Revista Hábitat Sustentable Vol. 15, N°. 1. ISSN 0719 - 0700 / Págs. 98 - 115
https://doi.org/10.22320/07190700.2025.15.01.08

THERMAL COMFORT ANALYSIS OF DWELLINGS WITH DIFFERENT CONSTRUCTION SYSTEMS LOCATED ABOVE 3000 M.A.S.L. IN THE RURAL ANDEAN ZONE OF ECUADOR

Recibido 29/03/2025
Aceptado 06/06/2025

ANÁLISIS DEL CONFORT TÉRMICO DE VIVIENDAS CON DIFERENTES SISTEMAS CONSTRUCTIVOS UBICADAS SOBRE 3000 M.S.N.M. EN LA ZONA RURAL ANDINA DE ECUADOR

ANÁLISE DO CONFORTO TÉRMICO DO HABITAÇÃO COM DIFERENTES SISTEMAS CONSTRUTIVOS LOCALIZADOS ACIMA DOS 3.000 METROS DE ALTITUDE ZONA RURAL ANDINA DO EQUADOR

Andrea Nataly Moreno-Albuja
Magíster en Construcciones
Estudiante-Graduada
Universidad de Cuenca, Riobamba, Ecuador
https://orcid.org/0009-0006-7579-4599
natalymorenoa@gmail.com

Vanessa Guillén-Mena
Magíster en Eficiencia Energética y Sostenibilidad en Edificación y Urbanismo
Estudiante de Doctorado en Eficiencia Energética y Sostenibilidad en Ingeniería y Arquitectura
Universidad del País Vasco, Bilbao, España
https://orcid.org/0000-0003-4001-1831
vguillen001@ikasle.ehu.eus

Nathalie Madeleine Santamaría-Herrera
Máster en Arquitectura
Estudiante de Doctorado en Eficiencia Energética y Sostenibilidad en Ingeniería y Arquitectura - Profesora de la Carrera de Arquitectura
Universidad del País Vasco - Universidad Nacional de Chimborazo, Bilbao, España
https://orcid.org/0000-0002-7854-3836
nsantamaria014@ikasle.ehu.eus

RESUMEN

Esta investigación analiza el confort térmico de cuatro unidades de vivienda no climatizadas con diferentes sistemas constructivos, ubicadas en una zona rural andina de Ecuador sobre los 3000 m.s.n.m., para determinar estrategias pasivas de diseño. Para esto se describen características del entorno y constructivas de dos viviendas neo vernáculas con materiales naturales (TRA-01 y TRA-02) y dos viviendas con materiales modernos (CON-01 y CON-02). Se monitorizaron las variables de temperatura y humedad relativa exterior e interior durante 8 días, así como temperaturas de superficies de la envolvente y se evaluó el rango de confort mediante la temperatura operativa. Los resultados mostraron que tres viviendas presentaron temperaturas interiores estables, aunque solo la vivienda de fardos de paja estuvo parcialmente dentro del rango de confort. El estudio concluye que el aislamiento térmico de la envolvente, el diseño bioclimático y calidad constructiva son necesarios para mantener temperatura adecuada en estas zonas de clima frío.

Palabras clave
aislación térmica, arquitectura bioclimática, eficiencia energética, sistemas constructivos

ABSTRACT

This research examines the thermal comfort of four non-air-conditioned dwellings located in a rural Andean region of Ecuador, at an altitude of 3,000 meters above sea level (masl), to identify passive design strategies. The study describes the environmental and construction characteristics of two neo-vernacular dwellings built with natural materials (TRA-01 and TRA-02) and two dwellings with modern materials (CON-01 and CON-02). Indoor and outdoor temperature and relative humidity variables were monitored for eight days, along with envelope surface temperatures. The comfort range was evaluated using the operating temperature. The results showed that three dwellings had stable indoor temperatures, although only the straw bale dwelling was partially within the comfort range. The study concludes that the envelope's thermal insulation, bioclimatic design, and construction quality are needed to maintain adequate temperatures in these cold climate zones.

Keywords
thermal insulation, bioclimatic architecture, energy efficiency, construction systems

RESUMO

Esta pesquisa analisa o conforto térmico de quatro unidades habitacionais sem ar condicionado, localizadas numa zona rural andina do Equador a uma altitude de 3000 metros acima do nível do mar, para determinar estratégias de design passivo. Para tal, são descritas as características ambientais e construtivas de duas casas neovernaculares construídas com materiais naturais (TRA-01 e TRA-02) e de duas casas com materiais modernos (CON-01 e CON-02). As variáveis temperaturas exterior e interior e humidade relativa foram monitorizadas durante 8 dias, assim como as temperaturas das superfícies do invólucro, a gama de conforto foi avaliada através da temperatura operacional. Os resultados mostraram que três casas apresentaram temperaturas interiores estáveis, embora apenas a casa de fardos de palha estivesse parcialmente dentro do intervalo de conforto. O estudo conclui que o isolamento térmico da envolvente do edifício, o design bioclimático e a qualidade da construção são necessárias para manter a temperatura adequada nessas zonas de clima frio.

Palavras-chave:
isolamento térmico, arquitetura bioclimática, eficiência energética, sistemas construtivos

Revista Hábitat Sustentable Vol. 15, N°. 1. ISSN 0719 - 0700 / Págs. 98 - 115
https://doi.org/10.22320/07190700.2025.15.01.08

INTRODUCTION

In recent years, emissions from the construction industry and those related to the operation of buildings have been responsible for 38% of global CO_2 emissions (Guillén Mena et al., 2015). Part of this situation is because there is a growing interest among people in improving their quality of life by adjusting the thermal environment of buildings (Chang et al., 2021).

