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Activated Carbon Panels from Agricultural Waste for Passive Thermal Comfort in High-Andean Housing

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Abstract The study addresses the problem of thermal comfort in high-Andean housing in Peru, where extreme climatic conditions and the use of traditional materials with low insulation capacity create inadequate indoor environments that affect health and well-being. As a sustainable alternative, the feasibility of activated carbon panels made from broad bean shells—an abundant agricultural resource in the Mantaro Valley—was evaluated. The research followed an experimental approach, installing the panels in a housing module and recording temperature and humidity parameters with high-precision digital instruments across different time scales. The results show favorable thermal performance: indoor temperatures remained between 23.6 ℃ and 24.9 ℃, with differences of up to 7.2 ℃ compared to the exterior, even 2.5 hours after sunset. Relative humidity stabilized within a range of 50.2% to 54.2%, creating a comfortable microclimate in contrast to external variations. These findings confirm that activated carbon acts as a passive regulator of heat and humidity, reducing nighttime heat loss and improving habitability without the need for active heating systems. In conclusion, activated carbon panels represent a technically viable, cost-effective, and low-impact environmental alternative. Their production from agricultural residues and integration through sustainable self-construction practices make it possible to mitigate energy poverty, reduce health risks associated with cold, and strengthen a resilient architectural model for high-Andean communities.

Keywords Thermal Comfort, High-Andean Housing, Activated Carbon, Broad Bean Shells, Sustainable Materials, Passive Regulation

1. Introduction

In the high-Andean regions of Peru, characterized by high altitude and extreme climatic conditions, thermal comfort in housing represents a critical challenge, especially for families in situations of socioeconomic vulnerability [1]. Many of these dwellings are built with traditional materials such as adobe, quincha, or stone, which present significant limitations in maintaining stable indoor temperatures against the low nighttime temperatures and marked daytime thermal fluctuations [2]. This problem intensifies during the coldest months (May–December), when temperatures drop to levels that affect the health of inhabitants, as evidenced by the high rates of respiratory diseases and infant mortality associated with cold exposure [3].

Various initiatives have sought to address this issue through the promotion of more efficient construction solutions. Non-governmental organizations and state programs have encouraged the use of sustainable techniques and materials, as well as community training in resilient construction [4]. However, these actions still face limitations in terms of coverage, sustainability, and adaptation to local conditions. The articulation between the different actors—government, civil society, and communities—is essential to achieve effective and sustainable long-term interventions [5].

In addition, the lack of access to adequate heating technologies and thermal insulation systems leads to the rapid loss of heat accumulated during the day [6]. These technical limitations are further aggravated by the economic precariousness of many families, who depend on subsistence agriculture and lack the resources to implement improvements in their homes. In this context, thermal comfort is not only a matter of habitability, but also of public health and social equity [7].

Recent studies reinforce the feasibility of porous materials and activated carbon combined with passive thermal regulation systems. For example, a thermal storage medium based on activated carbon impregnated with phase change materials was developed, demonstrating its ability to absorb heat during the day and release it at night [8]. Complementary evidence showed that the incorporation of activated carbon in particleboards decreases their thermal conductivity, improving insulation conditions [9]. More recently, biochar derived from wood residues has been shown to function as thermal energy storage matrices, maintaining stability after multiple cycles and highlighting the potential of agricultural waste as a low-cost resource for construction applications [10]. These international precedents support the exploration of accessible alternatives adapted to rural contexts of high vulnerability.

The growing interest in activated carbon in the construction field responds to its versatility as a sustainable and low-cost material capable of performing thermal regulation and hygrometric control functions. However, most previous studies have focused on its use in industrial contexts or in combination with phase change materials [8], [10], leaving limited evidence of its direct application in construction systems for rural housing in extreme climates. This gap opens a field of research aimed at exploring how an abundant agricultural resource in the Andes, such as the broad bean shell, can be transformed into an innovative construction material. In this way, locally produced activated carbon would not only contribute to improving habitability conditions, but also reduce dependence on imported or expensive solutions.

Faced with this reality, there is a need to develop accessible technological alternatives that improve the thermal conditions of high-Andean housing [11]. Within this framework, activated carbon panels emerge as a viable option due to their thermal properties, insulating capacity, and low-cost production potential through the use of local resources [12]. This material, widely used in filtration and purification processes, has a porous structure that confers adsorption and thermal storage properties useful for architecture in extreme climates [13].

