

DESIGN OF AN INDIRECT GREEN FAÇADE SYSTEM TO IMPROVE THERMAL COMFORT IN MULTIFAMILY HOUSING

DISEÑO DE SISTEMA INDIRECTO DE FACHADA VERDE PARA MEJORAR EL CONFORT TÉRMICO EN VIVIENDAS MULTIFAMILIARES

DESENHO DE SISTEMA INDIRETO DE FACHADA VERDE PARA MELHORAR O CONFORTO TÉRMICO EM HABITAÇÕES MULTIFAMILIARES

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ABSTRACT

Unplanned urban growth in Northern Lima has intensified urban heat islands, affecting thermal comfort in self-built multifamily housing. This study evaluates the performance of an indirect green façade system as a passive thermal mitigation strategy in a dwelling located in San Martín de Porres. A quantitative approach with a quasi-experimental design was employed, combining thermal simulation in SIMEDIF 2.0 with in situ measurements using a digital thermo-hygrometer. The results show a reduction in indoor temperature of up to 2 °C in real measurements and up to 3 °C in simulations, as well as a decrease in incident solar radiation on the façade. It is concluded that the system is constructively viable and improves thermal comfort in urban self-built contexts.

Keywords

indirect green façade, thermal comfort, thermal analysis, passive strategies, multifamily housing

RESUMEN

El crecimiento urbano no planificado en Lima Norte ha intensificado las islas de calor urbano, que afectan el confort térmico en viviendas multifamiliares autoconstruidas. Este estudio evalúa el desempeño de un sistema indirecto de fachada verde como estrategia pasiva de mitigación térmica en una vivienda ubicada en San Martín de Porres. Se empleó un enfoque cuantitativo con un diseño cuasiexperimental, que combina la simulación térmica en SIMEDIF 2.0 y mediciones in situ con un termohigrómetro digital. Los resultados muestran una reducción de la temperatura interior de hasta 2 °C en mediciones reales y de hasta 3 °C en simulaciones, además de una disminución de la radiación solar incidente sobre la fachada. Se concluye que el sistema es constructivamente viable y mejora el confort térmico en contextos de autoconstrucción urbana.

Palabras clave

fachada verde indirecta, confort térmico, análisis térmico, estrategias pasivas, viviendas multifamiliares

RESUMO

O crescimento urbano não planejado na região norte de Lima intensificou as ilhas de calor urbanas, afetando o conforto térmico em habitações multifamiliares autoconstruídas. Este estudo avalia o desempenho de um sistema indireto de fachada verde como estratégia passiva de mitigação térmica em uma habitação localizada em San Martín de Porres. Foi empregada uma abordagem quantitativa, com desenho quase experimental, que combina simulação térmica no SIMEDIF 2.0 e medições in situ realizadas com um termohigrômetro digital. Os resultados mostram uma redução da temperatura interna de até 2 °C nas medições reais e de até 3 °C nas simulações, além de uma diminuição da radiação solar incidente sobre a fachada. Conclui-se que o sistema é viável do ponto de vista construtivo e melhora o conforto térmico em contextos de autoconstrução urbana.

Palavras-chave

fachada verde indireta, conforto térmico, análise térmica, estratégias passivas, habitações multifamiliares

INTRODUCTION

Accelerated urban growth and high building density, which raise temperatures in densely urbanized areas due to the reduction of green areas and the predominance of surfaces such as concrete and asphalt, which affect environmental comfort and quality of life, have intensified urban heat islands (UHI) (Faragallah & Ragheb, 2022; Soberón Forsberg & Obregón Parraga, 2016). In Lima, this phenomenon is associated with the progressive replacement of vegetation by buildings and continuous urban growth, factors that favor the accumulation of heat and affect environmental comfort. Thermal differences of up to 3.7 °C have been recorded between districts and are associated with sparse vegetation (Barros & Menacho Casimiro, 2014). In San Martín de Porres, this phenomenon is exacerbated by unplanned urban growth, in which building expansion predominates over the preservation of green areas. The district has only 1.86 m² of green space per inhabitant, far below the World Health Organization (WHO) recommendation, leading to heat accumulation and reduced indoor thermal comfort.

Faced with this scenario, passive strategies have become increasingly relevant for improving thermal comfort in homes by reducing heat gain through low-consumption solutions. Among these strategies, vegetation, applied through direct (GF) or indirect (GFS) green facades, attenuates solar radiation, stabilizes the microclimate, and reduces wall and indoor temperatures, decreasing the need for mechanical ventilation (Marchioretto et al., 2023). Similarly, a systematic review of vertical vegetation systems indicates that these systems enhance the thermal performance of buildings through shading, insulation, and evaporative cooling, thereby reducing heat gains and improving indoor comfort (Bustami et al., 2018). While GF is applied directly on the wall and can retain moisture, GFS uses a separate structure that creates a ventilated air chamber, which protects the wall and is more suitable for self-built homes due to its low structural impact (El Menshawy et al., 2022).