In this sense, it has been observed that some vernacular constructions, typically located in rural areas of China and India, may require fewer energy resources to regulate the thermal environment of buildings, partly due to their passive design, and because rural residents tend to naturally adapt to the climate (Chang et al., 2021; Dhaka et al., 2015). For example, adaptation strategies include opening or closing doors and windows, ingesting hot or cold drinks, and adjusting the number of layers of clothing. (Dhaka et al., 2015; Indraganti, 2010). However, studies show that vernacular buildings can achieve energy savings in cooling and heating compared to modern or low-cost alternatives, mainly due to their passive design strategies and the use of local materials (Cojocaru & Isopescu, 2021).

A study conducted in the Andean highlands of Peru by Harman (2010) found that homes built with modern materials, such as concrete or steel, have a lower thermal resistance capacity, resulting in prolonged exposure to very low temperatures that negatively impact the health of families. However, another study in Peru found that the use of more efficient passive heating strategies resulted in an average increase of 9.5 °C inside high-Andean homes located between 3,000 and 5,000 meters above sea level (Cerrón Contreras, 2022).

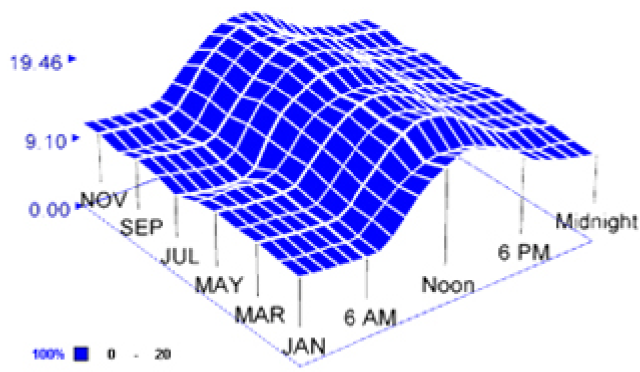
Although there is not enough research regarding the analysis of thermal comfort in buildings located in Ecuador (Gallardo et al., 2016; Mino-Rodríguez, 2021), and even less in vernacular buildings (Tapia, 2017; Moscoso-García & Quesada-Molina, 2023), it is also important to note that several constructions using traditional architecture may be relevant, especially those located in unfavorable climatic conditions. A study on vernacular buildings in these climatic conditions can significantly contribute to identifying effective passive strategies, thereby guiding the development of future buildings, since it should be borne in mind that just as buildings respond to a unique context, culture, and climate, so do the needs of thermal comfort and the expectations of the inhabitants (Gallardo et al., 2016).

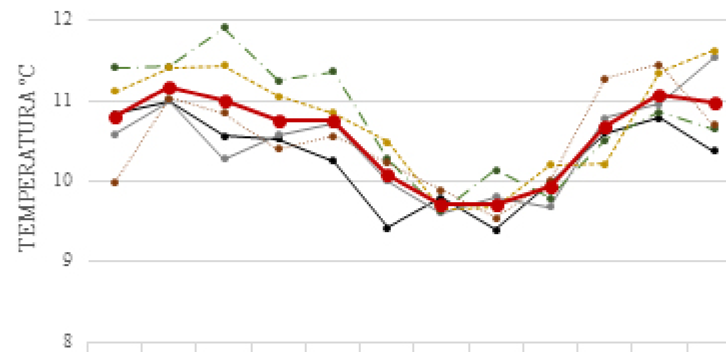
The primary objective of this research is to analyze the thermal comfort of housing units located above 3000 masl, which have different characteristics, including construction systems, materials, envelope thicknesses, number of floors, and orientation, to determine the most effective passive air conditioning strategies. To achieve this, a description of the characteristics of four housing units is proposed, two with neo-vernacular construction systems and two with modern construction systems. Subsequently, environmental variables such as air temperature and relative humidity, both inside and outside the buildings, as well as surface temperatures within the envelope, are monitored asynchronously. In this way, the research provides evidence of the effectiveness of passive design strategies in homes located in Andean areas above 3000 masl to achieve thermal comfort. Similarly, the research addresses the question of whether houses with neo-vernacular construction systems exhibit better thermal performance in cold climates than houses that use only modern materials.

CONDITIONS OF THE PLACE OF STUDY

The parish of San Juan (-1.633887, -78.781584), situated at an altitude of 3,160 masl, is located 16 km from the city of Riobamba, Ecuador. The Ecuadorian Construction Standard, in its Energy Efficiency chapter NEC-HS-EE (Ministry of Urban Development and Housing, 2018), classifies settlements located between 3000 and 5000 masl as a cold climate zone 5, equivalent to climate zone 5c according to the ASHRAE 90.1 classification. In the central Andes of Ecuador, thermal oscillation is not related to the seasons of the year; rather, it is characterized by a marked diurnal oscillation that occurs between day and night due to its geographical location at high latitudes and altitudes. Figure 1 presents the average monthly temperature for the 2018-2022 period, indicating an average monthly temperature of 10.55 °C. The coldest months are July, August, and September, with an average temperature of 9.71 °C. The hottest month is February, with an average temperature of 11.17 °C (INAHMI, 2023). This climatic information exhibits low seasonal variation, characteristic of high mountain climates in tropical regions. It also records high daily thermal amplitudes, as observed on November 3rd, 2020, when the minimum temperature was 0.3 °C and the maximum was 21.2 °C, an amplitude of 20.9 °C. These data allow contextualizing and justifying the climatic conditions under which the thermal comfort of the homes under study is evaluated, which, together with other environmental parameters such as relative humidity and wind direction, contribute to a better understanding. Regarding relative humidity, the monthly average is 80.82%, with its