Activated carbon is obtained through the controlled carbonization of organic materials such as wood or agricultural residues (e.g., broad bean, barley, or wheat husks), using broad bean shells as the main raw material [14]. Its high porosity allows the adsorption of moisture from the air, which helps maintain adequate levels of hygrothermal comfort in indoor spaces [15]. In addition, it acts as a passive thermal regulator: it absorbs ambient heat during the day and releases it progressively at night, reducing indoor thermal amplitude [16]. This thermal damping effect is especially beneficial in areas where temperatures vary sharply within a few hours [17].

Thus, the hypothesis is posed that activated carbon panels made from broad bean shells can function as a passive system of insulation and thermal regulation in high-Andean housing, reducing nighttime heat loss and stabilizing relative humidity levels. This hypothesis directs the research toward the experimental evaluation of its performance under real conditions, providing scientific evidence to validate its technical and social feasibility.

The implementation of activated carbon panels could reduce inhabitants' exposure to extreme temperatures, thereby mitigating the risk of cold-related illnesses, especially in children and the elderly [18]. Moreover, the use of regionally available materials would facilitate decentralized production and integration into existing buildings without requiring large investments or complex construction processes [19].

This article analyzes the technical feasibility of using activated carbon panels as a solution to improve thermal comfort in housing in the central Andes of Peru [20]. Their performance is evaluated under real conditions, considering environmental and construction parameters, as well as their adaptability to local socioeconomic contexts [21]. Likewise, their contribution to sustainable development and improvement of quality of life in vulnerable communities is highlighted through accessible, efficient, and resilient architecture [22]. For the first time, this study proposes the use of broad bean shells to produce activated carbon panels in high-Andean housing, experimentally evaluating their thermal performance under real conditions.

1.2. Research Problem

Housing in the high-Andean regions of Peru presents significant limitations in terms of thermal comfort [23]. This is due to the combination of traditional materials with low insulation capacity and the limited availability of efficient heating technologies [24]. As a consequence, inhabitants face inadequate thermal environments that directly affect their health and well-being, especially during the coldest months of the year [25].

The problem is evident in three main areas:

1. **High rates of respiratory diseases in children under five years old.** A study conducted in high-Andean communities of San Marcos (Cajamarca) reported an incidence of 6.2 episodes of acute respiratory illness (ARI) per child-year [26]. Of these cases, 4% were lower respiratory infections, and 1% required hospitalization.

2. **Substantial heat losses in uninsulated dwellings.** Research in the Colca Valley (Arequipa) shows that improving building envelopes, including roofs, can reduce energy demand by 23%, and comprehensive interventions by up to 29% [27]. Additionally, progressive insulation renewal proves to be more affordable and effective in constructive terms for inhabitants.
3. **Economic restrictions limiting access to thermal solutions.** Surveys in the Peruvian Andean region indicate that thermal insulation is practically nonexistent due to its high cost and low prioritization compared to other basic needs [27]. This scenario reinforces the socioeconomic impact on access to passive thermal comfort improvements.

In this context, the research hypothesis proposes that the incorporation of activated carbon panels, produced from local agricultural residues, can constitute a technical and economic alternative to reduce interior thermal variation in high-Andean dwellings. In this way, the aim is not only to mitigate heat loss and decrease the incidence of cold-related illnesses, but also to offer an accessible and sustainable solution in line with the socioeconomic conditions of these communities.

1.3. Research Objective

1.3.1. General Objective

To evaluate the technical feasibility of activated carbon panels as a solution to improve thermal comfort in high-Andean housing in Peru, through the analysis of their capacity to reduce interior thermal variation and contribute to the well-being of inhabitants in contexts of climatic and socioeconomic vulnerability.

1.3.2. Specific Objectives

- To determine the thermal and adsorption properties of activated carbon under controlled and real conditions.
- To compare the variation of indoor temperature between spaces with and without activated carbon panels during a complete thermal cycle.
- To evaluate the impact of panel implementation on thermal comfort and the health of vulnerable occupants, based on experimental results and specialized literature.
- To analyze the feasibility of manufacturing panels from local agricultural residues, promoting their implementation in sustainable self-construction practices.

2. Literature Review

2.1. Previous Studies

The incorporation of innovative materials in architecture has gained relevance in recent decades as a response to the need to optimize thermal comfort, reduce environmental impact, and improve indoor air quality. In this context, activated carbon has emerged as a material with high potential due to its high porosity, adsorption capacity, and thermal properties, making it applicable in construction elements such as panels, concrete, roofing, and filtration systems.

