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Regulatory Gap Versus Performance Reality: Thermal Assessment of a Social Housing Module in the Peruvian Andes

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Abstract

In high-altitude regions of the Global South, social housing programs are essential for mitigating vulnerability to low temperatures, but their standardized designs often fail to meet thermal performance codes. This study evaluates a "Sumaq Wasi" adobe housing module in the Peruvian Andes (Kunturkanki, 4237 m a.s.l.) during the 2023 frost season. We comparatively applied the 2014 and 2022 draft versions of the Peruvian standard EM.110 to assess the building envelope's thermal transmittance and condensation risk, benchmarking monitored indoor temperatures against adaptive comfort models. The results revealed widespread non-compliance with thermal transmittance limits, especially for the roof and floor, although condensation risk was low. While indoor temperatures failed to meet conventional standards, they aligned with regionally adapted comfort ranges. We conclude that the standardized module design is insufficient for local climatic demands and argue that social housing policies must evolve, balancing regulatory stringency with context-aware bioclimatic design to be effective.

Keywords: high-Andean climate; social housing; thermal performance; building energy codes; Peru

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1. Introduction

In high-altitude regions, vulnerable populations face increasing threats from intense seasonal climate variations [1–3]. This challenge has driven global research on adaptive thermal comfort and social housing performance in cold climates, often benchmarked against international standards such as ASHRAE 55 [4,5].

Regarding vernacular and contemporary housing in these regions, studies indicate that passive design is highly sensitive to severe local climates [6]. Key findings highlight that altitude is the main factor influencing the temperature difference between the interior and exterior [7], alongside the critical role of residents' adaptive thermal comfort and the climatic responsiveness of the dwelling [8,9]. However, thermal comfort standards often fail to be met because vernacular dwellings do not comply with evaluation methods proposed by these standards [10]. Therefore, there is a recognized need to continue reviewing the energy efficiency of buildings—both vernacular and contemporary—in high-altitude contexts characterized by intense precipitation and freeze–thaw cycles (Bhat et al., 2025) [11], as research remains limited in many regions of the Global South.

While Andean countries have implemented thermal regulations [12–14], their effectiveness and evolution in response to accelerating climate change remain a critical research area. Indeed, global analyses confirm that regularly updating building codes is fundamental to improving housing resilience. Implementing above-code energy efficiency measures can reduce mortality in extreme cold events by up to 69% [15]. This global perspective underscores the need to assess whether local regulations, such as Peru's, are evolving adequately.

In Peru, where winter temperatures in high-Andean zones can drop to −21 °C [16], three scenarios are being considered to improve the thermal performance of vernacular Andean dwellings. First, in homes built by local residents, targeted interventions were implemented using simple, low-cost passive systems in the bedrooms [17,18]. Experimental prototypes were also designed in academia, such as the Orduña and Imata prototypes, which were monitored and validated in the field, yielding positive results in the performance of building envelopes [19,20]. Similarly, as a government policy, two "Sumaq Wasi" prototypes (Quechua for "Beautiful House"), one made of adobe and the other of brick, were proposed for construction starting in 2019 to alleviate housing insecurity [21–23]. Despite this large-scale intervention, prior studies are limited. They have focused on thermal transmittance analysis under a single version of the Peruvian code (EM.110-2014) [24–27] or have highlighted the lack of cultural and climatic suitability in standardized designs [28].

The fundamental research gap is the lack of a comparative analysis assessing how updates to Peru's technical standard impact the thermal performance of these dwellings. Specifically, no study has examined how the transition from the 2014 standard to the 2022 draft modifies compliance criteria and, ultimately, occupant comfort. This comparison is vital not only to validating public investment but also to guiding future social housing policies in an increasingly extreme climate.

This study investigates the gap between regulatory standards and real-world thermal performance in a Sumaq Wasi adobe housing module in Kunturkanki, Cusco, during the 2023 frost season. Our research has two objectives: (1) to quantify the differences in thermal transmittance and surface condensation risk by applying the 2014 and 2022 methodologies of the EM.110 standard; and (2) to assess whether the resulting thermal performance meets regulatory limits and achieves recommended adaptive comfort ranges. We hypothesize that the standardized design is insufficient for the local climate, failing to meet the stricter updated limits and provide adequate thermal comfort.

2. Materials and Methods

The methodology comprised three phases: (1) characterizing the case study by documenting its building composition and monitoring local climatic conditions; (2) calculating the envelope's performance (thermal transmittance, condensation risk) by comparatively applying the 2014 and 2022 draft versions of the Peruvian standard EM.110; and (3) assessing indoor thermal comfort using monitored data and adaptive comfort models.

2.1. Study Area and Case Study

The research was conducted in the Kunturkanki district, Cusco, Peru (14.47225° S, 71.29688° W, 4237 m a.s.l.) (Figure 1). The local climate features a dry season (June–August) with severe frosts known as *heladas* and a marked diurnal thermal oscillation. During this period, temperatures can drop to a minimum of −4.6 °C in the early morning and reach peaks of 19.7 °C in the afternoon (Figure 2).