Revista Hábitat Sustentable Vol. 15, N°. 1. ISSN 0719 - 0700 / Págs. 98 - 115
https://doi.org/10.22320/07190700.2025.15.01.08





	ENE	FEB	MAR	ABR	MAY	JUNI	JUL	AGO	SEPT	OCT	NOV	DIC
2022	10,83	11,00	10,56	10,52	10,25	9,43	9,80	9,39	9,98	10,60	10,79	10,38
2021	10,59	10,99	10,27	10,57	10,71	10,00	9,61	9,80	9,68	10,79	10,96	11,54
2020	11,42	11,43	11,91	11,26	11,37	10,28	9,63	10,14	9,80	10,51	10,86	10,65
2019	11,12	11,41	11,44	11,05	10,85	10,48	9,66	9,68	10,20	10,21	11,36	11,63
2018	10,00	11,03	10,85	10,40	10,56	10,22	9,89	9,55	10,00	11,27	11,46	10,69
PROMEDIO	10,79	11,17	11,01	10,76	10,75	10,08	9,72	9,71	9,93	10,68	11,08	10,98

MESES DEL AÑO

Figure 1. Average monthly temperature of the 2018-2022 period. Source: INAHMI (2023).

highest values occurring in April, May, and June. The predominant wind direction originates from the East-Southeast, with August and September being the windiest months, with average speeds of 2.41 and 2.48 m/s, respectively (INAHMI, 2023).

The first inhabitants of this parish were descendants of the Puruhá, who built their homes with stone, mud, or adobe as an envelope and load-bearing structure and straw or tile for the roof (Villacís, 2010). In the last four housing censuses conducted in Ecuador, in 1990, 2001, 2010, and 2022, it was observed that in the Parish of San Juan, the use of brick or adobe decreased by 41%, 22%, 14%, and 5%, respectively. Meanwhile, the use of bricks or blocks increased from 57% in 1990 to 86% in 2022 (National Institute of Statistics and Censuses [INEC], 2024). As for the roof, the use of straw has been replaced by zinc, tile, fiber cement, and a concrete slab, with the latter being the most common, at 43%.

This phenomenon not only leads to the loss of the thermal qualities associated with vernacular constructions that use local materials and passive strategies adapted to the environment, but also the loss of a valuable source of ancestral knowledge—a key resource for offering sustainable solutions relevant to contemporary design. (Moscoso-García & Quesada-Molina, 2023).

METHODOLOGY

The proposed methodology comprises four phases: the description of four case studies, monitoring of the houses, determination of the thermal comfort range, and its respective analysis. This last phase is addressed in the presentation of the results and the discussion.

PHASE I: SELECTION OF CASE STUDIES

For this study, four houses were chosen: two neo-vernacular houses built with natural materials, TRA-01 (108.72 m²) with one floor and restored brick walls, and TRA-02 (171.51 m²) with two floors and straw bale walls, featuring a contemporary design. Additionally, there are two modern houses, one of which is a single-floor house (CON-01, 89.20 m²) constructed with brick, and the other is a two-floor house (CON-02, 127.41 m²) made of concrete blocks (Figure 2). The construction systems, materials, and envelope thicknesses found in the houses are presented in Table 2. There is no mechanical cooling system installed in any house, nor is a heating system in operation.

As for the immediate surroundings of the houses, they are located within a 2 km radius. CON-02 is in the center of the town of San Juan, with a semi-urban environment, unlike the other isolated houses. As a result, they have better lighting and interior ventilation, but are more influenced by the prevailing easterly winds (Table 1).

Figure 2. Selected case studies: (a) TRA-01 traditional brick dwelling; (b) TRA-02 straw bale dwelling; (c) CON-01 brick dwelling; (d) CON-02 concrete block dwelling. Source: Preparation by the Authors.

Table 1. Characteristics of the dwelling. Source: Preparation by the Authors.

House ID	Area (m2)	Altitude (m.a.s.l.)	# of floors	Orientation of the main facade	Prevailing wind direction	Heating system	Location/Context	Infiltrations
TRA-01	108.72	3,263	1	E	E	None	Detached in a non-urban context, with partial enclosure	Yes
TRA-02	171.51	3,243	2	N	E	None	Detached in a non-urban context, without enclosure, with a vegetation barrier	Yes
CON-01	89.20	3,276	1	E	E	None	Detached in a non-urban context, located on a hill, without enclosure	Yes
CON-02	127.41	3,229	2	NW	E	None	Detached, built in a semi-consolidated urban context, without neighbors, with enclosure	Yes

Revista Hábitat Sustentable Vol. 15, N°. 1. ISSN 0719 - 0700 / Págs. 98 - 115
https://doi.org/10.22320/07190700.2025.15.01.08

Table 2. Construction systems, materials, envelope thicknesses, and Thermal Transmittance (U-value). Source: Preparation by the Authors.