On the other hand, several studies have demonstrated the effectiveness of indirect green facade systems as a passive thermal mitigation strategy through experimental and simulation studies. Ramadhan and Mahmoud (2023) report that these facades reduce thermal loads, energy consumption (by up to 75%), and CO₂ emissions (by 45%), while maintaining suitable comfort conditions. Tudiwer and Korjenic (2017) have also

shown, through experimental tests, that indirect green walls can lower indoor temperature by up to 5 °C and block about 90% of incident solar radiation. Similarly, Lesjak et al. (2020) conclude, based on experimental measurements and thermal simulations, that indirect green facades are an effective strategy to prevent building overheating by reducing incident solar radiation on the envelope and lowering indoor operating temperatures, thereby improving thermal comfort during the summer.

Suárez et al. (2023) have demonstrated its effectiveness in arid climates by achieving reductions in room temperature of up to 4.4 °C in summer and decreases in the average outdoor temperature of up to 3.9 °C in the warm season. Meanwhile, Gomez et al. (2023), through thermal simulations and orientation-based radiation analysis, demonstrated reductions of up to 74% on east facades, resulting in indoor temperature decreases of between 0.6 °C and 4.5 °C. Finally, Suárez et al. (2020) reported reductions of up to 26.5 °C and 27.4 °C in outdoor surface temperature during the 2019 and 2020 evaluation periods, respectively. In addition, the green-facade wall exhibited a thermal amplitude of nearly 6 °C, significantly lower than that of the facing wall, which ranged from 24 °C to 31 °C.

Although several studies have shown the effectiveness of green facades in reducing indoor temperatures, most have been developed through simulations or in climatic contexts other than Lima's. However, research combining experimental monitoring and thermal simulation has shown that incorporating vegetation into vertical elements is an effective passive strategy to reduce heat gain and improve indoor environmental quality (Domínguez Cicorio et al., 2022). Despite this, there is still little empirical evidence from on-site measurements of the thermal performance of indirect green facade systems in self-built homes in coastal arid climates such as Lima. Consequently, this study seeks to address this gap by evaluating the thermal performance of an indirect green facade system using in situ measurements and thermal simulations.

The research problem lies in the low thermal comfort of self-built homes in San Martín de Porres, due to the absence of passive thermal regulation strategies, limited green areas, and high urban temperatures. These houses, built without technical criteria, have inadequate orientations, poor natural ventilation, and inefficient spatial distribution, which favor the accumulation of heat indoors and affect occupants' well-being. In this context, the following question arises: How does the design of



Figure 1. Study area, SMP, Lima. Source: Google Earth.
 Figure 2. Photo of the dwelling. Source: Prepared by the authors.

an indirect green facade system improve thermal comfort in multifamily housing?

The general objective of the study is to design an indirect green facade system that improves thermal comfort in a multifamily home. To do this, the climatic conditions of San Martín de Porres are identified using data from the National Meteorology and Hydrology Service of Peru (SENAMHI), and a lightweight, easy-to-install prototype compatible with self-built homes is developed. Its thermal performance is evaluated through on-site measurements and computer simulations, which compare indoor temperatures before and after its implementation. It is hypothesized that the implementation of a GFS in the house will reduce the indoor temperature by approximately 2-3 °C, due to the decrease in solar radiation and the thermal damping provided by the air chamber and vegetation, as noted by Abdeen and Rafaat (2024) and Suárez et al. (2020) regarding the potential of green facades to improve indoor thermal comfort.

CASE STUDY

The case study is located at coordinates 12.026287° S, 77.082624° W, in the district of San Martín de Porres (SMP), Lima, Peru (Figure 1), and is a self-built multifamily housing unit (Figure 2). The main facade, facing southeast, is exposed to direct solar radiation during the summer, primarily in the morning, which increases the envelope's thermal gains and contributes to higher indoor temperatures. In certain environments, this condition is also associated with operating temperatures above 29 °C.

The building is built with 15-cm-thick hollow-brick load-bearing walls, which limit interventions that

would substantially modify the structural layout. This condition limits the feasibility of incorporating certain passive environmental conditioning strategies. The compactness of the floor plan and the small dimensions of the openings also limit the potential for natural ventilation and daylighting, promoting heat accumulation in indoor spaces.

METHODOLOGY

This project adopts a quantitative approach to evaluate the impact of the indirect green facade system by analyzing indoor thermal records and using computer simulations. Its scope is explanatory, as it seeks to identify the causal relationship between the implementation of the indirect green facade system and the reduction in indoor and surface temperatures of the rooms, as well as its effectiveness against solar radiation.

A quasi-experimental design is used, in which surrounding conditions are not manipulated, and the thermal behavior of the rooms is compared with and without the green facade system, allowing analysis of its effects under real conditions. The design is also transversal, since the thermal measurements are carried out over a specific period of time, so the thermal behavior of the rooms is analyzed at a single point in time without longitudinal monitoring.

The study population comprises multifamily dwellings in San Martín de Porres that are exposed to solar radiation. The sample is a second-floor apartment whose orientation allows evaluating the thermal performance of the green facade system. The measurements were taken in the rooms facing said facade, producing detailed data on thermal behavior for the case study.

ETAPAS METEODOLÓGICAS

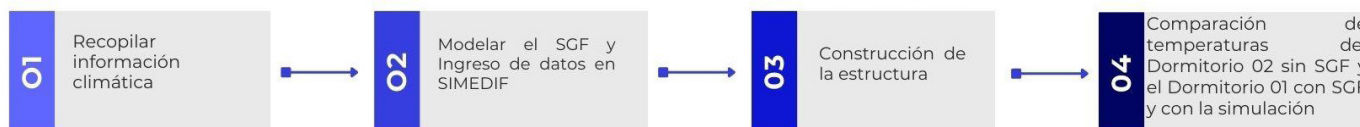


Figure 3. Methodological phases. Source: Prepared by the authors.