Figure 1. Location of the studied housing module in Kunturkanki, Cusco.

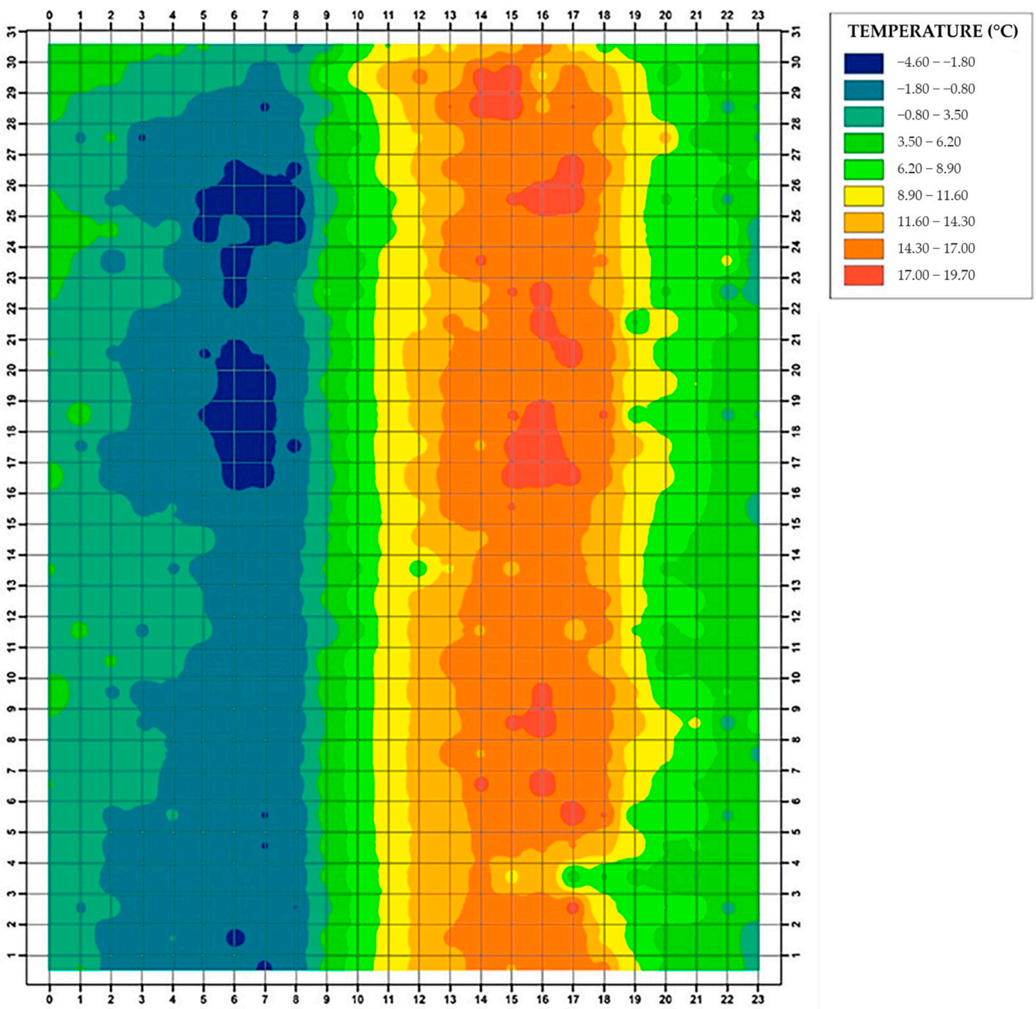

Figure 2. Outdoor thermal profile during the frost season in Kunturkanki (June–August 2023). The *x*-axis represents the hours of the day, and the y-axis represents the days of the month.

The Sumaq Wasi module, as a habitable space, is inserted into the typical dispersed organization of a rural high-rise dwelling, which is usually configured with domestic, productive, and sanitary spatial units [28] (Figure 3). The specific module studied, built in 2022, is a representative case study as it embodies the standard government design for the Cusco region. It has a 33 m^2 floor area and a 2.12 m ceiling height and includes two bedrooms and a dining area (Figure 4). Its envelope consists of adobe walls, a concrete floor, and a zinc-and-polystyrene roof [29]. An on-site visit verified that the construction matched the government's technical documents. A detailed breakdown of all building layers and thicknesses is provided in Appendix A.