House ID	Component	Material	Thickness (cm)	U [1] (W/m²K)
TRA-01	FOUNDATION	Continuous stone foundation	40	-
	STRUCTURE	Self-supporting brick	80	-
	EXTERIOR WALLS	Paint+Fiberglass Mortar+Brick+Mortar+Paint	1.5+80+1.5	0.94
	INTERIOR WALLS	Paint+Cement Mortar+Brick+Cement Mortar+Paint	15	-
	FLOOR	Concrete slab+Half pine stave	40+2.5	1.53
	ROOF	Aluminum sheet+Wooden beams+Air chamber+Gypsum board	0.6+5+1.2	2.87
	WINDOWS	Wooden frame+glass	4+0.6	1.51
TRA-02	FOUNDATION	Concrete foundation slab	0.15	-
	STRUCTURE	Eucalyptus ladder-type wooden post and beam	40	-
	EXTERIOR WALLS	Lime+Clay plaster+Straw bales+Clay plaster+Lime	0.5+2.5+35+2.5+0.5	0.21
	INTERIOR WALLS	Lime+Clay plaster+quincha+Clay plaster+Lime	0.5+2.5+6+2.5+0.5	-
	FLOOR	Concrete slab+Pumice+Wood forging+Triplex board+Floating floor	10+15+6+1.8+1.4	0.55
	ROOF	Asphalt sheet+triplex board + Straw between beams+tetrapack board and totora reed mat	0.2+1.8+15+1.2+1.5	0.45
	WINDOWS	Glass +Air chamber +Glass. PVC Frame	0.6+6+0.6	2.75
CON-01	FOUNDATION	Insulated concrete footings	120	-
	STRUCTURE	Metal structure	-	-
	EXTERIOR WALLS	Paint+Mortar Cement+Brick+Mortar+Paint	1+10+1	3.10
	INTERIOR WALLS	Paint+Mortar Cement+Brick+Mortar+Paint	1+10+1	-
	FLOOR	Concrete subfloor +Tile	40+0.4	2.00
	ROOF	Corrugated fiber cement sheet or translucent sheets + Gypsum board	0.4+1.2	5.21
	WINDOWS	Aluminum frame+Glass	0.4	5.73
CON-02	FOUNDATION	Insulated concrete footings	120	-
	STRUCTURE	Reinforced concrete	-	-
	EXTERIOR WALLS	Mortar plastering+Concrete block+Mortar plastering	1.5+10+1	2.83
	INTERIOR WALLS	Paint+Mortar+Concrete Block+Mortar+tile	1+0.7+1.5	-
	FLOOR	Concrete subfloor +Tile	25+0.4	2.54
	ROOF	Flat concrete slab+pumice blocks	25	4.02
	WINDOWS	Aluminum frame+Blue glass	0.4	5.73

1 Thermal Transmittance values calculated based on Ministry of Urban Development and Housing, 2018; Ministry of Housing and Urban Agenda, 2022

Table 3. Detailed information on the measuring equipment. Source: Preparation by the Authors.

#	Commercial Name	Description	Measurement parameters	Range	Precision
1	ESP32	Microcontroller with wireless connectivity	Wi-Fi connection 802.11 b/g/n, Bluetooth 4.2 and BLE	150 Mbps	
2	LM35	Integrated circuit temperature sensor	Temperature	-55 to 150°C	± 0.5°C
3	Datalogging traceable barometer	Digital recorder of room temperature, relative humidity, and barometric pressure	Room temperature	0 to 65°C	± 0.4°C
			Humidity	0% to 95%	±3%
			Barometric pressure	500 mbar to 1030 mbar	±4 mbar

PHASE II: HOUSING MONITORING

At this stage, equipment for measuring air temperature, relative humidity, and surface temperature sensors was used. Figure 3 illustrates the locations in the architectural plans and photographs, showing the placement of interior and exterior elements, while Table 3 presents the specifications of the measuring equipment.

The relative humidity and air temperature variables of the four houses were monitored every 5 minutes for 8 days each, between May 20th and July 31st, 2023. The frequency and period of monitoring are based on the study by Quesada Molina and Bustillos Yaguana (2018). The measurement of the dwellings was not synchronous, as equipment availability allowed for one dwelling to be measured at a time, which is discussed in the limitations of the study.

Three thermohygrometers were placed in each house (Figure 3), one outside (A), another in the indoor social area (B), and the third in the coldest bedroom (C). The indoor sensors were placed in the center of the rooms or at least 1m away from the exterior walls, and at a height of 1.10m that follows the guidelines of the Spanish Standard UNE-EN ISO 7726, which indicates that "when it is not possible to interrupt the ongoing activity, it is necessary to place the sensors in positions such that the thermal exchanges are approximately equal to those to which the person is exposed" (UNE-EN ISO 7726, 2020). The outdoor sensors were placed in a place protected from rain and direct solar radiation.

The temperature measurements of the interior surfaces were conducted at six locations, as indicated by Atecyr (2010), including one wall for each orientation, the roof, and the floor in contact with the ground. The monitoring was carried out in the house's social area (B) every 30 minutes for three days, and an average was obtained for each day. Measurements were taken on the surfaces to calculate the mean radiant temperature (MRT). With this value, the operative temperature (Opt) was determined, which will serve as a basis for a comprehensive comfort evaluation.

To acquire the temperature data of the interior surfaces, ESP32 microcontrollers were used wirelessly, each with an LM35 sensor that is capable of measuring the temperature in a range from -55°C to 150°C with a sensor output interval of 10mV for each degree Celsius, and sending it to a master microcontroller that records the information in an SDCARD memory in a .txt extension file, to process the information later.

PHASE III: DETERMINATION OF THE THERMAL COMFORT RANGE

To understand the role that the envelope plays in the homes' thermal comfort, the aim is to define the thermal comfort range of the 4 case studies. As mentioned by Chang et al. (2021) in their study, the operating temperature (Opt) is one of the most widely used thermal comfort indices relevant to this study, as it considers the effects of outdoor air temperature and radiation (ASHRAE Standard 55, 2020). The Opt calculation is shown in Equation 1, where (MRT) is the mean radiant temperature obtained based on Equation 2, which uses the temperature of the house's surfaces when the walls, floor, and roof are at different temperatures (Atecyr, 2010).

