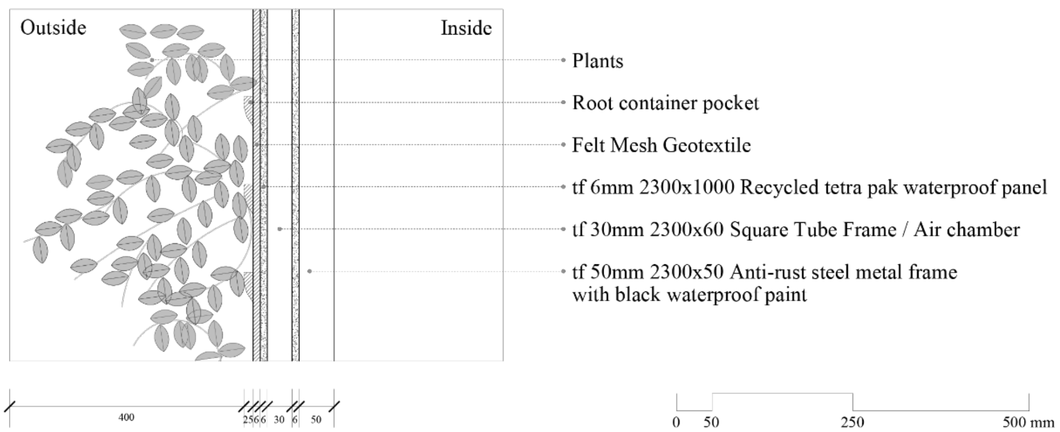


Figure 6. Detail section of hydroponic system. Drawing by Kamila Ramirez & Kristopher Buitron.

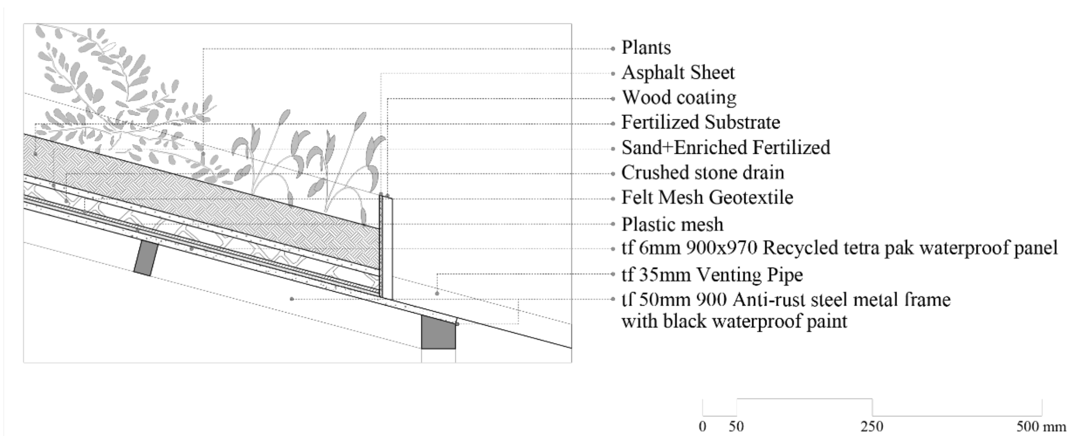
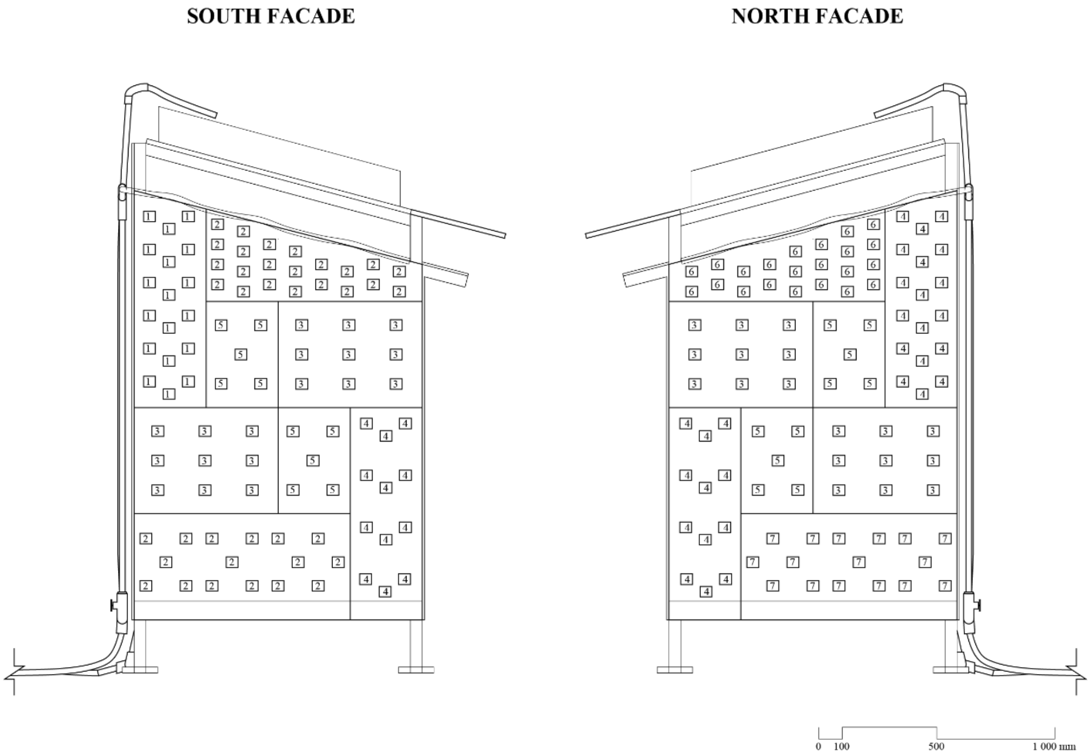