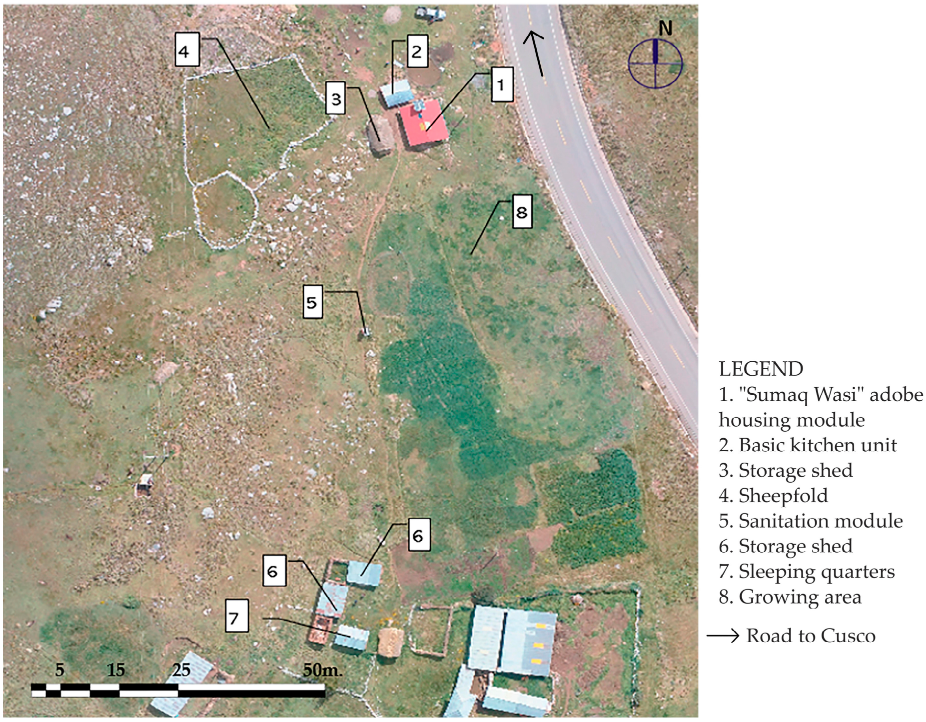

Figure 3. Aerial view of the rural dwelling and its dispersed units. Image captured via drone (UAV) on 1 June 2023, providing a zenithal view of the main housing module and its surrounding dispersed units.

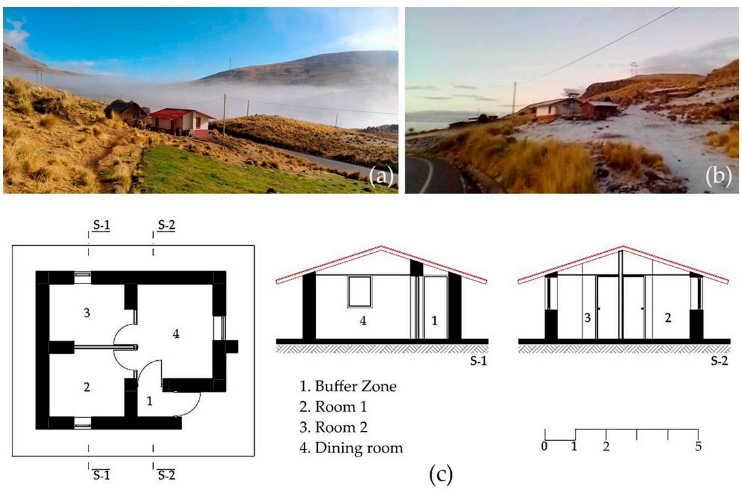

Figure 4. Contextual and Spatial Documentation of the Sumaq Wasi Housing Module. The figure provides the visual and technical context of the case study: (**a**) Module view and landscape context (3 October 2022); (**b**) Module during the frost season (30 July 2023); (**c**) Floor plan and spatial layout of the module, indicating the locations of Section 1 (S-1) and Section 2 (S-2).

Calculations for this study were based on data gathered from technical documents and an on-site visit. During the visit, building materials were documented (Figure 5) and hygrothermal data loggers (ELITECH RC-4HC sensors, compliant with ISO 7726–1998 [30]) were installed both inside and outside the module. On-site monitoring was conducted over a 72 h period (23–26 July 2023). This short-term, intensive period was intentionally selected to capture the building's response during one of the region's most severe frost events (heladas), providing a snapshot of its performance under critical thermal stress. To isolate the passive performance of the building envelope—a primary objective of this study—the dwelling was kept unoccupied, thereby eliminating the variable influence of internal heat gains from occupants and activities.