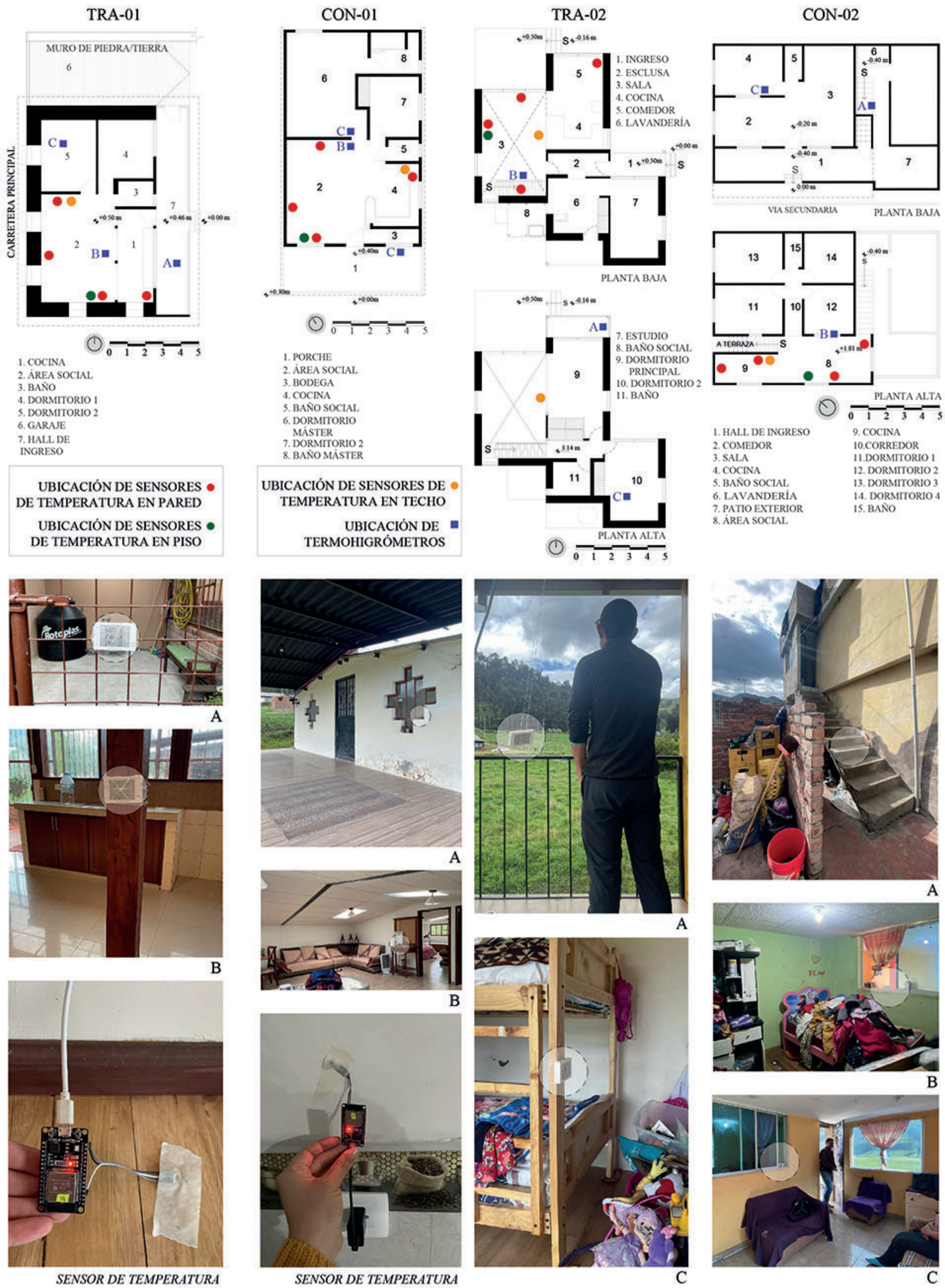


Figure 3. Floor plans and equipment location in case studies. Source: Preparation by the Authors.

Once the Opt was obtained, the thermal comfort range in the studied homes (Table 4) was determined using the Berkeley Thermal Comfort CBE Tool (Tartarini et al., 2020), based on the adaptive method outlined in the UNE-EN 16798-1 Standard. With this tool, the comfort ranges (classes) were determined using the predominant average outdoor temperature, which responds to "the arithmetic mean of the average daily outdoor temperature for a period of not less than 8, nor more than 30 consecutive days prior to the day in question" (ASHRAE Standard 55, 2020).

The EN 16798 Standard establishes three classes of thermal comfort, which vary according to their level of demand and acceptance. The comfort hours of each house will be based on the Thermal Comfort Class III range.

$$T_{op} \approx \frac{T_{rm} + T_s}{2}$$

$$T_{rm} = \frac{(0{,}08(T_{s\,techo} + T_{s\,suelo}) + 0{,}23\,(T_{s\,derecha} + T_{s\,izquierda}) + 0{,}35(T_{s\,dante} + T_{s\,detrás}))}{2(0{,}08 + 0{,}23 + 0{,}35)}$$

RESULTS AND DISCUSSION

INDOOR AND OUTDOOR TEMPERATURE MONITORING

Figure 4 shows the minimum, maximum, and average temperatures of the monitored spaces. When monitoring the house's outdoor air temperature (Figure 5), the lowest temperatures were recorded in the early morning, between 3:00 a.m. and 6:00 a.m. In contrast, the highest temperatures were recorded between 2:00 p.m. and 4:00 p.m.

The TRA-01 one-story house recorded a minimum outdoor temperature of 3.77°C, a maximum of 29.33°C, and an average of 12.22°C. In the social area (B), the absolute minimum temperature was 11.70°C, while in the bedroom (C) it was 11.80°C, with an average temperature of about 13.00°C. The 0.80 m thick brick walls contributed a low thermal transmittance (Table 2) and a maximum thermal amplitude of 3 °C to the interior.