YEAR	2024				2025			
Month	FEB	MAR	AUG	SEPT	FEB	MAR	AUG	SEPT
Max. Temperature (°C)	31.9	29	20	21.3	29.5	29.4	20.6	23.2
Humidity	47.43	56.06	67.73	63.93	56.67	51.56	67.9	69.67

Table 1. Monthly temperature in SMP (2024-2025) Source: Prepared by the authors using SENAMHI data (n.d.)

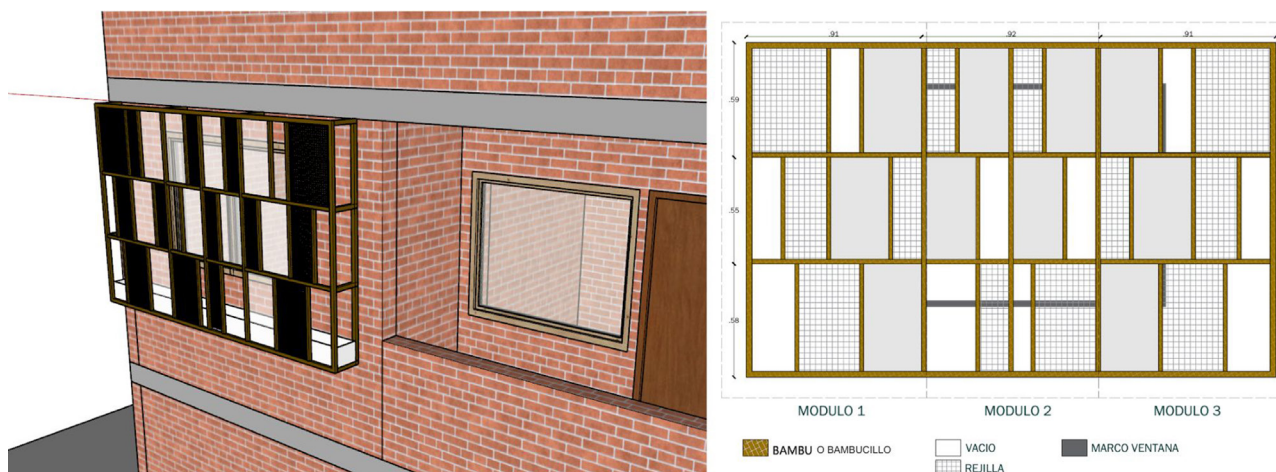


Figure 4. Modeling in SketchUp of the structure and materiality of the dwelling. Source: Prepared by the authors.
 Figure 5. GFS structure in AutoCAD. Source: Prepared by the authors.

The techniques used in the research are based on computational models developed primarily in SIMEDIF. This thermal simulation program enables analysis of room thermal behavior based on the materials, climatic conditions, and construction characteristics. AutoCAD and SketchUp were also used, and measurements with a digital indoor thermohygrometer were verified by comparative readings to record the prototype's indoor temperatures.

Below, the methodological stages used in this research are presented, with each phase of the process described from information collection and thermal modeling to data analysis and evaluation of the green facade's impact on thermal comfort (Figure 3).

FIRST PHASE

Climatic data for the district of San Martín de Porres were collected from the records of the National Meteorology and Hydrology Service of Peru [SENAMHI] for the 2024-2025 period, covering maximum temperature, average temperature, and relative humidity in summer and winter.

Table 1 shows monthly temperatures ranging from 20.6 °C to 29.5 °C, with a summer peak of 31.9 °C. The analysis focused on the summer and winter months, the periods with the most extreme values. The months of November, December, February (Summer), and August (Winter) were selected to evaluate the indirect system's performance under these thermal conditions.



Figure 6. Assembly of the bamboo structural system. Source: Prepared by the authors.



Figure 7. Assembly of the structural system of the bambucillo and installation on the wall. Source: Prepared by the authors.

SECOND PHASE

In the second stage, materials were defined, and prototypes of the indirect system were developed. For the structure, bamboo was used for its strength, sustainability, and ease of construction. Two initial prototypes were developed: one made of bamboo, more complex to assemble, and another of fishpole bamboo (bambucillo), which turned out to be lighter and easier to handle. Both were 3D modeled in AutoCAD and SketchUp (Figure 4 and Figure 5). Considering the use of climbing vegetation on support structures, a characteristic configuration of indirect green facade systems, the climbing species *Epipremnum aureum*, with a growth of $LAI \approx 2.5$, *Vinca major*, *Ficus pumila*, and *Hedera helix*, with $LAI \approx 2.5$, were also selected due to their resistance to direct solar radiation.

The SIMEDIF software was used for the thermal simulation, where three thermal zones, bedroom 1, bedroom 2, and the living room, were defined, according to the data shown in Table 2. The simulation incorporated the parameters of Table 3, which specify the characteristics of walls and floors, such as

LOCAL	FLOOR AREA m2	VOLUMEN m3
Bedroom 1	10.61	31.09
Living/dining room	9.09	51.024
Bedroom 2	11.21	30.67

Table 2. Characteristics of the thermal zones. Source: Prepared by the authors.