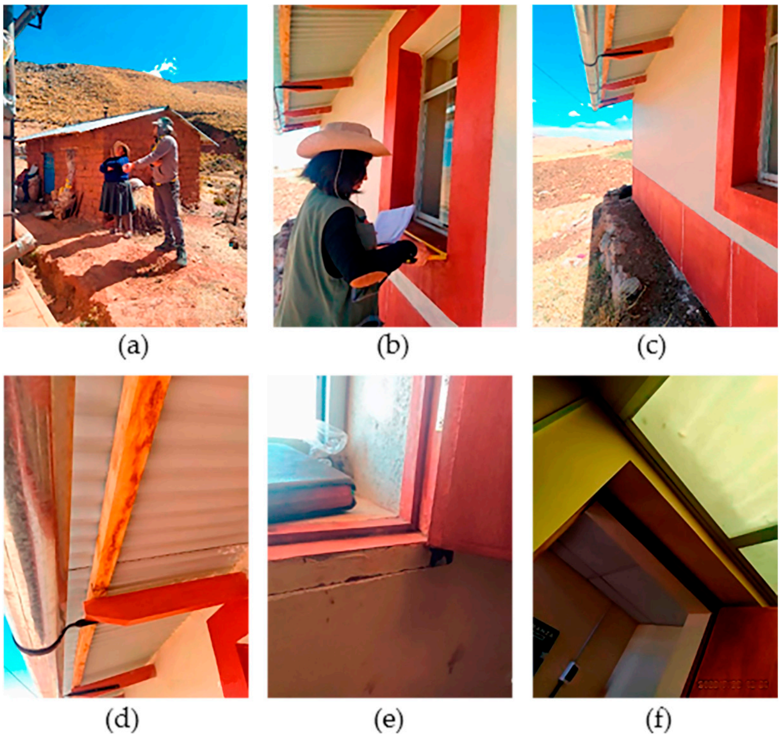

Figure 5. On-site Documentation of the Sumaq Wasi Module's Envelope and Occupancy Context. The figure documents the physical characteristics and context of the case study: (**a**) Interview with the homeowner to establish occupancy patterns and history; (**b**) Verification of on-site measurements for modeling accuracy; (**c**) Condition of the foundation, subfloor, and adobe wall assembly; (**d**) Detail of the roof overhang and its connection to the wall; (**e**) Detail of the aluminum window frame and wooden shutter assembly; (**f**) Interior view of the polycarbonate skylight in the social area. All photographs were taken during the monitoring period (23–26 July 2023).

2.2. Building Envelope Performance Assessment (EM.110-2014 vs. 2022)

We assessed the building envelope's performance following the Peruvian Technical Standard EM.110 (2014 version and 2022 draft) [14,31], which classify the site as 'High-Andean' and 'Very Cold Continental', respectively. The detailed calculation process, including all input parameters and intermediate steps for both methodologies, is provided in the Supplementary Materials [File S1].

2.2.1. Thermal Transmittance (U-Value) Evaluation

We calculated the thermal transmittance (U-value) of each building component according to ISO 6946 [32]. Although the underlying principle remains consistent, the two versions of EM.110 differ in three methodological respects:

1. Heterogeneous layers: the 2022 draft requires differentiated calculation accounting for both horizontal and vertical heat flows; the 2014 version uses a simplified approach.
2. Thermal bridges: the 2022 draft eliminates the exclusion of surface resistances (e.g., beams, columns) and mandates specific calculation for openings instead of tabulated values.
3. Floor assembly: the 2014 standard calculates U based on material layers; the 2022 draft assigns a predetermined U-value depending on the type of perimeter insulation.

These methodological updates reflect a shift toward a more detailed and internationally aligned assessment. The resulting U-values were compared against the maximum permissible limits of each standard (Table 1).

Table 1. Thermal transmittance (U-value) compliance analysis [14,31].

Peruvian Technical Standard EM.110 (2014)					**Peruvian Technical Standard Project EM.110 (2022)**				
Bioclimatic zone		TTM [a] (w/m^{2}k)			Bioclimatic zone		TTM [a] (w/m^{2}k)		
		Wall	Roof	Floor			Wall	Roof	Floor (level or ventilated)
5	High-Andean	1.00	0.83	3.26	6	Continental very cold	1.9	0.8	1.2

[a] TTM: Maximum Thermal Transmittance.

2.2.2. Surface Condensation Risk Verification

We evaluated the surface condensation risk following ISO 13788, ensuring the internal surface temperature (Tsi) remained above the dew point temperature (Tr). This analysis was based exclusively on the theoretical calculation method stipulated in the EM.110 standard. No on-site visual inspection or instrumental monitoring was conducted, as the study's objective was to verify theoretical regulatory compliance. Empirical validation of these calculations is recommended for future research.

2.3. Adaptive Thermal Comfort Assessment Methodology

We assessed thermal comfort using recognized adaptive models [19]. Model inputs were derived from outdoor temperatures recorded at the nearest meteorological station during the frost season (June–August). An 80% occupant satisfaction criterion was established, corresponding to an acceptable comfort range of ±3.45 °C from the neutral temperature. Based on these models, indoor temperatures should remain between 12 °C and 24 °C. For context, Peru's Occupational Health manual specifies an optimal winter temperature between 17 °C and 22 °C at 30–70% relative humidity [33].

3. Results

The thermal performance assessment of the adobe-built Sumaq Wasi module, including analyses of thermal transmittance, surface condensation risk, and adaptive thermal comfort, reveals a notable non-compliance with Peruvian regulations and an inability to ensure thermally comfortable conditions for its occupants. For full transparency and reproducibility, the complete, step-by-step calculation sheets for these values and the condensation analysis are provided in the Supplementary File [File S1].