The use of activated carbon in construction has been explored in various international contexts, with contributions that are highly relevant to the present research. In Malaysia, for example, activated carbon derived from palm shell was incorporated into lightweight concrete, achieving improvements in mechanical strength and thermal stability, which demonstrates its potential as a multifunctional material in buildings [28]. Similarly, in China, a composite of activated carbon with carbon nanotubes and emulsified asphalt was developed, achieving high thermal conductivity and adsorption capacity, thereby reinforcing its applicability in constructions with high energy demand [29].

In Europe, research has focused on enhancing the conductivity of activated carbon. In Germany, its combination with expanded graphite enabled conductivity up to 34 times higher than that of granular carbon, which is key to the development of passive adsorption cooling systems [30]. Meanwhile, in the United Kingdom, a permeable roof system with activated carbon was designed, which reduced up to 90% of pollutants such as CO, SO_2, and particulate matter, confirming its dual benefit: thermal comfort and indoor air quality improvement [31].

In Latin America, progress has also been identified. In Mexico, the addition of activated carbon in compressed earth blocks reduced indoor humidity and improved the thermal inertia of dwellings, a finding that reinforces the relevance of its application in regions with significant thermal amplitude [32]. In Brazil, material derived from agricultural biomass was used in interior coatings, highlighting its contribution to both temperature regulation and air purification, in line with the principles of sustainability and circular economy [33].

In the Peruvian context, it has been observed that high-Andean housing, especially in regions such as Jun ń, presents insulation deficiencies that compromise habitability conditions [34]. Within this framework, activated carbon panels emerge as an innovative proposal that not only makes use of local agricultural waste but also provides a technically and culturally adaptable alternative to improve thermal comfort in vulnerable communities.

To systematize the international evidence regarding the application of activated carbon in construction systems, Table 1 presents a comparative summary of previous studies, highlighting source materials, applications, key findings, and identified research gaps relevant to the present investigation.

Table 1. Comparative Summary

Country / Region	Source Material	Main Application	Key Findings	Identified Gaps
Malaysia [28]	Palm shell	Lightweight concrete	Improved mechanical strength and thermal stability	Focus limited to urban infrastructure, not rural housing
China [29]	Composite with nanotubes + asphalt	Coatings and pavements	High thermal conductivity and adsorption	High costs, low applicability in rural areas
Germany [30]	Activated carbon + expanded graphite	Adsorption cooling systems	Conductivity up to 34 times higher	Focused on industrial/urban environments
United Kingdom [31]	Activated carbon in permeable roofs	Urban housing	Up to 90% reduction in air pollutants	Does not address extreme climate conditions or high thermal variability
Mexico [32]	Compressed earth blocks with activated carbon	Rural housing	Reduced humidity and improved thermal inertia	Limited research in high-Andean zones
Brazil [33]	Agricultural biomass	Interior coatings	Thermal regulation and air purification	Lacks experimental evaluation in extreme cold climates
Peru [34]	Local agricultural residues (e.g., broad bean shells)	Panels for insulation in high-Andean housing	Viable and culturally adapted option	Not yet experimentally validated under real conditions

As shown in Table 1, although significant advances have been achieved internationally, experimental validation under high-Andean climatic conditions remains limited. This gap justifies the present experimental approach.

Analysis: The review shows that although there are international advances in the use of activated carbon in construction, validation is lacking for its application in high-Andean housing. This research evaluates broad bean shell-based panels as a sustainable and adaptable thermal solution for extreme climates.

3. Materials and Methods

3.1. Materials

The primary materials used for the production of activated carbon from broad bean shells are detailed in Table 2, including their technical specifications and functional characteristics relevant to the experimental process.

The transformation process from agricultural residue to activated carbon was carried out in sequential stages. The complete methodological procedure and operational parameters are presented in Table 3 to ensure reproducibility.

This transformation process results in an activated carbon material with enhanced porosity and moisture adsorption capacity, making it suitable for incorporation into panel systems for passive thermal regulation. The use of low-temperature carbonization and solar drying reflects a context-adapted approach, consistent with sustainable construction strategies in rural high-Andean environments.

The activated carbon used in this study was derived from broad bean shells, an agricultural by-product widely available in the central Andean region. Although broad bean shells are not construction materials per se, their transformation through carbonization and activation processes yields a material with physical and hygrothermal properties suitable for passive building applications. To assess this suitability, the key physical, thermal, and moisture-related properties of the resulting activated carbon were identified and are summarized in Table 4.