SOLID WALL	SOLAR ABSORPTION	W/m2-K	THICKNESS (m)
Exterior	0.55	8	0.12 y 0.30
Interior	0.15	6	0.12
Floor	0.3	0.01	0.20
Roof	0.4	6	0.20

Table 3. Thermal properties. Source: Prepared by the authors.

conductance, thermal transmittance (U), and thermal inertia. The dimensions of the indirect system (2.5 × 4.5 m) were also input to evaluate its thermal behavior in the model.

For the green facade, the *Hedera helix* plant was proposed with a leaf length of 0.15m, a stomatal resistance of 160 s/m, and air renewal rates of 23 1/h in summer and 5 1/h in winter.

THIRD PHASE

The objective of this phase was to build the GFS prototype and verify its constructability and integration with vegetation.

In the third stage, two prototypes were built. The first prototype, made of bamboo (2.5 × 1.70 m), required a prior drying process and a complex assembly, with fish-mouth-type cuts, studs, washers, and nuts used to ensure stability (Figure 6). The second prototype, made with 1 1/2" bambucillo, used blade-type tie-downs with a ribbon, which allowed not only to replicate the original design, but also to expand its dimensions to 2.5 × 4.5 m, thanks to its lower weight. Finally, the structure was varnished to improve its durability and resistance to moisture (Figure 7).

FOURTH PHASE

In this phase, the indoor air temperature was compared. For this, the thermal zone 03 was used as a reference room, where the temperature was measured without intervention. Subsequently, a comparison was made with thermal zone 1, in which the indirect green facade system would be installed (Figure 8). This choice is based on the fact that both bedrooms have the same spatial distribution, dimensions, and window-opening size, which minimizes the influence of geometric variables on the results and ensures comparability between the two environments. In addition, the results under these real conditions will be compared with those from the thermal simulation to verify the efficiency of the proposed system.

The measurements were made with a MDL 2140 digital thermohygrometer, with a temperature measurement range of -50 °C to +70 °C and a tolerance of ±1 °C in the range of 0 °C to +40 °C; data were recorded every four hours (8:00, 14:00 and 20:00) during the period from November 1st to December 12th, 2025, selected for representing warm climatic conditions characteristic of the study area.

The sensor was located 1.10 m above floor level and at a minimum distance of 1.0 m from the facade wall; the criteria of the UNE-EN ISO 7726 Standard were followed to represent the occupied area and to avoid interference from surface radiation. During the measurements,

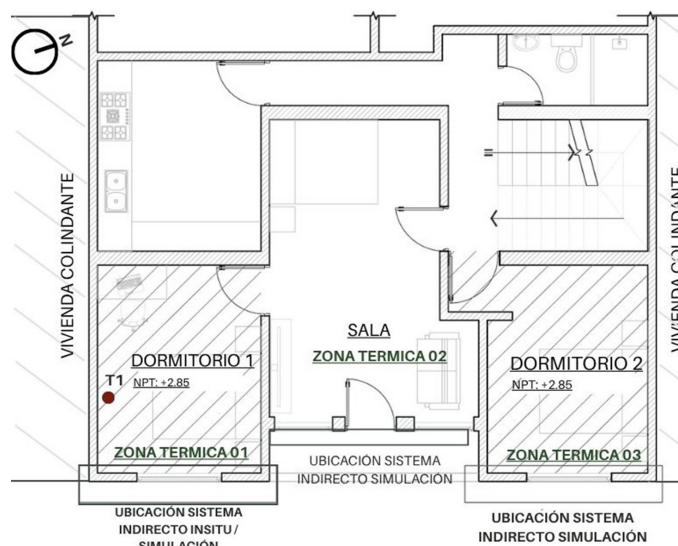


Figure 8. Dwelling's floor plan and location of the thermohygrometer. Source: Prepared by the authors.

the bedroom was kept unoccupied, with the doors and windows closed. No mechanical ventilation was used, and measurements were taken on days without atypical weather, such as rain or strong winds, to ensure comparable conditions before and after the system was installed. Prior to taking the records, the equipment was checked using comparative readings in the same environment to verify data stability.

The data obtained were organized in spreadsheets and analyzed using time profiles, which allowed evaluating the thermal variation generated by the implemented system and comparing the actual thermal behavior of the room with the simulation results.

RESULTS

Two scenarios were considered for the analysis: the base model without intervention and the model with the implementation of the GFS. Both were evaluated using the SIMEDIF program, into which thermal and technical data for walls and windows were input, complemented by real indoor temperature measurements. Finally, the simulation results were compared with those of the in-situ prototype.

BASE MODEL

Figure 9 shows the indoor air temperature forecast in the thermal zones evaluated before the implementation of the green facade for November, December, February, and August. The results show a seasonal increase in indoor temperature from winter to summer, with the most unfavorable thermal conditions in February. In this month, Bedroom 1 recorded the highest maximum temperature (32.5 °C), followed by Bedroom 2 at a