Figure 7. Detail section of vegetated pitched roof. Drawing by Kamila Ramirez & Kristopher Buitron.



No.	Scientific Name	Common Name	Cant.
1	Alternanthera porrigens	Alcancel, Moradilla	18
2	Chlorophytum comosum	Mala madre	38
3	Nephrolepis exaltata	Helecho	27
4	Magnoliopsida	Vinca	39
5	Bergenia crassifolia	Hortensia	23
6	Calamagrostis effusa	Pajonal	17
7	Aerva Sanguinolentaa	Escancel Rojo	20

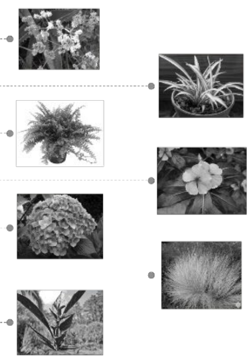
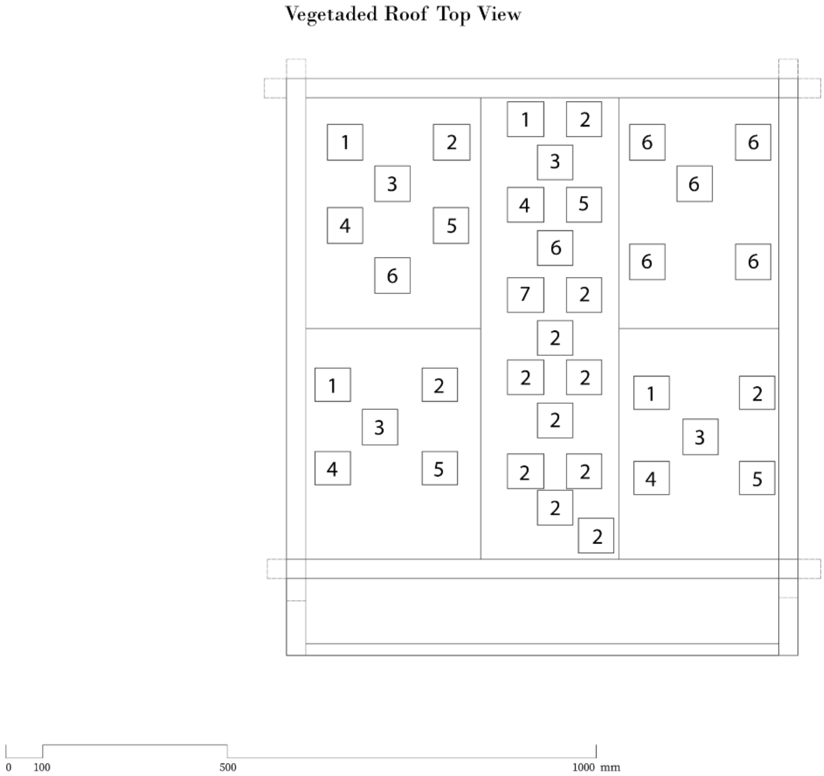


Figure 8. Facade´s plant placement of P1. Drawing by Kamila Ramirez & Kristopher Buitron.



No.	Scientific Name	Common Name	Qty
1	Alternanthera porrigens	Alcancel, Moradilla	4
2	Chlorophytum comosum	Mala madre	13
3	Nephrolepis exaltata	Helecho	4
4	Magnoliopsida	Vinca	4
5	Bergenia crassifolia	Hortencia	4
6	Calamagrostis effusa	Pajonal	7
7	Aerva Sanguinolentaa	Escancel Rojo	1

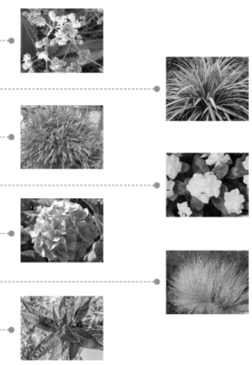


Figure 9. Roof´s plant placement of P1. Drawing by Katherine Armijos.

Figure 10. Images of base case prototype and vegetated prototype.