To evaluate the suitability of the material for passive construction applications, the physical and hygrothermal properties of the activated carbon are summarized in Table 4, providing the technical basis for its incorporation into panel systems.

As shown in Table 4, the activated carbon derived from broad bean shells exhibits low thermal conductivity, high porosity, and significant hygroscopic capacity. These characteristics support its potential use as a functional component in passive panel systems, contributing to thermal and humidity regulation when integrated into building envelopes.

Table 2. Materials for Activated Carbon Production

Materials	Technical Specifications	Photographs
Broad Bean Shells	The dry shell is a by-product of broad beans. State: Solid Length: Variable Thermal conductivity: 0.0360 W/mK Humidity: 8%–10% Cost: USD 0.20 per kg	
Phosphoric Acid	Chemical compound with formula H_3PO_4, aqueous at 85%. State: Liquid Measurement in ml Thermal conductivity: Non-conductive Humidity: 85% Properties: Impurity isolator Cost: USD 8.44 per liter	
Distilled Water	Obtained through distillation, eliminating impurities, minerals, and ions. State: Liquid Length: Variable according to volume Thermal conductivity: 0.6 W/mK at 20 ℃ Properties: Acoustic insulator Cost: USD 1.27 per liter	
Metal Bucket	Metallic container with handle, used to transport or store liquids and solids. Capacity: 20 liters Material: Stainless steel Base: Flat for greater stability	

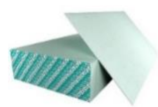
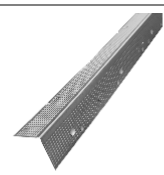
Table 3. Activated Carbon Production Process

Scenario	Process Description	Parameters	Technical justification
1. Picking and preparing raw materials	The bean husks were collected as agricultural waste and cleaned manually to remove soil and residual organic matter.	Environmental conditions	Ensures material purity and prevents contamination during heat treatment
2. Initial drying of biomass	The cleaned husks dried naturally before carbonation.	Reduces initial moisture content, improving carbonization efficiency and preventing incomplete thermal degradation	Reduces initial moisture content, improving carbonization efficiency and preventing incomplete thermal degradation
3. Carbonization	The dried biomass was carbonized in a cylindrical metal container with a sealed lid, limiting oxygen intake. The container was exposed to direct fire.	Temperature range: 150–200 ℃; duration: 3 hours; Direct combustion heating	It converts biomass into carbon-rich material by removing volatile compounds and avoiding complete combustion
4. Cooling and recovery	After carbonation, the container was allowed to cool naturally before opening.	Natural cooling under ambient conditions	Prevents oxidation of the charred material and structural damage
5. Chemical activation (impregnation)	The charred material was impregnated with phosphoric acid to enhance pore formation.	Phosphoric acid (H_3PO_4, 85%): 250 mL; carbon mass: 4 kg; Impregnation ratio ≈ 0.06 L/kg	Encourages the development of micro and mesoporous structures, increasing adsorption and hygroscopic capacity
6. Contact Activation Period	The impregnated carbon was allowed to react with the activating agent.	Static contact under ambient conditions	Allows the penetration of acids and the chemical activation of the internal structure of the pores
7. Washing and neutralization	The activated charcoal was washed with distilled water to remove residual phosphoric acid.	Distilled water volume: 4 L; Washing continued until a near-neutral pH was reached	Prevents material degradation and ensures safety in construction applications
8. Final drying	The washed activated carbon was dried prior to panel manufacturing.	Outdoor solar drying for 8 hours; ambient temperature ≈ 20 °C; Dry weather conditions	Removes residual moisture and stabilizes material properties
9. Sieving and storage	The dry activated carbon was sifted to achieve a uniform particle size and stored in sealed containers.	Dry and airtight storage	Ensures homogeneity and preserves adsorption performance