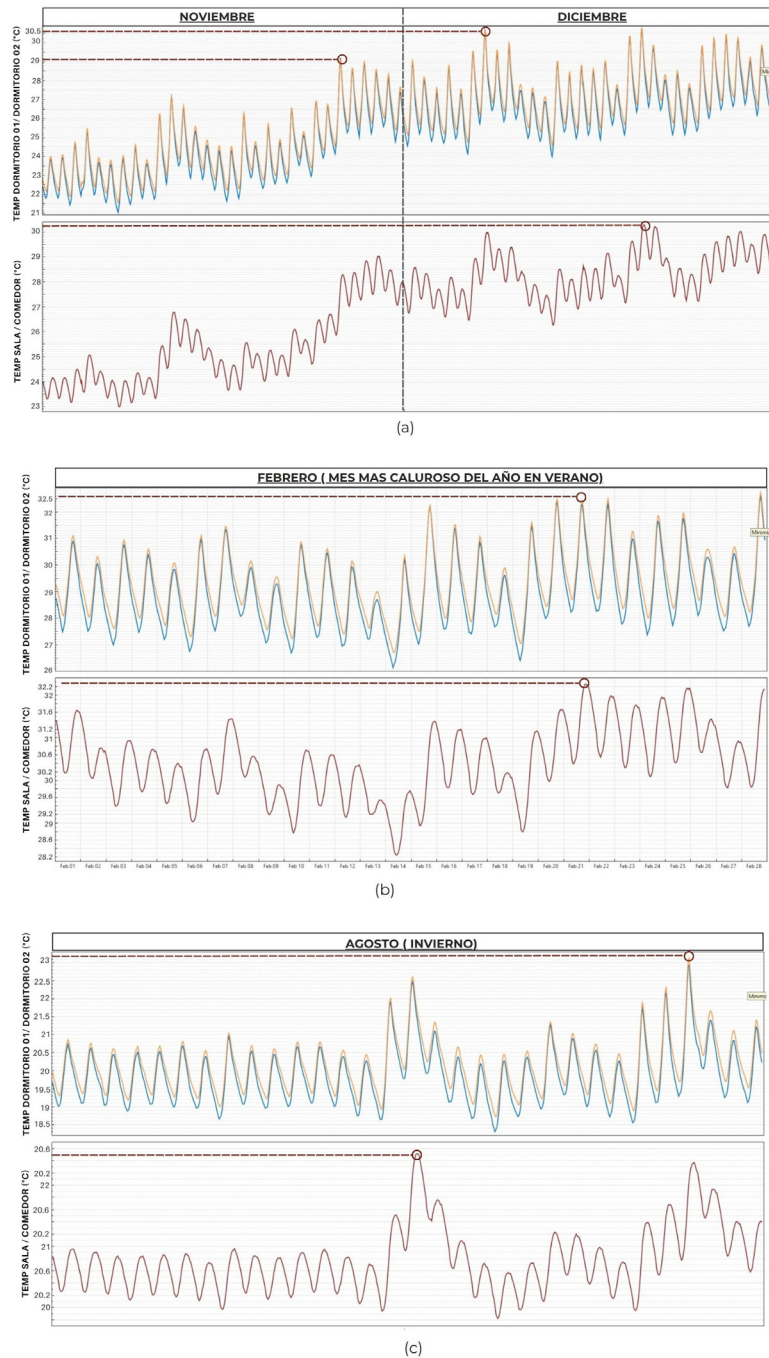


Figure 9. Surface temperature of the thermal zones without the implementation of the GFS in the 4 months analyzed. Source: Prepared by the authors with data from the SIMEDIF.

similar value, while the Living Room reached 32.0 °C. In December, the maximum temperatures ranged from 30.0 to 30.5 °C, while in November they ranged from 28.5 to 29.0 °C. In contrast, during August, a period of lower thermal demand, temperatures dropped to a range of 22.5-23.0 °C.

In comparative terms, the differences between environments were less than 1.0 °C across all months analyzed, indicating a homogeneous indoor thermal response. This behavior suggests that spatial

temperature variation is reduced and that the observed overheating is relatively uniform throughout the evaluated dwelling.

Figure 10 presents the hourly distribution of indoor temperature as heat maps, enabling identification of the daily thermal evolution pattern across the four months analyzed. In all cases, the temperature increases progressively from the early morning and reaches values close to 25 °C by noon. However, the period of greatest thermal demand is concentrated

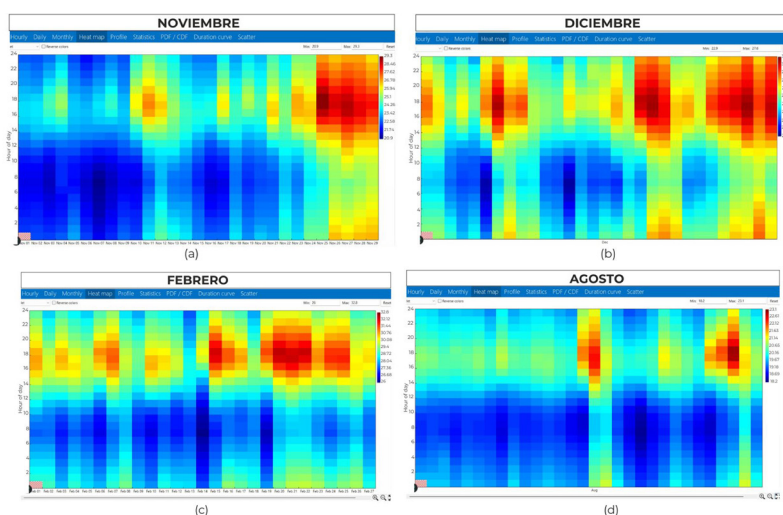


Figure 10. Heat map by time range without GFS. Source: Prepared by the authors with SIMEDIF data.