The TRA-02 house had a minimum outdoor temperature of 6.15°C, a maximum of 21.95°C, and an average of 12.07°C. The social area ranged from 16.43 to 21.95°C, and the room ranged from 17.50 to 24.05°C. The average temperature in the social area was 19.88°C, and in the room, 20.46°C. On the second floor, it is slightly higher, possibly due to solar radiation captured on the roof. The maximum thermal amplitude was 7.52°C; the contemporary design included straw bale walls as an insulating material. This system contributes to increasing the indoor

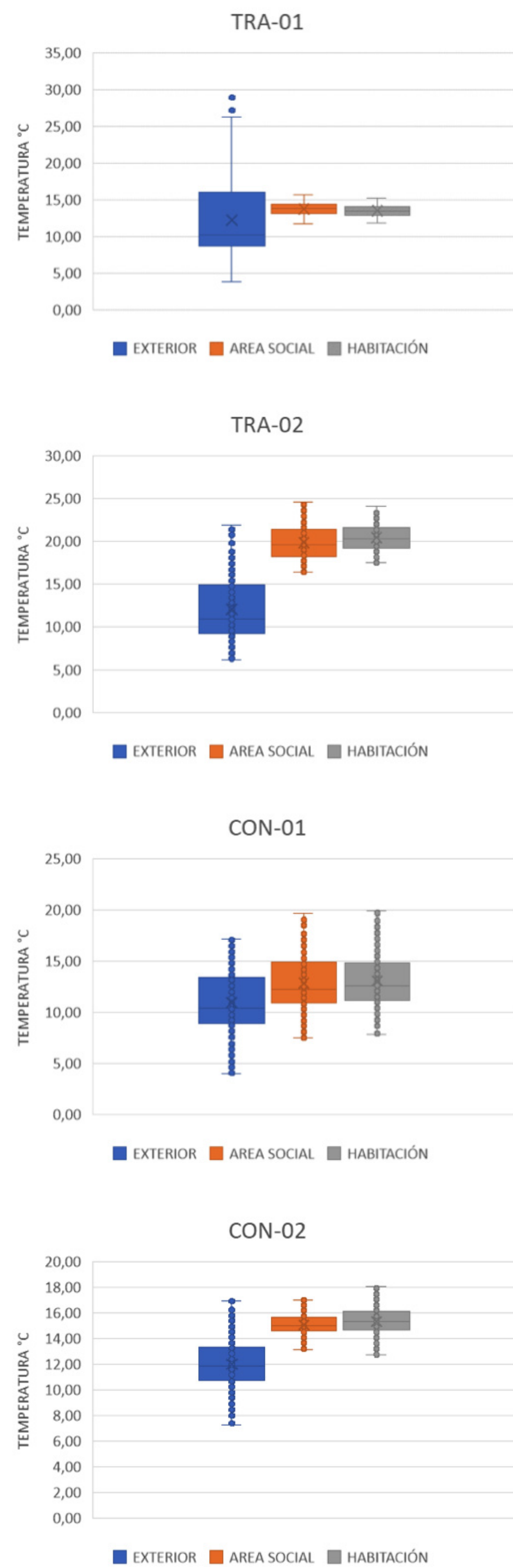


Figure 4. Minimum, maximum, and average temperatures of each case study. Source: Preparation by the Authors.