Table 4. Materials / Material Characterization

Ownership	Description / Value	Method/Source	Construction
Thermal conductivity (W/m·K)	0.030 – 0.045 W/m·K	Estimated from literary values for biomass-derived activated carbon [12], [17], [21]	Comparable to conventional insulating materials; Helps reduce heat loss and stabilize indoor temperature
Reaction to fire	Charred, low volatile; Non-flammatory under passive thermal conditions	Qualitative assessment based on the nature of the material and the reported behavior of the activated carbon [14], [16]	Better fire performance compared to gross biomass; Suitable for passive insulation when encapsulated in panels
Water vapour adsorption	High hygroscopic capacity due to porous structure	Literature on the adsorption properties of activated carbon [15], [17]	Allows to stabilize the indoor relative humidity within comfort ranges
Behavior under exposure to liquid water	Loses adsorption efficiency when saturated; Yield recovers after drying	Reported behavior of activated carbon materials [14], [22]	Requires protection from direct exposure to liquid water; Suitable for interior wall and ceiling applications
Porosity	High micro and mesoporous structure	Typical of chemically activated carbons [14]	Improves heat storage capacity and humidity regulation
Volumetric density (kg/m^3)	350 – 500 kg/m^3	Reported range for agricultural residue-based activated carbons [12], [21]	Lightweight material, suitable for low-load building systems

Table 5. Materials for Sample Simulation Model

Materials	Technical Specifications	Photographs
Pine Wood	Lightweight strip, clear and easy to work with, used in carpentry and light construction. State: Solid Length: 1'x3'x10.5' inches Properties: Resistant Cost: USD 4.08	
Drywall	Dry construction system with gypsum boards on metal structure. State: Solid Length: 3/8" 1.22m x 2.44m Thermal conductivity: 0.037 W/mK Properties: Thermal and acoustic insulation Cost: USD 7.66	
Drywall Screws	Metal fasteners with a fine tip and a special thread for securing gypsum boards to metal or wooden structures. State: Solid Length: 6x1 5/8" Properties: Acoustic insulation Cost: USD 8.42 (600 units)	
Drywall Profile	Galvanized metal piece forming the base structure for fixing gypsum boards. State: Solid Length: 3.00 m x 3 cm x 3 cm Thermal conductivity: 0.037 W/mK Properties: Thermal and acoustic insulation Cost: USD 1.72 per unit	
Corrugated Sheet (Calamina)	Thin sheet of galvanized steel, corrugated or trapezoidal, used in roofs and enclosures for its resistance and durability. State: Solid Length: Variable Properties: Acoustic insulation Cost: USD 4.22 per sheet	

The construction materials employed for the fabrication of the experimental simulation module are listed in Table 5, detailing their dimensions and relevant thermal properties.

The measurement and fabrication equipment utilized during the experimental phase are described in Table 6, including their operational ranges and technical specifications.

3.2. Study Design

The experimental model allowed manipulation of independent variables to observe their effects on dependent variables in a controlled environment, establishing cause–effect relationships. This approach is useful for testing scientific hypotheses [35]. The tests also determined the performance of thermal regulation under different conditions, enabling precise evaluation of manipulated factors.

Table 6. Electrical Equipment

Materials	Technical Specifications	Photographs
Electronic Scale	Device with electronic sensors providing accurate and fast weight readings on a digital screen. Measurement: 0.1 g–5000 g Model: OPALUX Base: Non-slip	
Grinder	Tool with rotating disc at high speed for cutting iron or wood. Adjustable speed Model: Truper Material: Heat-resistant plastic with metal components	
Drill/Driver	Reversible tool for screwing, unscrewing, and drilling. Adjustable speed Model: Dewalt	
Digital Thermo-Hygrometer	Instrument measuring temperature and humidity. Range: –10 ℃ to 50 ℃ (temperature) and 5%RH–99%RH (humidity) Model: BENETECH GM 1361	
Mini Digital Anemometer	Instrument measuring wind speed and air temperature. Model: UNI-T UT363 Portable	
Pyrometer	A pyrometer measures temperatures from -50 ℃ to 3000 ℃ with an accuracy of ±1%, using infrared sensors or thermocouples, and provides analog and digital outputs.	

3.2.1. Thermal Measurement Equipment

Activated carbon was produced from broad bean shells and used to manufacture prototype panels for an experimental housing module. These panels were installed for measurement tests aimed at evaluating their thermal performance both inside and outside the living space, thereby determining their effectiveness in temperature regulation.

Control Condition — Quasi–Experimental Design

Due to the exploratory nature of this study, a quasi-experimental design was adopted. Indoor hygrothermal conditions were measured inside the simulation module equipped with activated carbon panels, while outdoor environmental measurements were recorded simultaneously and used as a baseline control condition. Both indoor and outdoor values were collected under the same high-Andean climatic exposure, without mechanical ventilation or heating, allowing comparison and inference regarding the thermal regulation capacity of the activated carbon panels.