2.4. Experimental Prototyping, Tools and Equipment

To simulate the optimal conditions of Prototype 1, the vegetation layer of the green wall and roof underwent a 12-week adaptation and maturation period. During this time, efforts were made to ensure the plants were in optimal condition, aiming for the green wall and roof vegetation coverage to reach 90% of the total area as noticed in Figure 10.

Precision thermal couples (Table 1) calibrated for recording data at 15-minute intervals were used for internal temperature and relative humidity measurements (The 15-minute intervals were chosen as it was the minimum time allowed to calibrate the device). These thermal couples were suspended at the centre of each prototype, maintaining the same distance between the four walls and also between the base and cover. Throughout the measurements, both prototypes were kept sealed without opening the door during the various data collection periods. The objective was to prevent air infiltrations through the joints and gaps in the envelope (Hassouneh et al., 2012). To initiate the recording of measurements, a 24-hour period was observed after sealing and maintaining the prototypes in a sealed condition. The 24-hour waiting period was necessary to allow them to achieve temperature equilibrium. By stabilizing inside conditions, this reduced temperature and humidity variations and produced more precise and trustworthy readings.

The external temperature, wind, and rainfall conditions were monitored and recorded using a fixed weather station (Table 1) located in the same study area. The prior assessment of these climatic conditions enabled adjustments to be made for certain vegetation specimens susceptible to strong winds or frost. Similarly, the study of precipitation and solar incidence allowed us to configure two types of irrigation for the hydroponic substrate system of the green walls: the first for the dry period (June–August) using drip irrigation with a duration of 1 minute every 10 minutes, and for the rainy season (September–May) with a duration of 30 seconds every 15 minutes.

Table 1. Characteristics of the measurement instruments.

Parameters	Instrument	Measuring Range	Accuracy
Indoor air temperature (°C)	Elitech RC-4HC	−40 °C to 85 °C	±0.5 °C
Indoor relative humidity (%)	Elitech RC-4HC	0% to 99%	±3%RH (25 °C, 20%RH to 90%RH), ±5%RH(other range)
Surface temperature (°C)	NF-521	−20 °C to 400 °C	±1.8% (0 °C to 400°)
Rainfall (mm)	Ecowitt WH536	0–6000 mm	±5%
External wind speed (m/s)	Ecowitt WS68	0–50 m/s	±1 m/s (<5 m/s), ±10% (≥5 m/s)

2.5. Growth Behaviour of the Vegetation Layer in Green Walls

The vegetation layer on both walls of Prototype 1 underwent growth and adaptation for four months before the initial measurement recording. During this period, the plant elements developed their root systems and anchored themselves through the geotextile. One indicator of the system's maturity was the abundant flowering observed in the perennial flowering species (Kontoleon & Eumorfopoulou, 2010).

In the third month, a malfunction in the drip system occurred, resulting in the degradation of 20 plants in two consolidated patches. These plants had to be replaced with new ones of the same species, accounting for 10.99% of the coverage. Despite this, the vegetation percentage reached maturity, albeit with some limitations in providing uniform shade and controlling heat transfer in those areas.

During experiments 3 and 4, scheduled pruning was carried out as part of the maintenance of the green wall and green roof. This pruning was emphasized in two vegetation varieties: the Calamagrostis effusa species and alternanthera porrigens. However, even after pruning, the total coverage of their implantation areas was maintained.

2.6. Growth Behaviour of the Vegetation Layer in Green Roofs

The vegetation arranged on the green roof underwent a single change during the prototype assembly phase for wind attenuation reasons. As the experiments were conducted in a steep area, the northeast strip was reconfigured with the native species Calamagrostis effusa, which effectively controlled excessive wind for the rest of the ornamental species. The bio indicator that allowed us to confirm the proper wind control was the presence of nests and eggs of the local bird species Zenaida auriculata.

2.7. Data Collection

Four experiments were conducted during the months of July to September 2022, each spanning periods of 5 to 10 days (Table 2). The objective was to record events characterized by high radiation levels as mentioned in Parra and Flores report (Parra et al., 2019) (on-site UVI recorded at 11) as well as the occurrence of rainfall (on-site recordings of 8.3 mm and 18.6 mm/hr), both phenomena typical of the region. The purpose was to facilitate temperature and humidity comparisons.

Another data derived from the experiment was the recording of external temperature through thermal imaging (Figures 11 and 12), where higher temperatures were observed compared to the baseline or Prototype 2.