3.1. Thermal Transmittance (U-Value)

The thermal transmittance calculations reveal deficient insulation in most of the building envelope. The wall, with a U-value of 1.93 W/m^{2}K, exceeds the limit of the 2014 standard (1.00 W/m^{2}K), although its recalculated value under the 2022 draft update (1.61 W/m^{2}K) does meet the more flexible threshold of 1.90 W/m^{2}K. However, both the roof and the floor fail under both assessments. The roof significantly exceeds the limits for both 2014 (1.07 vs. 0.83 W/m^{2}K) and 2022 (1.32 vs. 0.80 W/m^{2}K). Similarly, the floor surpasses the corresponding thresholds with values of 3.78 vs. 3.26 W/m^{2}K (2014) and 1.87 vs. 1.20 W/m^{2}K (2022) (see Figure 6).

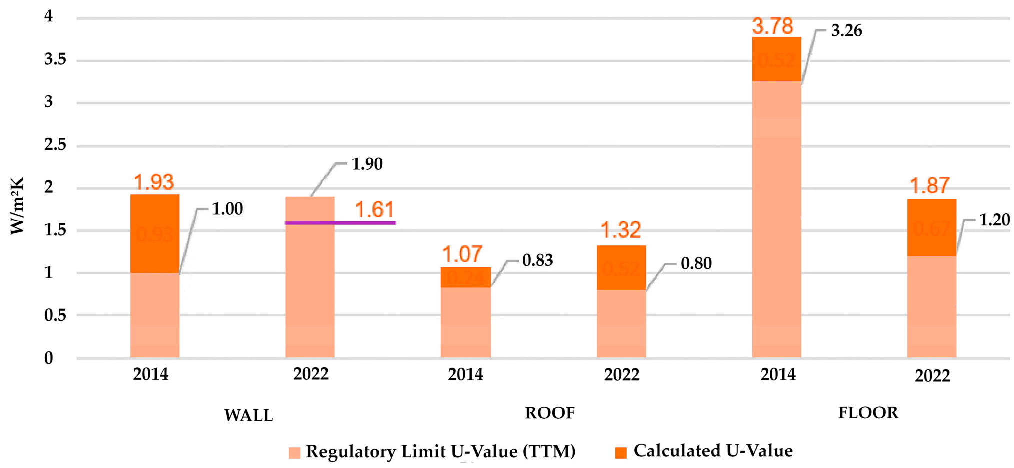

Figure 6. Comparative table of final thermal transmittance values. Maximum thermal transmittance (TTM) values for each methodology studied (Authors 2023) [14,31].

3.2. Surface Condensation Risk

3.2.1. Calculation of Dew Point Temperature (Tr)

Using field data, the dew point temperature (Tr) was determined. Considering the minimum recorded indoor temperature of 7.30 °C (Figure 7) and its corresponding indoor relative humidity of 36.7% (Figure 8) (Table 2), the resulting Tr was −6.70 °C.

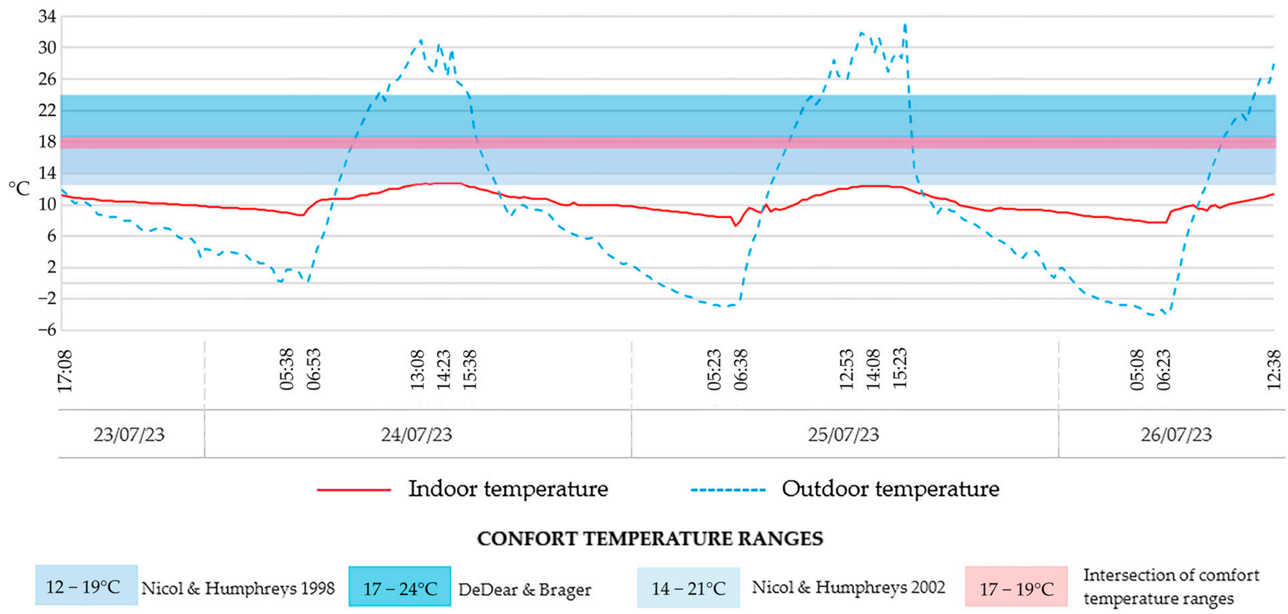

Figure 7. Monitored indoor versus outdoor air temperature profile.