3.2.2. Measurement Method

Thermo–hygrometric data were collected using a structured periodic monitoring protocol. The monitoring campaign was conducted from June 15 to August 15, covering approximately 60 consecutive days under natural exposure conditions, without the use of heating systems or mechanical ventilation, in order to replicate the real operating conditions of a rural high-Andean dwelling.

Indoor and outdoor air temperature and relative humidity were simultaneously recorded using a calibrated digital thermo-hygrometer positioned in both environments. Measurements were taken at five representative time points—06:00, 09:00, 12:00, 15:00, and 20:00 h—selected to capture diurnal solar heat gains, thermal stabilization phases, and the characteristic nocturnal temperature decay associated with high-altitude climates.

This monitoring frequency, maintained consistently over a two-month period, enabled the construction of daily, seasonal, and comparative thermal profiles. The resulting dataset provided a robust basis for assessing the passive thermal performance of the activated carbon panel system relative to the outdoor environment, which served as the baseline control condition.

3.3. Prototype Development

To evaluate the influence of panel dimensions on thermal performance, three prototypes of different scales were constructed. Their dimensions, material configuration, and observed behavior are detailed in Table 7.

The structural composition and assembly process of the activated carbon panel system are illustrated in Figures 1–3. Figure 1 presents the individual components of the panel. Figure 2 shows the assembled configuration. Figure 3 illustrates the integration of the panel within the experimental simulation module.

The sequential phases of construction of the experimental module are summarized in Table 8, including design development, material selection, system installation, and testing procedures.

Table 7. Construction of Measurement Module – Prototypes

Prototype	Dimensions / Size	Function / Observations
	Small (20 cm x 20 cm) Activated carbon, glass, pine wood, mosquito mesh	Low thermal adsorption due to a small proportion of activated carbon; condensation on the glass cover.
	Medium (20 cm x 40 cm) Activated carbon, glass, pine wood, mosquito mesh	Adsorbs heat but cools rapidly due to the limited amount of activated carbon; condensation similar to prototype 1.
	Large (40 cm x 80 cm) Activated carbon, glass, pine wood, mosquito mesh	Good heat adsorption due to a larger amount of activated carbon; condensation mitigated with a transparent thin level hose, optimizing ventilation.

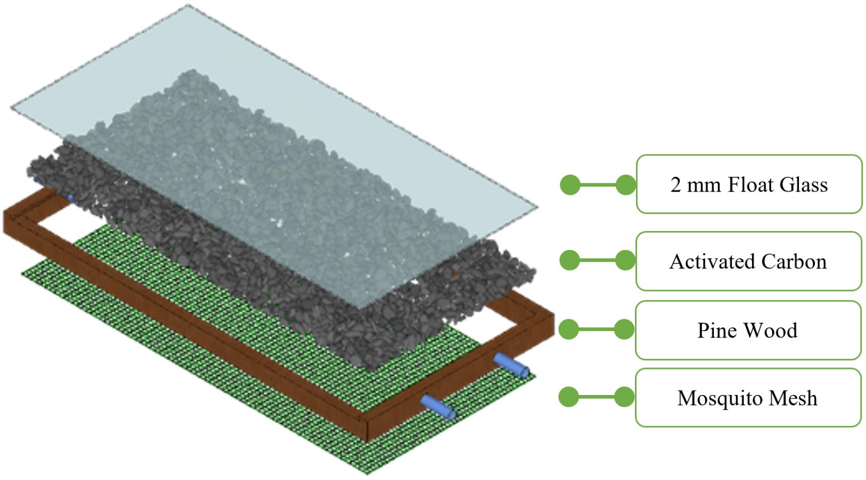


Figure 1. Components of Activated Carbon Panel

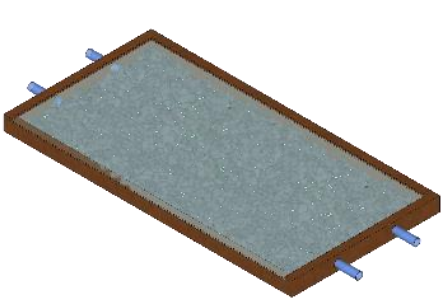
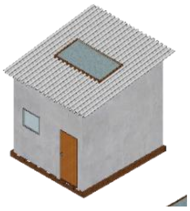