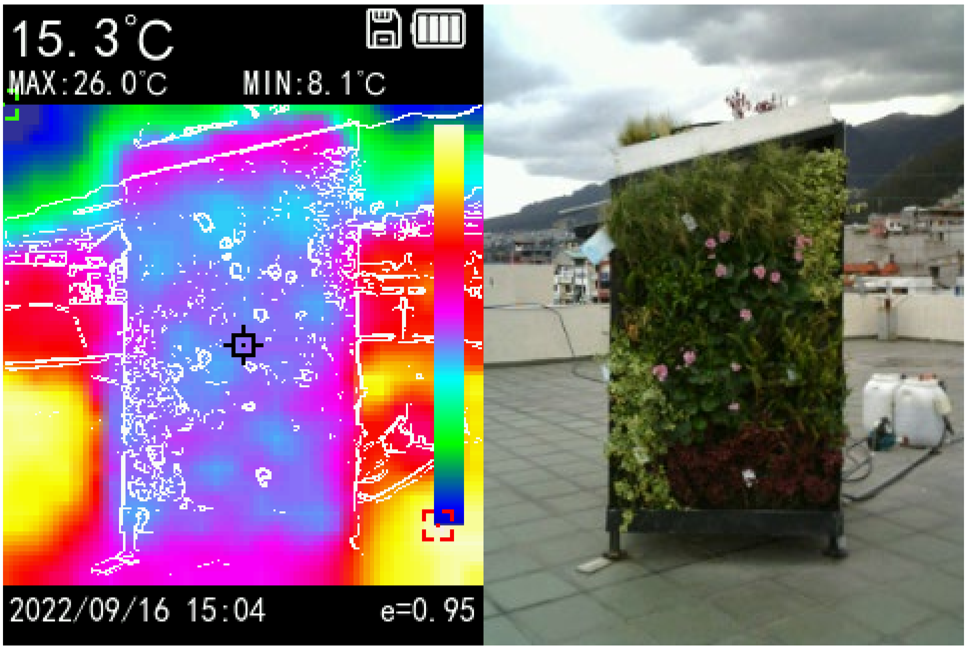


Figure 11. Thermal imaging of north-east façade of prototype 2.

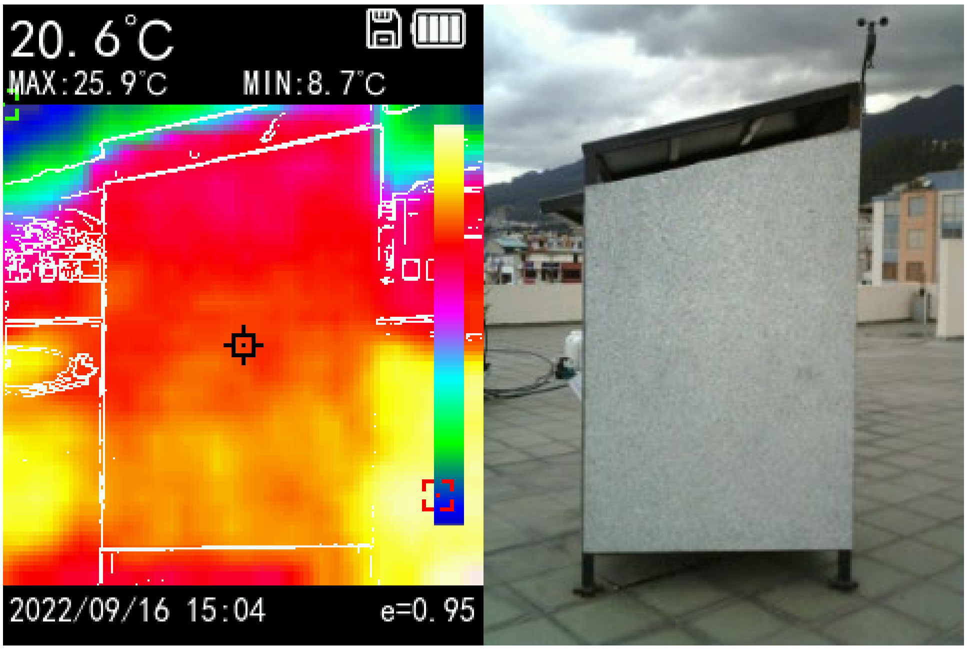


Figure 12. Thermal imaging of north-east façade of prototype 1.

Table 2. Experiments periods.

No. of experiment	Start date (2022)	End Date (2022)	Climatic season	Precipitation days (rainfall > 0.5 mm)	UV Max Index	Average solar irradiance (W/m^2)
Experiment 1:	July 4	July 8	Dry season	0/6	10	375.4
Experiment 2:	July 11	July 19	Dry season	4/9	10	368.2
Experiment 3:	July 25	August 8	Dry season	3/15	11	412.2
Experiment 4:	August 19	September 5	Wet season	8/18	11	298.3

3. Results and Discussion

3.1. Temperature Variations

In the different experiments, daily abrupt temperature variations were recorded, which are typical in Quito's climatology. The temperature inside experienced a variation of 15.5 °C, with average environmental temperature changes of 19.4 °C. The maximum temperature was reached between 12:15 PM and 1:45 PM, while the minimum temperatures occurred at dawn between 5:30 AM and 6:30 AM.

This phenomenon allowed us to identify two moments of interest regarding the thermal performance of the prototypes in this study, namely, the peak highs and lows of temperature (see Figures 13, 14, 15, 16).