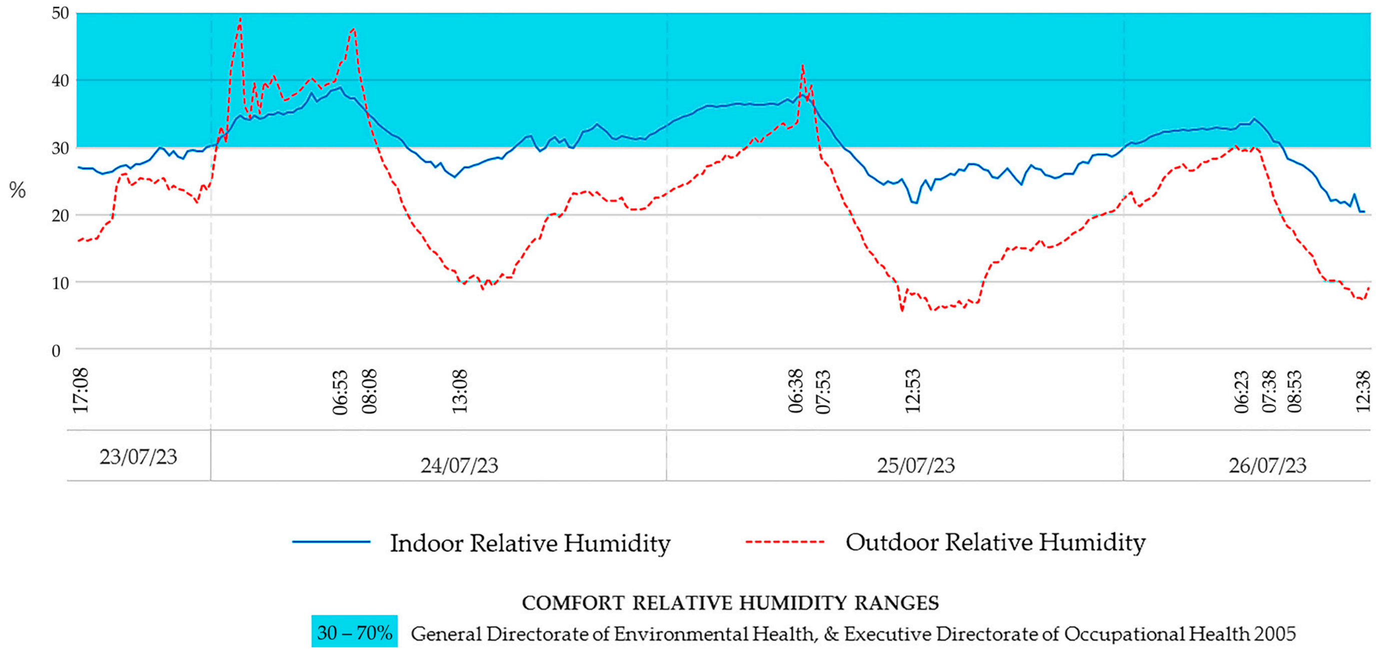

Figure 8. Monitored indoor versus outdoor relative humidity profile.

Table 2. Summary of monitored indoor and outdoor temperatures (24–26 July 2023).

Date	Indoor Temperature (°C)		Hri [1] (%)		Outdoor Temperature (°C)		HRe [2] (%)	
	Max	Min	Max	Min	Max	Min	Max	Min
24 July 2023	12.7	8.7	39.0	25.6	19.4	0.2	49.2	8.9
25 July 2023	12.4	7.3	37.9	21.8	20.7	−3.0	42.4	5.5
26 July 2023	11.3	7.7	34.2	20.4	20.6	−4.0	43.0	7.2
Average	12.13	7.9	37.03	22.6	20.23	−2.27	44.87	7.2

[1] Indoor Relative Humidity, [2] Outdoor Relative Humidity.

3.2.2. Calculation of Internal Surface Temperature (Tsi)

The internal surface temperature (Tsi) was calculated for each envelope assembly based on the formulas presented in the methodology section. The key input values, which differ between the two standards, were as follows:

- EM. 110-2014: The internal surface resistance (Rsi) was set at 0.11 m^2K/W for the wall and 0.09 m^2K/W for the roof and floor.
- EM. 110-2022: The Rsi values were obtained from the draft standard, establishing 0.13 m^2K/W for the wall, 0.10 m^2K/W for the roof, and 0.17 m^2K/W for the floor.