Figure 2. Assembled Panel

Figure 3. Simulation Module with Inserted Panel

Table 8. Construction Phases of Measurement Module

Phase	Description	Image	Observations
Initial Design	Architectural sketch of the module (1.20 m x 1.40 m x 1.40 m, scale 1:2)		
Material Selection	Drywall panels, pine wood strip, screws, drywall profile, corrugated sheet		Choice based on similarity to Andean housing materials.
Partial Construction	Basic structure erected		Adjustments in joints
System Installation	Placement of activated carbon panels		Start of thermal testing
Completed Module	Final prototype view		Ready for testing
Testing	Measurement of thermal comfort		Data on temperature and humidity

4. Results

The experimental evaluation of the activated carbon panels made from broad bean shells focused on two key variables: temperature regulation and relative humidity control. The results demonstrate the material's ability to passively improve indoor comfort in the constructed simulation module.

Outdoor environmental measurements are presented as baseline control values to allow comparison with the indoor performance of the module containing the panels. As shown in Table 9, indoor temperature remained consistently higher than outdoor baseline measurements throughout the monitoring period, indicating a thermal damping effect attributable to the activated carbon panels.

4.1. Thermal Behavior

The measurements showed significant differences between the indoor environment with activated carbon panels and the external environment.

4.1.1. Temperature

- Indoors: stabilized between **23.6 °C and 24.9 °C** during daytime hours.
- Outdoors: fluctuations ranged from **17.7 °C to 24.9 °C**, with a thermal amplitude of 7.2 °C.
- Even 2.5 hours after sunset, indoor temperatures remained within the comfort range, while the exterior showed sharp drops.

4.1.2. Relative Humidity

- Indoors: stabilized between 50.2% and 54.2%, maintaining a comfortable microclimate.
- Outdoors: recorded oscillations between 42% and 68%, with significant variability.

The comparative indoor and outdoor thermal data are presented in Table 9, highlighting the magnitude of temperature and humidity stabilization achieved by the panel system.

Table 9. Indoor vs. Outdoor Thermal Data

Variable	Indoors (with panels)	Outdoors	Difference
Temperature (℃)	23.6 – 24.9	17.7 – 24.9	Up to 7.2 ℃
Relative Humidity (%)	50.2 – 54.2	42 – 68	Up to 16%

4.2. Statistical Analysis

The data collected were processed using descriptive statistics, emphasizing maximum, minimum, and average values.

4.2.1. Temperature

- Mean indoor temperature: 24.2 °C
- Mean outdoor temperature: 21.0 °C
- The difference of 3.2 °C confirms the insulating and regulatory effect of activated carbon panels.

4.2.2. Humidity

- Mean indoor relative humidity: 52.4%
- Mean outdoor relative humidity: 55.0%
- While the average difference is small, the critical finding is the stability of indoor humidity, avoiding abrupt variations.

The descriptive statistical analysis of indoor and outdoor variables is presented in Table 10, allowing quantitative evaluation of thermal stabilization and variability reduction

Table 10. Descriptive Statistics of Indoor and Outdoor Variables

Variable	Minimum	Maximum	Mean	Standard Deviation
Indoor Temperature (℃)	23.6	24.9	24.2	0.4
Outdoor Temperature (℃)	17.7	24.9	21.0	2.6
Indoor Relative Humidity (%)	50.2	54.2	52.4	1.6
Outdoor Relative Humidity (%)	42.0	68.0	55.0	6.7

As observed in Table 10, the reduced standard deviation of indoor variables confirms the stabilizing effect of the activated carbon panels compared to outdoor conditions.

The graphs illustrate how the activated carbon panels dampen temperature fluctuations and maintain a more stable hygrothermal environment compared to outdoor conditions.

4.3. Interpretation of Results

The experimental results confirm the hypothesis that activated carbon panels function as a **passive thermal regulator**:

- They **retain heat during the day** and release it gradually at night, preventing abrupt losses.
- They **stabilize humidity** within the comfort range, despite external fluctuations.
- The panels contribute to reducing **energy poverty**, as they provide comfort without the need for external heating systems.

The reduction in standard deviation from 2.6 ℃ outdoors to 0.4 ℃ indoors represents an 84.6% decrease in thermal variability, reinforcing the regulatory capacity of the activated carbon panels.

In summary, the implementation of activated carbon panels in high-Andean housing significantly improves indoor thermal comfort, validating their technical feasibility as a sustainable and accessible solution for vulnerable communities.

5. Discussion

The results obtained demonstrate that activated carbon panels manufactured from broad bean shells present a high potential to improve thermal comfort in high-Andean housing, validating the initial research hypothesis. The evidence collected shows that the panels operate as passive systems capable of reducing the thermal amplitude between day and night, while stabilizing relative humidity levels within comfort ranges.