It is deduced from the experiments that the presence of green roofs and green walls played a pivotal role in reducing daytime temperatures by up to 4.3 °C, representing a 10% greater reduction compared to the prototype without vegetation (Table 3). This observed phenomenon of controlling temperature aligns with expectations drawn from an extensive literature review(Besir & Cuce, 2018b; Jamei et al., 2021; Jamei et al., 2023b; Olivieri et al., 2017; Song et al., 2025). Notably, during night-time hours, when temperatures tend to drop, departing from the thermal comfort range in the area, the vegetated prototype demonstrated a superior ability to maintain internal temperatures by a modest percentage (<1.0 °C). This is clearly evident in the data presented in Table 3 and the comparative charts for each experiment.

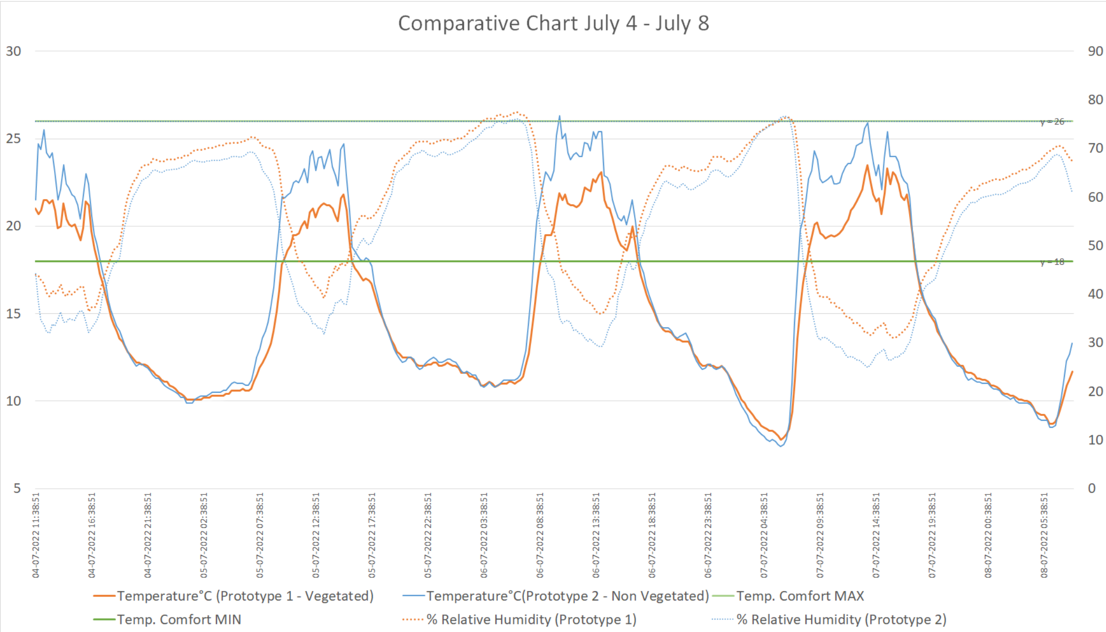


Figure 13. Comparative chart of experiment 1.

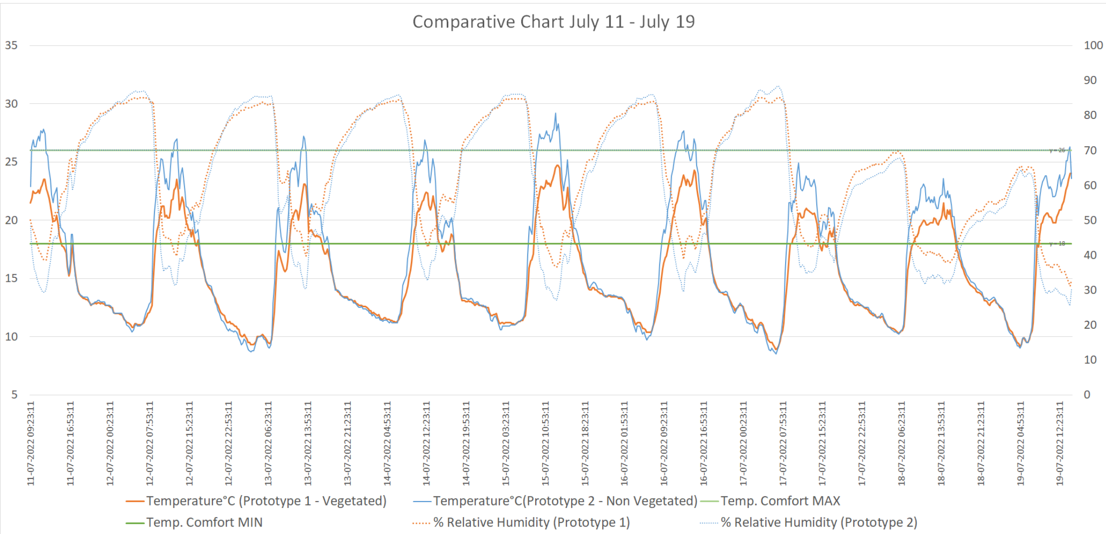


Figure 14. Comparative chart of experiment 2.