The most critical recorded field data were used for the indoor (Ti) and outdoor (Te) temperatures, which were 7.30 °C and −3.00 °C, respectively (Table 2). The total thermal resistance (Rt) for each assembly was derived from the previously calculated thermal transmittance values.

Under both methodologies, the calculated Tsi values for each envelope assembly were higher than the dew point temperature (Tr). Although the Tsi values differed slightly between the two standards, both scenarios indicated that the risk of surface condensation was avoided (Table 3).

Table 3. Surface condensation risk analysis (Tsi versus Tr).

Envelope Component	Tr (°C) [a]	EM.110-2014	EM.110-2022
		Tsi (°C) [b]	Tsi (°C) [b]
Wall		6.71	5.14
Roof	−6.70	6.43	5.94
Floor		7.06	4.12

[a] Dew Point Temperature, [b] Internal Surface Temperature.

3.3. Adaptive Thermal Comfort Assessment

The collected data show that the adobe housing module fails to reach the target comfort temperature range of 17–19 °C at any point during the day. Instead, it recorded average indoor temperatures between 8.7 °C and 11.4 °C during the occupants' resting hours (17:00 to 05:00) (Figure 7). Regarding indoor relative humidity, the module was partially within the comfort limits, with average values ranging from 26.7% to 37.8% during the hours of greatest use (Figure 8).

4. Discussion

The thermal performance assessment of the Sumaq Wasi module reveals two critical findings: a significant failure to comply with national building codes and a fundamental paradox within the evolution of Peru's thermal standards. This discussion examines these findings by addressing the study's two primary objectives: (1) it first analyzes the module's poor performance and non-compliance by comparing the 2014 and 2022 versions of the EM.110 standard; and (2) it then explores the implications of these results for the definition of adapted thermal comfort in the high-Andean context and the development of future housing policies.

The module's poor thermal performance, particularly the significant heat loss through the roof, exemplifies the shortcomings of a standardized solution in a specialized environment. While the wall's U-value (1.93 W/m^2K) narrowly fails the 2014 standard but passes the 2022 draft, the roof (1.07 W/m^2K) and floor (3.78 W/m^2K) significantly exceed all regulatory limits. The roof's performance is consistent with similar findings in the Colca Valley for uninsulated metal roofs [17], identifying it as the most critical building element.

This poor performance contrasts sharply with established bioclimatic optimization strategies in similar high-altitude regions. For instance, traditional and optimized designs in Tibet and Nepal prioritize thermal mass and multi-layered structures to minimize heat loss. Walls in these regions are typically thick (600–700 mm) and composed of high-density materials like adobe or stone, maximizing heat storage to regulate extreme diurnal variations [6,9]. Furthermore, contemporary retrofits in masonry structures have shown that adding just 2 inches of insulation can improve thermal stability by up to 38%, achieving U-values around 0.8 W/m^2K, significantly lower than the module's wall [11]. Similarly, roof optimization in traditional housing relies on multi-layered structures [6] or mud roofs in Nepal [9], with low U-values to provide effective insulation and passive heating effects. The Sumaq Wasi module's reliance on a lightweight, poorly insulated roof structure fundamentally contradicts these proven high-altitude design principles, confirming its lack of climatic suitability and contrasting sharply with prototypes such as the one in Orduña, which achieved a wall U-value of 0.667 W/m^2K using local materials [19].

Furthermore, the comparative analysis of the EM.110 standards uncovers a crucial paradox in the new 2022 draft, especially regarding the floor. The 2022 update represents a significant step towards international best practices by demanding more rigorous calculations. However, by drastically lowering the floor's U-value limit from 3.26 to 1.20 W/m^2K, it incentivizes greater insulation. This approach overlooks a key passive strategy highlighted by previous research: leveraging the ground's stable thermal inertia (16–18 °C) as a natural heat source [17]. This tension is particularly relevant given that earthen floors and thick thermal mass floors in traditional high-altitude dwellings are known to act as effective heat storage elements, absorbing solar heat during the day and releasing it gradually at night to maintain a warm indoor environment [9]. The draft regulatory (EM. 110-2022) push for extreme insulation risks negating this passive geothermal benefit, potentially leading to over-insulation solutions that are costly and less effective than a balanced design that utilizes the earth's thermal mass. This finding underscores the need for future regulations to promote intelligent bioclimatic design, balancing technical calculations with passive strategies adapted to the local context.

This study also reinforces the argument that thermal comfort standards must be adapted to the high-Andean context. During early morning hours, the module's indoor temperatures (8.7 °C to 11.4 °C) were far below the 18 °C target of the 2014 standard but were comparable to temperatures found in other regional studies in Orduña at 4260 m a.s.l. (8 °C to 10 °C) [19] and Imata at 4500 m a.s.l. (9.5 °C to 15.3 °C) [20]. This consistent pattern across different studies suggests that high-mountain populations are acclimatized to a lower indoor temperature range than prescribed by conventional standards [6,9,18]. Therefore, imposing international comfort benchmarks may be both unrealistic and unnecessary. Future policies should focus on developing regionally adapted comfort models that prioritize preventing extreme cold rather than achieving idealized thermal optimums.