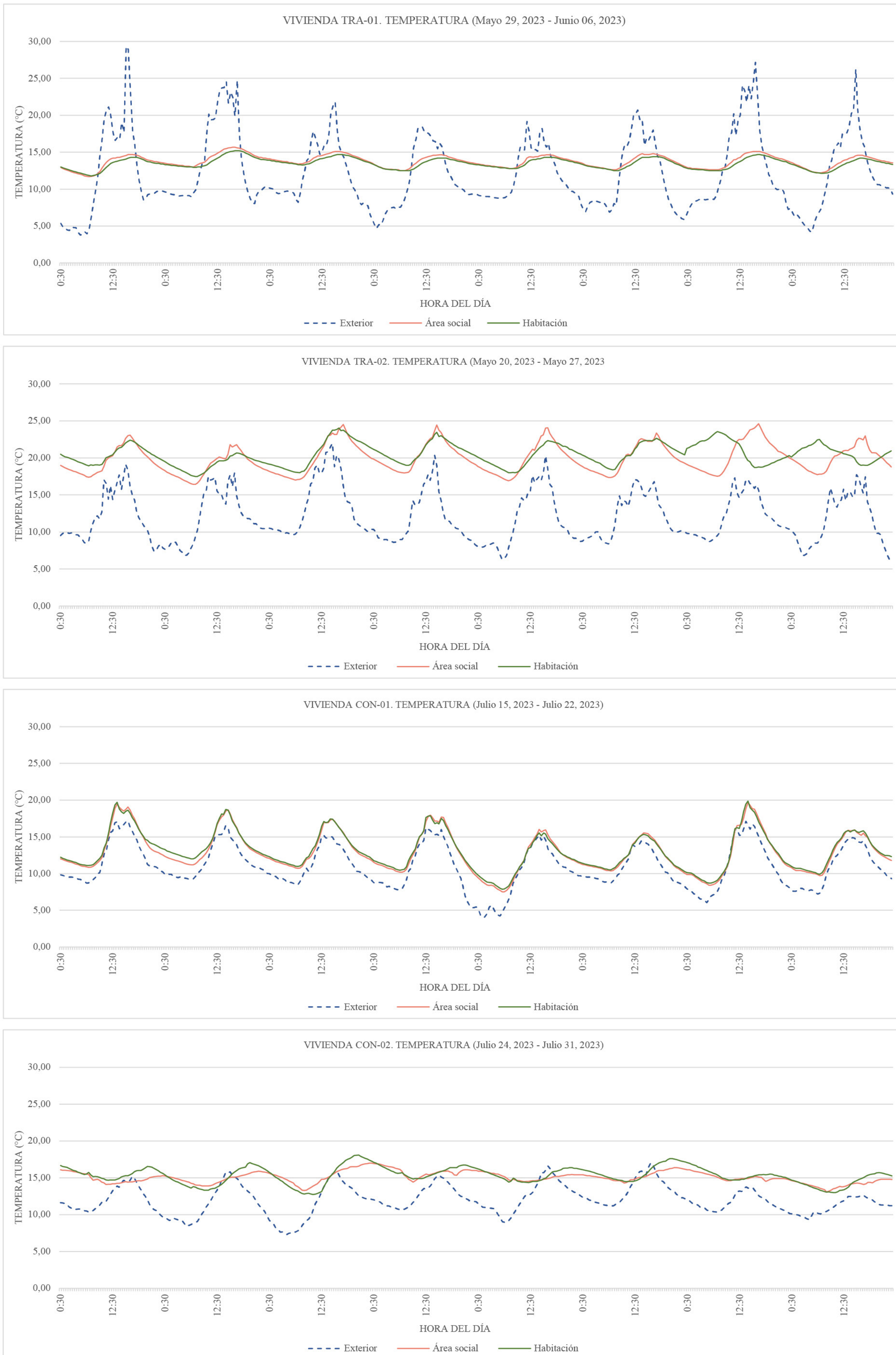


Figure 5. Indoor and outdoor temperature monitoring. Source: Preparation by the Authors.

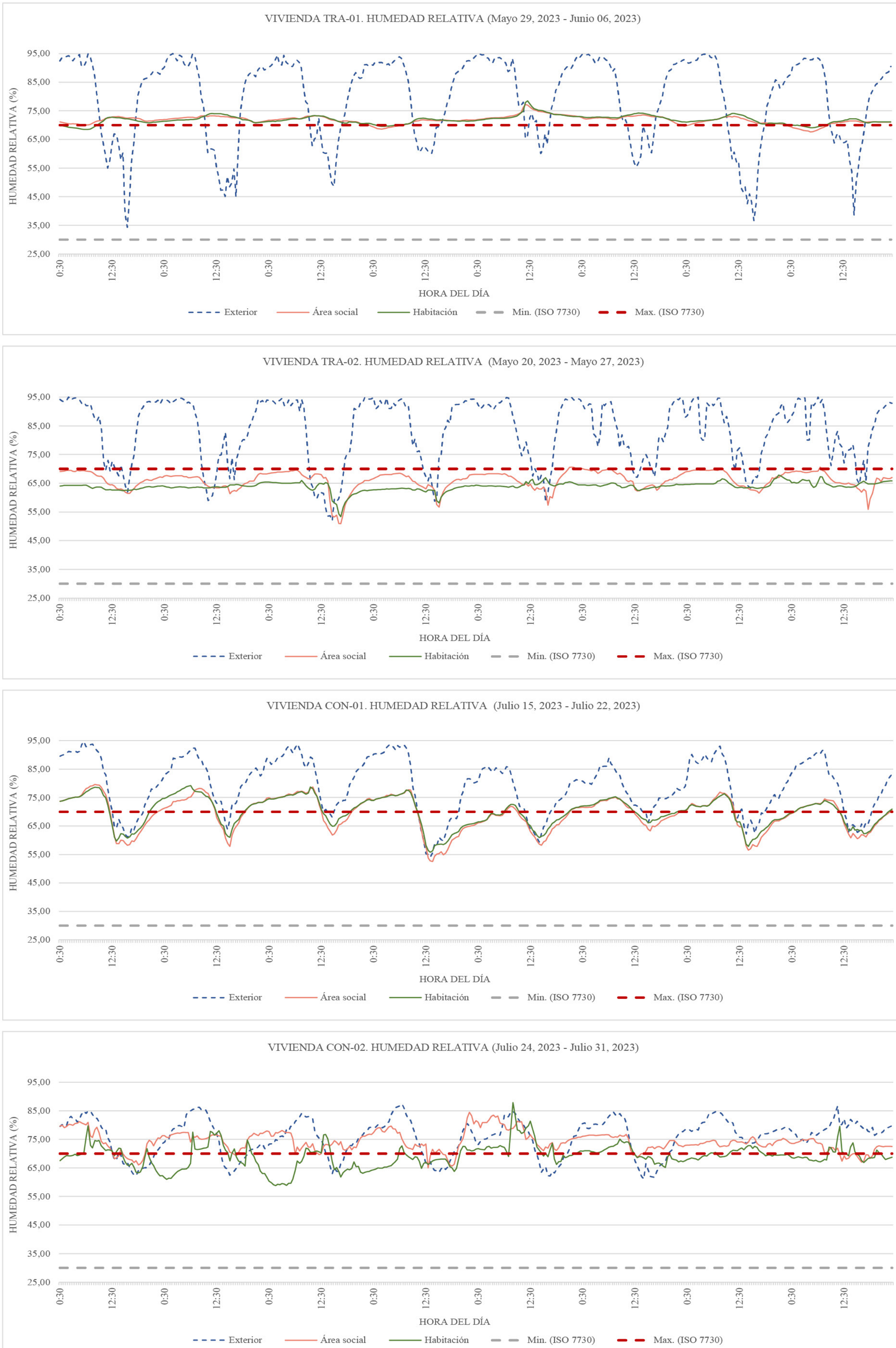


Figure 6. Indoor and outdoor relative humidity monitoring. Source: Preparation by the Authors.