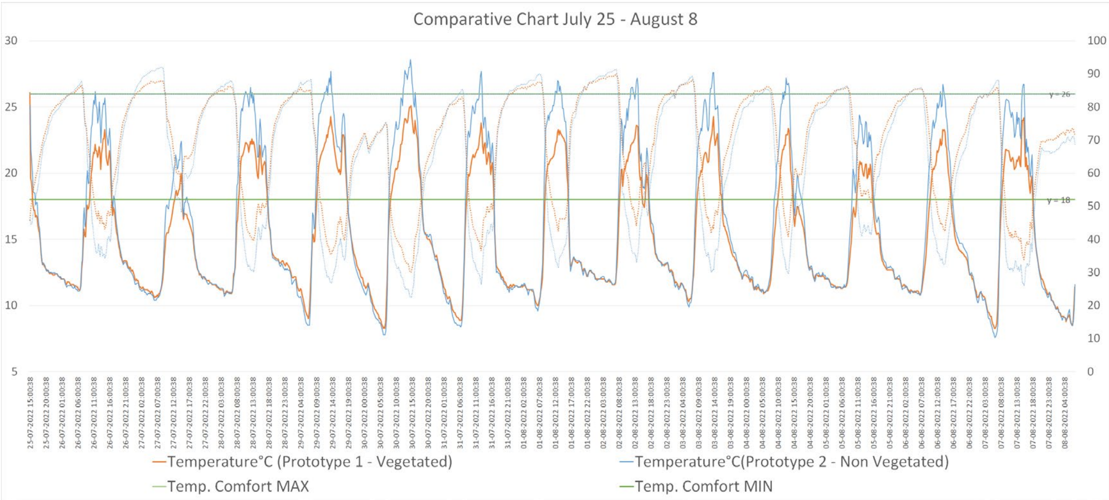


Figure 15. Comparative chart of experiment 3.

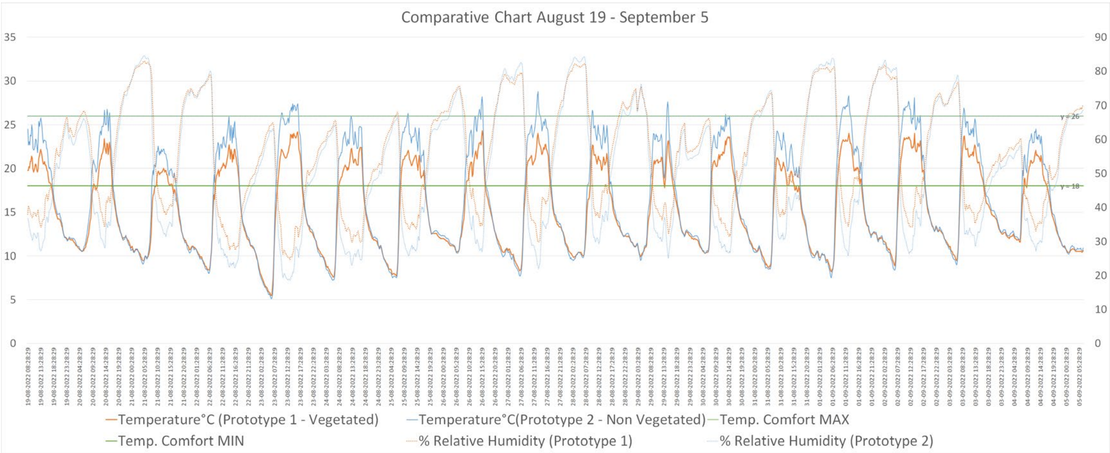


Figure 16. Comparative chart of experiment 4.

Delving into the dataset amassed during these experiments, detailed in Table 4, it becomes apparent that the maximum temperature recorded within the vegetated prototype was consistently lower, ranging from 2.8 °C to 4.3 °C, with the most substantial temperature difference noted during the rainy period. Conversely, a meticulous examination of the minimum temperatures in Table 4 reveals that the vegetated prototype experiences a more modest temperature loss, ranging from 0.4 °C to 0.7 °C. This underscores the ongoing recommendation to advocate for and implement green walls and roofs for effective thermal regulation in Quito.

Table 3. Accumulated temperature and difference of prototypes (13 days long).

Prototype 1 (P1)			**Prototype 2 (P2)**			**Difference value (P1-P2)**		
Day	Night	All day	Day	Night	All day	Day	Night	All day
11626,20	7992,40	19618,60	12920,20	7941,10	20861,30	−1294,00	51,30	−1242,70

Table 4. Indoor temperature and relative humidity.