The findings of this study should be considered in the light of certain methodological limitations. The on-site monitoring was constrained to a short-term, 72 h period under unoccupied conditions. While this approach was optimal for isolating the passive performance of the building envelope against extreme cold, it does not account for the dynamic thermal impact of occupancy, including internal heat gains from inhabitants and their daily activities. Logistical challenges, common in fieldwork in remote rural areas, precluded a longer monitoring period.

Therefore, to build upon these findings, future research is strongly recommended. Long-term monitoring under typical occupied conditions is necessary to develop a more comprehensive understanding of the dwelling's year-round performance. Furthermore, calibrated whole-building energy simulations developed specifically for high Andean regions would be invaluable for testing various retrofitting scenarios (e.g., different levels of insulation, improved glazing) and quantifying their potential energy savings and comfort improvements.

In light of these findings, the implications for public housing policy are clear. The Sumaq Wasi program requires a design revision focused on roof insulation as the highest-priority intervention. The exploration of low-cost, locally sourced insulating materials, such as the totora reeds used in successful bioclimatic prototypes, should be considered [18,19]. For floors, a balanced approach that improves airtightness without completely decoupling the slab from the ground's thermal mass is recommended. Future research should use parametric simulations to determine an optimal floor U-value that balances insulation with passive heat gain. Ultimately, effective social housing in the Andes must evolve from deploying standardized modules to promoting adaptive design frameworks that are both technically sound and climatically and culturally responsive.

5. Conclusions

This study reveals a critical disconnect between Peruvian thermal regulations and the actual performance of the Sumaq Wasi module in the high Andes. The design fails to ensure thermal resilience due to envelope deficiencies—particularly in the roof—and unintended conflicts within evolving building codes. Key findings:

1. Systemic Non-Compliance: The building envelope exceeds U-value limits of EM.110 (2014 and 2022 draft), with the roof exhibiting the highest thermal transmittance.
2. Normative Contradiction: The 2022 draft's stringent floor U-value risks decoupling slabs from beneficial ground thermal mass, countering regional bioclimatic principles.
3. Misaligned Comfort Targets: Indoor conditions fall below official standards but match those in adapted Andean homes, underscoring the need for localized adaptive comfort models.

Based on these findings, the following practical, forward-looking recommendations are proposed:

4. Prioritize roof retrofitting using high-performance, low-cost local materials (e.g., totora reed mats, straw-clay composites).
5. Optimize floor design with insulated perimeters while retaining partial ground contact to leverage thermal inertia.
6. Formalize high-Andean adaptive comfort ranges in national policy, grounded in field data on acclimatized populations.

In conclusion, thermal resilience in Andean social housing requires shifting from rigid, universal modules to adaptive, performance-driven frameworks that harmonize passive design, local materials, and context-specific comfort criteria.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15244401/s1, File S1: Detailed Excel spreadsheet containing the step-by-step calculation process for the thermal transmittance (U-value) of the building envelope components under EM.110-2014 and EM.110-2022, as well as the surface condensation risk analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

UNSAAC	Universidad Nacional de San Antonio Abad del Cusco
MVCS	Ministerio de Vivienda, Construcción y Saneamiento
SENAMHI	Servicio Nacional de Meteorología e Hidrología

Appendix A

Table A1. Building Envelope Composition of the Sumaq Wasi Module (organized from exterior to interior layer) [29].

Envelope	Constructive Element	Thickness (m)
Exterior walls	**Foundation sill**	-
	Cement-Sand Mortar	0.02
	Plain Concrete Mix	0.4
	Gypsum Plaster	0.01
	Baseboard	-
	Cement-Sand Mortar 1:3	0.02
	Adobe	0.4
	Gypsum Plaster	0.01
	Wall	-
	Gypsum Plaster	0.01
	Adobe	0.4
	Gypsum Plaster	0.01
	Beams	-
	Gypsum Plaster	0.01
	Collar Beam	0.1016
	Gypsum Plaster	0.01
Exterior Door	Phenolic Plywood	0.0065
	Unventilated Air Cavity	0.03
	Phenolic Plywood (3 Layers)	0.0065
Windows	Aluminum Tube (frame)	0.0254
	Clear Single Glass	0.06
Windows shutter	Lightweight Wood (frame)	0.054
	Plywood (exterior layer)	0.004
	Unventilated Air Cavity	0.03
	Plywood	0.004
Roof	11-Channel Galvanized Corrugated Sheet	0.0003
	Expanded Polystyrene	0.05
Skylight (Roof)	Transparent Corrugated Polycarbonate	0.001
Ceiling (opaque part)	Vinyl Tile	0.01
Skylight-Ceiling	Aluminum Tube (frame)	0.0254
	Cellular Polycarbonate	0.006
Floor	Polished Cement Floor with Steel Reinforcement	0.08
	Stone Bed	0.1016

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