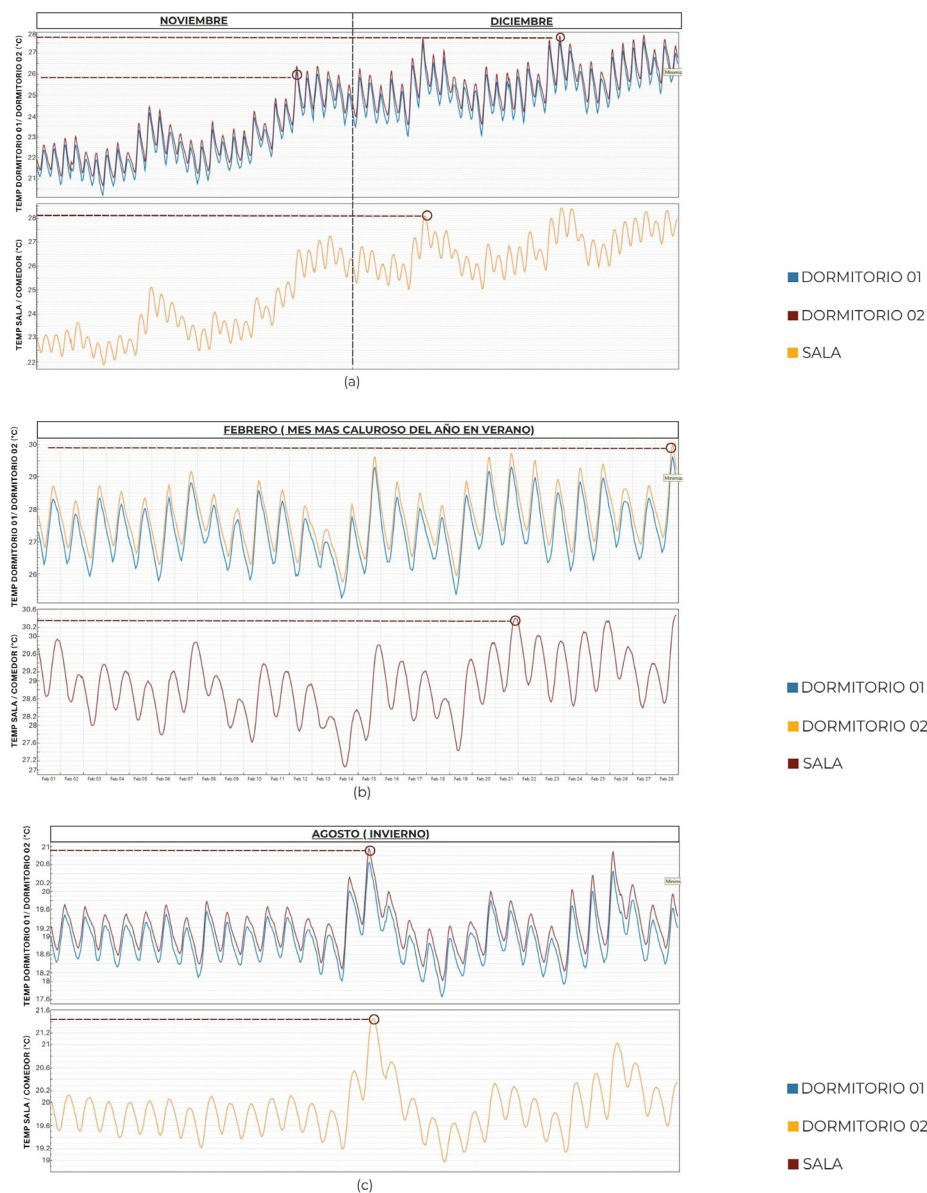


Figure 11. Temperature simulation result with the GFS. Source: Prepared by the authors with data from SIMEDIF.

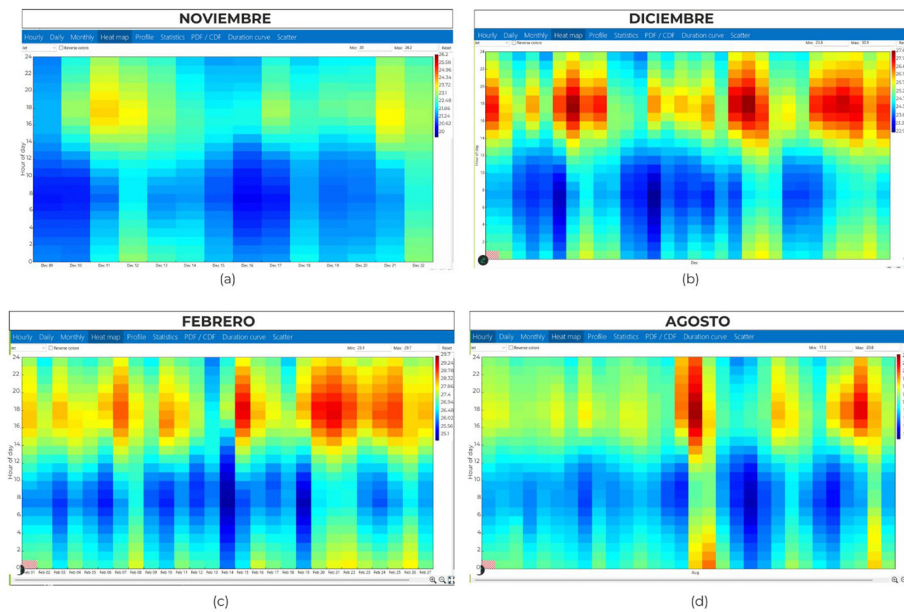


Figure 12. Heat map with time range of the 3 thermal zones with the GFS. Source: Prepared by the authors with data from SIMEDIF.

between 2 pm and 6 pm, during which the three rooms simultaneously reach their maximum values. This behavior confirms the existence of a diurnal thermal delay and identifies this timeframe as the critical period for thermal accumulation inside the dwelling.