Date Range		**GR & GW–Prototype 1**			**Base case–Prototype 2**		
		Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Experiment 1: July 4–July 8 (376 readings)	Indoor temperature (°C)	23,50	7,80	14,88	26,30	7,40	15,85
	Indoor relative humidity (%)	77,40	31,00	58,04	76,60	24,90	53,66
Experiment 2: July 11–July 19 (795 readings)	Indoor temperature (°C)	24,30	8,90	15,22	27,70	8,50	16,21
	Indoor relative humidity (%)	85,10	31,10	60,49	88,40	25,60	56,72
Experiment 3:	Indoor temperature (°C)	24,20	8,30	14,76	27,20	7,60	15,77

July 25–August 8 (1314 readings)	Indoor relative humidity (%)	86,10	33,90	68,25	88,20	26,00	63,11
Experiment 4: August 19–September 5 (1632 readings)	Indoor temperature (°C)	24,00	8,90	15,80	28,30	8,40	16,88
	Indoor relative humidity (%)	81,80	33,10	56,20	83,30	25,70	52,79

Turning our attention to relative humidity, a comprehensive analysis of all records summarized in Table 4 highlights the superior performance of vegetated prototypes, showcasing fewer instances of high and low humidity peaks. However, when considering average records, the humidity values fluctuate between 56.2% and 68.25%, whereas the prototype without vegetation maintains more favourable ranges, oscillating between 52.79% and 63.11%. Consequently, in vegetated buildings, it becomes imperative to devise strategies aimed at marginally reducing relative humidity. Nevertheless, it is crucial to note that ASHRAE Standard 62.1-2016 recommends maintaining relative humidity in occupied spaces at levels below 65% to minimize the likelihood of conditions conducive to microbial growth and other issues. This phenomenon is observed in both the improved case and the vegetated prototype and is not solely attributable to the presence of green walls and roofs.

3.2. Influence of Rainy Days on Prototype Behaviour

Rain plays a significant role in the thermal behaviour of green infrastructures, as evidenced during Experiment 3 (Figure 15), which coincided with the most intense rainfall event recorded in this study. On July 31, 2022, the precipitation rate reached 18.6 mm/h, altering the usual temperature and relative humidity patterns in both prototypes. Under these conditions, the vegetated prototype demonstrated notable resilience, maintaining its thermal performance, while the base prototype exhibited greater deviation from its typical behaviour.

The vegetated prototype demonstrated consistent thermal regulation during heavy rainfall, maintaining more stable internal temperatures compared to the base prototype. Specifically, while the base prototype experienced a temperature drop of up to 1.3 °C, the vegetated prototype exhibited only a minimal fluctuation of 0.5 °C. This finding aligns with previous research, such as that of Nasr et al. (Nasr et al., 2024), which highlights the insulating properties of green roofs under variable climatic conditions. Similarly, Raji, Tenpierik, Sailor and Sittipong (Nasr et al., 2024; Permpituck & Namprakai, 2012; Raji et al., 2015; Sailor et al., 2012) observed comparable resilience in vegetated systems, attributed to the capacity of the substrate layer and vegetation to act as a buffer against sudden environmental changes.

The thermal stability observed in the vegetated prototype during heavy rainfall highlights its ability to mitigate abrupt changes in interior temperature, an essential feature for maintaining thermal comfort in regions with variable climates, such as Quito. This result aligns with findings documented by Cuce, Susca, Eumorfopoulou, and Safikhani (Cuce, 2017; Eumorfopoulou & Aravantinos, 1998; Safikhani et al., 2014; Susca et al., 2011), who emphasized the benefits of green walls in enhancing interior thermal stability, particularly in temperate climates.

Intense rainfall also altered the relative humidity patterns. The vegetated prototype showed a reduced range of fluctuation compared to the base prototype. Specifically, while the base prototype experienced relative humidity peaks exceeding 88%, the vegetated system remained below 86.1%, suggesting a greater capacity to moderate humidity levels during adverse climatic conditions. These findings align with those of Moghbel, Kazemi, and Courard (Kazemi & Courard, 2022; Moghbel & Erfanian Salim, 2017), who indicate that the variation in temperature and internal humidity of roofs in buildings with green roofs was reduced by increasing the thickness of the drainage and substrate layers.

The ability of green infrastructures to maintain stable thermal performance during heavy rainfall has been reported in various studies. For example, a study in Austria by the European Commission (European Commission, 2017) showed that green roofs provide better protection than conventional ones, although their effectiveness decreases under dry conditions due to substrate drying. After rainfall, the thermal amplitude in green roofs decreased from 17 °C to 7 °C, while in metal roofs, it remained high, from 55 °C to 40 °C.

However, few studies have focused on the specific impact of intense rainfall on the thermal behaviour of green walls and roofs in continental temperate climates. This study fills that gap, providing new insights particularly relevant for architects and urban planners designing in regions such as Quito, characterized by significant diurnal temperature variations and intermittent rainfall.

By addressing both temperature regulation and relative humidity dynamics, this study contributes to the growing body of evidence supporting green infrastructures as a sustainable and adaptive solution for the design of climate-sensitive buildings.