One methodological limitation of this first-phase research is the absence of a parallel indoor control module without activated carbon panels. However, the use of simultaneous outdoor measurements as a baseline control under identical climatic exposure provides a valid first-order comparison for preliminary evaluation. Future studies should incorporate paired modules and expanded monitoring periods to strengthen causal inference and enable inferential statistical testing.

5.1. Comparison with Previous Studies

These findings are consistent with international precedents. Research in Mexico demonstrated that adding activated carbon to compressed earth blocks improves thermal inertia and reduces humidity levels indoors [32]. Similarly, studies in Brazil identified that activated carbon derived from agricultural biomass contributes to temperature regulation and indoor air purification [33].

The present research advances these contributions by validating the performance of panels under real Andean climatic conditions. Unlike other studies that focus on industrial or urban contexts [29], [30], this work confirms the feasibility of incorporating activated carbon directly into construction systems intended for vulnerable rural communities.

5.2. Technical Feasibility

The experimental data reveal that the panels maintain indoor temperatures within a comfort range (23.6–24.9 ℃), even when the outdoor environment exhibits sharp drops. This phenomenon is explained by the porous structure of activated carbon, which allows for heat absorption and subsequent progressive release [14], [16]. In addition, the stabilization of relative humidity between 50.2% and 54.2% highlights its hygroscopic role, preventing abrupt variations that can deteriorate both dwellings and occupants' health.

The construction of the experimental module showed that the incorporation of panels does not require advanced technology, which facilitates their implementation in self-construction processes typical of the Andean region. The use of broad bean shells as the main raw material not only reduces costs but also adds value to agricultural waste, strengthening circular economy practices.

5.3. Social and Environmental Impact

From a social perspective, the improvement of indoor thermal comfort directly reduces health risks associated with cold, especially respiratory diseases affecting children and the elderly [26]. At the same time, the implementation of panels offers a low-cost alternative for families that cannot afford conventional insulation systems [27].

From an environmental standpoint, the use of agricultural residues contributes to reducing waste and CO_2 emissions associated with the production of conventional materials. This aligns with the principles of sustainable architecture and the Sustainable Development Goals (SDGs), particularly Goal 11 (sustainable cities and communities) and Goal 13 (climate action).

5.4. Limitations and Future Research

Although the results are promising, it is important to recognize some limitations:

1. The tests were carried out in a simulation module, which, although representative, does not fully replicate the structural complexity of traditional housing.
2. The evaluation period was limited; longer monitoring would provide more robust information about seasonal behavior.
3. It is necessary to explore the durability of the panels over time, considering exposure to environmental factors such as precipitation and solar radiation.

Future research should address these aspects through pilot programs implemented in real high-Andean dwellings, evaluating not only thermal performance but also social acceptance, economic feasibility, and long-term durability. Likewise, it would be valuable to explore the combination of activated carbon with other natural insulating materials, such as straw or clay, to optimize performance.

6. Conclusions

The study confirmed the technical feasibility of activated carbon panels manufactured from broad bean shells as a passive alternative for improving thermal comfort in high-Andean housing.

The main conclusions are as follows:

1. **Thermal and hygrometric performance:** Activated carbon panels maintained indoor temperatures within a comfort range (23.6 °C – 24.9 °C) and stabilized relative humidity between 50.2% and 54.2%, even when outdoor conditions fluctuated sharply.
2. **Passive regulation system:** The porous structure of activated carbon allowed the absorption of heat during the day and its gradual release at night, reducing thermal amplitude by up to 7.2 °C and preventing sudden changes in humidity.

3. **Social feasibility:** The use of an abundant and low-cost agricultural residue, such as broad bean shells, facilitates the development of accessible solutions for vulnerable Andean communities, where families have limited resources to invest in conventional insulation systems.
4. **Environmental sustainability:** The incorporation of agricultural residues into construction materials contributes to circular economy practices and reduces the environmental impact associated with traditional building materials.
5. **Research projection:** The results open the door to large-scale application of panels in real dwellings, as well as to their combination with other natural insulating systems to optimize performance.

In conclusion, activated carbon panels represent a low-cost, **environmentally sustainable, and socially viable innovation** that can significantly contribute to improving habitability and health in high-Andean communities, offering a resilient alternative to the challenges of climate change and energy poverty.

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