MODEL WITH GFS IMPLEMENTATION

Figure 11 shows the indoor thermal behavior after implementing the Green Facade System (GFS) in the evaluated rooms. Compared with the baseline scenario, a reduction in maximum temperatures is observed across all the cases. In Bedroom 2, the maximum values were 21.4 °C in August, 26.0 °C in November, 28.5 °C in December, and 30.0 °C in February, the latter remaining the month of greatest thermal demand. However, even under this condition, the average temperature recorded in February remained around 28 °C, indicating reduced overheating compared to the scenario without GFS.

In Bedrooms 1 and 2, the average temperature in November was approximately 22.8 °C, a decrease of about 2 °C compared to the scenario without intervention. In comparative terms, this decrease was consistent in both rooms, confirming a uniform reduction of the thermal load in long-term spaces.

The analysis of the 24-hour thermal profile indicates that the daily highs remain concentrated between 2 pm and 4 pm, i.e., within the period of highest thermal demand. However, the magnitude of these peaks is

lower than in the case without GFS, which evidences a thermal damping effect of the system.

Figure 12 presents the hourly heat maps, showing a progressive decrease in indoor temperature during the night. The average values in this range were approximately 22 °C in November, 26 °C in December, 27 °C in February, and 18 °C in August. Taken together, these results show that implementing the GFS reduces the intensity of daytime overheating and modifies the indoor cooling pattern throughout the daily cycle.

The results from thermal simulations in SIMEDIF and on-site measurements were compared to evaluate the thermal behavior of the Indirect Green Facade System (GFS) in Bedrooms 1 and 2. Table 3 presents the hourly indoor temperature profiles with and without the system's implementation during November and December, for both evaluation methods.

The measurements were carried out under the same time conditions: the first and last three days of each month were analyzed at 2 pm and 8 pm, the periods of maximum daytime thermal load, and the night period of accumulated heat release. In both methods, lower indoor temperatures were recorded in the GFS scenario than in the case without intervention (Tables 4 and 5).

In the *in-situ* measurements, the average indoor temperature difference between the two scenarios was close to 2 °C; maximum reductions of up to 3 °C were observed, with greater differences recorded at night. On the other hand, the SIMEDIF simulation showed decreases of 1-2.5 °C, maintaining similar thermal

DATE	BEDROOM 2 WITHOUT GFS		BEDROOM 1 WITH GFS	
	14:00PM	20:00PM	14:00PM	20:00 PM
01/11/2025	22.8°C	21.5°C	21.2°C	19.4°C
02/11/2025	23.6°C	21.9°C	22.3°C	20.9°C
03/11/2025	22.5°C	20.9°C	21.5°C	19.2°C
28/11/2025	24.9°C	23.5°C	22.7°C	21.3°C
29/11/2025	24.2°C	22.8°C	22.2°C	21.4°C
30/11/2025	25.3°C	24.8°C	23.4°C	22.8°C
01/12/2025	24.4°C	22.6°C	22.3°C	20.9°C
02/12/2025	24.8°C	23.6°C	23.2°C	22.5°C
03/12/2025	25.5°C	22.9°C	23.5°C	22.9°C

Table 4. Comparison of temperatures with and without GFS, by on-site measurement in November and December.
 Source: Prepared by the authors.

DATE	BEDROOM 1 WITHOUT GFS SIMEDIF		BEDROOM 1 WITH GFS SIMEDIF	
	14:00PM	20:00PM	14:00PM	20:00 PM
01/11/2025	23.7°C	23.1°C	22.24°C	22.04°C
02/11/2025	23.83°C	22.96°C	22.36°C	21.89°C
03/11/2025	24.12°C	23.49°C	22.34°C	22.06°C
28/11/2025	28.03°C	27.39°C	25.43°C	25.51°C
29/11/2025	27.54°C	26.97°C	25.3°C	25.08°C
30/11/2025	27.14°C	26.32°C	24.89°C	24.63°C
01/12/2025	28.05°C	27.41°C	25.44°C	24.27°C
02/12/2025	27.88°C	26.87°C	25.51°C	25.13°C
03/12/2025	26.65°C	26.33°C	24.69°C	24.59°C

Table 5. Comparison of temperatures with and without green facade system (GFS) in Bedroom 1 using SIMEDIF simulation. Source: Prepared by the authors.

behavior across the evaluated times and slight variations among the analyzed days. The greatest thermal differences were observed in November, mainly in the afternoon.

In general, both methods show a consistent trend towards lower indoor temperatures associated with the incorporation of GFS across all evaluated cases (Tables 4 and 5).