4. Conclusions

This study focused on evaluating the thermal performance of green roof and wall systems in a climatic context characterized by abrupt daily temperature variations, as is the case in Quito. Through controlled experiments, key aspects related to internal thermal regulation, interaction with rainfall conditions, and implications for the exterior temperature of facades were analysed. In this section, the main conclusions arising from the analysis and discussion of the results are presented, highlighting both the effectiveness of these sustainable solutions and the areas where further research and optimization are still required.

Consequently, we can confidently infer that the judicious application of green walls and roofs not only fails to compromise the thermal sensation for buildings in Quito but can, in fact, enhance it. The experimental study demonstrates the effectiveness of green walls and roofs in reducing daytime temperatures. Notably, the research indicates that these systems not only help in lowering temperatures during the day but also possess the capability to maintain temperatures during the night and early morning, addressing significant temperature drops that occur during these periods. This finding suggests that green walls and roofs contribute to thermal comfort and energy efficiency in buildings, particularly in temperate climates like Quito's.

In addition, these findings not only validate existing literature but also provide empirical evidence supporting the use of green infrastructure for thermal regulation and comfort enhancement in buildings, particularly in regions like Quito.

Detailed examination of temperature differentials between vegetated and non-vegetated prototypes reveals consistent lower maximum temperatures within vegetated structures, especially during rainy periods. Conversely, the minimum temperature differentials are more modest, indicating a more stable thermal environment within vegetated prototypes. This analysis underscores the efficacy of green walls and roofs in mitigating temperature fluctuations and maintaining comfortable indoor conditions, thus reinforcing the recommendation for their implementation in building rehabilitation projects.

The study also evaluates the impact of green infrastructure on relative humidity levels. While vegetated prototypes demonstrate superior performance in terms of fewer instances of extreme humidity peaks, average humidity values fluctuate within a slightly wider range compared to non-vegetated prototypes. This highlights the importance of devising strategies to marginally reduce relative humidity in vegetated buildings. However, it's crucial to note that maintaining relative humidity below 65% is recommended for occupied spaces to mitigate potential issues such as microbial growth, a phenomenon observed in both vegetated and non-vegetated prototypes. This suggests that while green walls and roofs contribute to humidity regulation, additional measures may be necessary to optimize indoor air quality such as air-purifying indoor plants like Spathiphyllum or Sansevieria (Gunasinghe et al., 2023; Kavathekar & Bantanur, 2022) and increasing natural cross ventilation rate (Awoyera et al., 2024).

While the study demonstrates the significant benefits of green walls and roofs in regulating indoor temperature and controlling humidity, certain limitations must be acknowledged. First, the experiments were conducted under controlled conditions, which may not fully replicate the complexities of real-world environments, such as external climate fluctuations or occupant behaviour (Abdallah et al., 2015). Additionally, the duration of the experiments could have been extended to assess the long-term performance and maintenance requirements of the green systems and their subsequent thermal performance.

Limited Information on Green Infrastructure in Cold Climatic Conditions: The research addresses a gap in the literature concerning experiences with living green roof and green wall systems in cold climatic conditions. While numerous studies have focused on warm climates, there is limited documented information on the performance of green infrastructure in cold climates characterized by heating degree days (HDD). This research contributes valuable insights into the thermal performance of green walls and roofs in a temperate continental climatic zone, providing essential knowledge for architects, engineers, and urban planners in similar regions.

Impact of Rainfall on Thermal Behaviour: The study explores the influence of rainfall on the thermal behaviour of green wall and roof prototypes. During periods of heavy rainfall, typical temperature and humidity patterns were disrupted, yet the vegetated prototype exhibited consistent thermal performance, indicating resilience to adverse weather conditions. This finding suggests that green walls and roofs can maintain their effectiveness even in challenging weather scenarios, emphasizing their potential as sustainable building solutions for various climates.

However, to optimize their performance, future studies should explore the integration of advanced drainage systems that prevent waterlogging and further enhance thermal stability. Additionally, comparisons with data from colder climates, where rainfall coincides with low temperatures, would provide a more comprehensive understanding of their global applicability.

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Conflict of Interest Statement
The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. The author has no competing interests to declare.

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Nomenclature and Abbreviations

4C	A type of climate defined in the ASHRAE 169-2006 standard consisting of Climate Zone Number 4 and Climate Zone Subtype C.
Climate Zone	4C is defined as Mixed – Marine with IP Units 3600 < HDD65ºF ≤ 5400 and SI Units 2000 < HDD18ºC ≤ 3000
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CONELEC	National Electricity Council of Ecuador
CO_2	Carbon dioxide
CDD	Cooling degree days
EPW	EnergyPlus Weather Files
GWs	Green walls
GRs	Green roof systems
HVAC	Heating, Ventilation and Air Conditioning
HDD	Heating degree days
INEC	National Institute of Statistics and Censuses of Ecuador
MIDUVI	The Ministry of Urban Development and Housing of Ecuador
P1	Prototype 1 (Improved)
P2	Prototype 2 (Baseline Case)
RH	Relative Humidity expressed in %
UVI	The ultraviolet (UV) index
λ	Thermal conductivity in units of W/mK

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