DISCUSSION

The thermal simulation developed in SIMEDIF identified the indirect green facade system's behavior faced with overheating in the analyzed dwelling. In the base scenario, Bedroom 1 exhibited the most critical condition, with maximum temperatures of up to 32.5 °C in February, while incorporating the system resulted in an approximate 3 °C reduction. This performance suggests that the system attenuates the

thermal gain through the vegetation shading and the damping effect of the air chamber, thereby moderating the indoor temperature. This behavior aligns with what Manso and Castro-Gomes (2015) noted: green wall systems improve the microclimate of the envelope by providing shade, complementary insulation, and evaporative cooling generated by vegetation. Perini et al. (2011) also argue that the presence of an air layer between the vegetation cover and the facade can increase the thermal resistance of the envelope and reduce heat transfer to indoor spaces, reinforcing the thermal protection effect observed in the present study.

The *in-situ* measurements confirmed a temperature decrease during the most demanding hours, with reductions of up to 2 °C, consistent with the simulation. This reinforces the robustness of the observed behavior. It aligns with the findings reported by Suárez et al. (2020) on the ability of green facades to reduce heat transfer to the interior. Similarly, Padovan et al. (2022) recorded an average reduction of 4.4 °C in indoor air temperature, with maximum decreases of up to 7.3 °C in rooms protected by an indirect green facade. Susorova et al. (2013) also point out that vegetation reduces the facade's surface temperature and limits heat transfer by conduction into the building, thereby reducing thermal loads in protected spaces. In this framework, the findings support the research hypothesis by showing that green facades can reduce the thermal gain in self-built homes. However, their effectiveness depends on context variables such as incident radiation, orientation, and ventilation. Unlike previous studies conducted in more industrialized systems, this case shows that it is possible to achieve measurable thermal improvements through solutions with low construction complexity and that use locally available materials. This observation is consistent with Perini et al. (2011), who point out that indirect green facade systems can be implemented using different support structures and materials, maintaining thermal benefits on the envelope without necessarily requiring complex or high-tech modular systems.

However, the study's limitations should be considered when interpreting its results. At the methodological level, the evaluation was focused on a small number of rooms, which limits the scope for generalization. At the instrumental level, the analysis was based primarily on air temperature and did not incorporate additional thermal comfort variables, such as relative humidity, air velocity, or radiant temperature. The simulation also used standardized parameters that simplify the urban environment, so there may be differences between the modeled behavior and the system's actual behavior.

From a constructive perspective, the prototype's implementation allowed seeing the relevant differences among the materials used. The use of 3-inch bamboo was limited by weight, making it difficult to use in

precarious buildings, whereas 1 1/2-inch bambucillo was more suitable as a lightweight structural alternative. This observation not only has practical implications for the system's viability but also broadens the discussion about the adaptability of green facades in contexts of self-construction and structural constraints.

Taken together, the study demonstrates that the green facade system can improve the thermal performance of low-cost housing through a technically feasible and constructively adaptable passive strategy. Its main contribution lies in providing quantitative evidence on the system's behavior in a humid coastal climate such as that of San Martín de Porres, Lima, where the effectiveness of these solutions has been little explored. Incorporating bambucillo as a lightweight alternative also makes a practical contribution to the design of passive solutions that are replicable in similar urban contexts.

CONCLUSIONS

The evaluation of the indirect green facade system (GFS) showed improved indoor thermal performance compared with the no-intervention scenario. In the base model, the simulations showed indoor temperatures of up to 32.5 °C in February, the warmest month, in E-SE-facing spaces, peaking between 2 pm and 8 pm. After implementing the GFS, maximum temperatures in the living room decreased by up to 7.7%, with similar reductions in the bedrooms and greater thermal stability. This effect was most noticeable during the hours of greatest thermal load (2 pm - 4 pm), as it attenuated the overheating peaks.

The comparison between the thermal simulations and the on-site measurements showed a consistent trend. In the evaluated bedroom, the GFS reduced the indoor temperature by approximately 2 °C under real conditions, while the SIMEDIF simulation indicated a decrease of approximately 3 °C. This difference is due to the model assuming fully developed vegetation cover, whereas *in situ*, the vegetation was in an intermediate growth stage, attenuating the observed thermal effect.

In the winter months, the system helped maintain more stable indoor temperatures, with values between 20.5 °C and 21.4 °C, avoiding sharp decreases at night, when lows near 18 °C were recorded. This behavior suggests that GFS not only reduces summer overheating but also favors greater seasonal thermal stability.

In this context, the implementation of passive strategies, such as the indirect green facade system, represents an accessible alternative for improving living conditions in self-built high-density urban housing, where technical

and economic limitations make it difficult to incorporate more complex solutions. Its application allows reducing the indoor thermal load and dependence on mechanical air conditioning systems.

Finally, the main contribution of this study is to demonstrate that a green facade system can improve the thermal performance of low-cost self-built homes, providing applied evidence for the development of passive environmental conditioning strategies. The work also expands knowledge of the performance of these systems in humid coastal climates, such as Lima, where their effectiveness is usually reported as more limited than in other climatic contexts, yet quantifiable thermal improvements were identified.

Additionally, the study incorporates bambucillo as a viable alternative for lightweight structures, increasing the system's constructability in homes with structural constraints. Together, these findings provide technical and constructive criteria that can guide the design, adaptation, and implementation of passive solutions in urban environments with similar building and climatic characteristics.

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