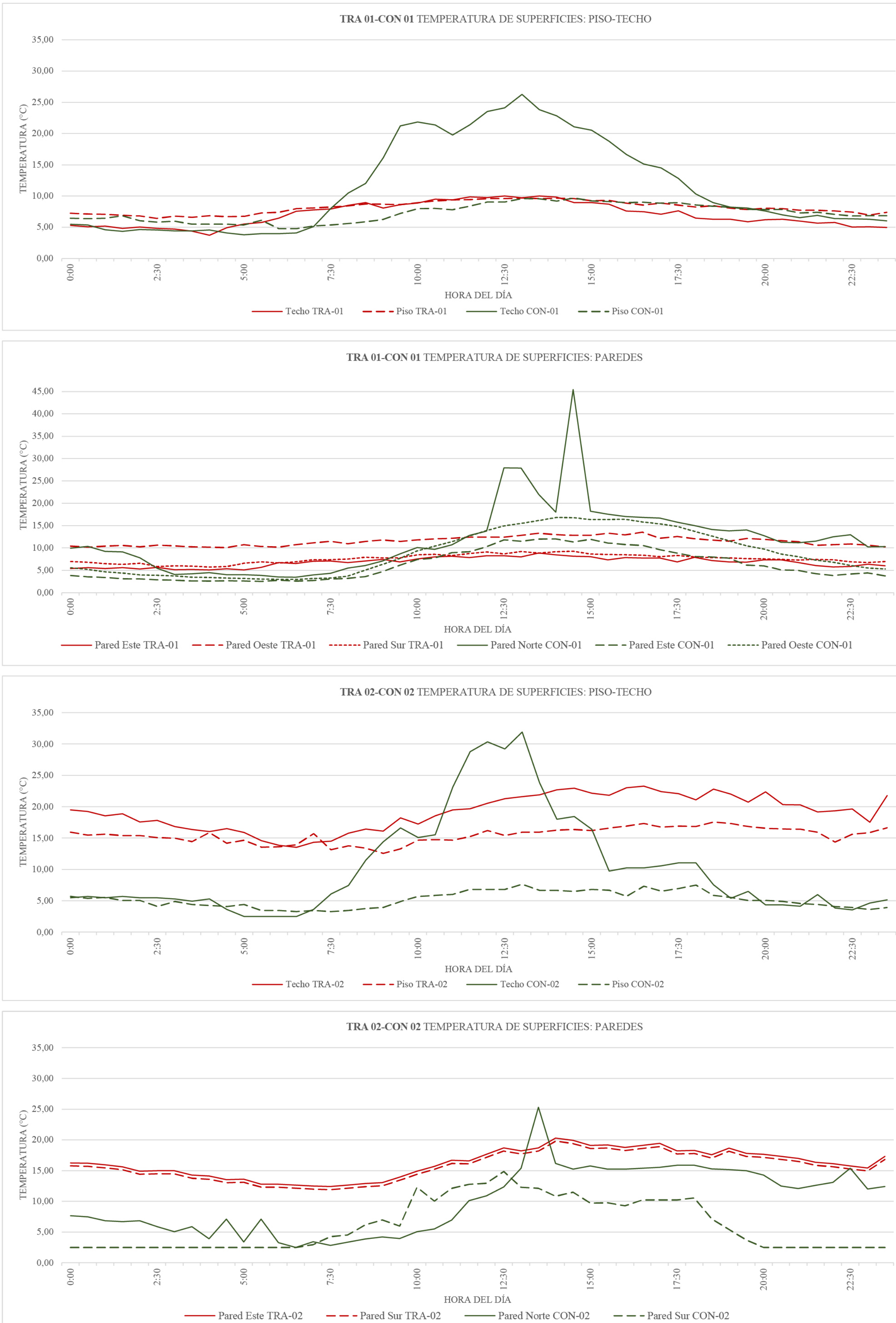


Figure 7. Surface temperatures. Source: Preparation by the Authors.

Table 4. Range of comfort assessment of dwellings. Source: Tartarini et al., (2020).

House ID	Predominant average outdoor temperature (°C)	Comfort range Class I (°C)	Comfort range Class II (°C)	Comfort range Class III (°C)
TRA-01	12.22	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8
TRA-02	12.07	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8
CON-01	10.95	19.4 - 24.4	18.4 - 25.4	17.4 - 26.4
CON-02	12.00	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8

temperature by up to 9°C compared to the outside, according to Suasaca Pelinco et al. (2020).

The one-story CON-01 house, featuring 0.10 m-thick brick walls, exhibited a maximum thermal amplitude of 11.17°C. In the social area (B), the absolute minimum temperature was 7.52°C, and in the bedroom (C) it dropped to 7.87°C. The average indoor temperature was approximately 13°C, and the outside temperature was 11°C, with similar day-to-night temperature fluctuations both indoors and outdoors.

CON-02, a two-story concrete and block structure, exhibited regular thermal oscillation. The average temperatures outside were 12°C, with a social area of 15.07°C and a bedroom of 15.33°C. The interior spaces showed minimum temperatures of 13.10°C (B) and 12.75°C (C), and maximum temperatures of 17°C (B) and 18°C (C).

INDOOR AND OUTDOOR RELATIVE HUMIDITY MONITORING

The relative humidity (RH) outside the four homes studied fluctuates between 35% and 95%, being higher when the temperature is lower and vice versa (Figure 6).

As for the indoor RH, the limits according to the Ecuadorian Technical Standard [NTE] INEN-ISO 7730 are 30% to 70%. The social area (B) of the TRA-01 housing was within the limits only 9.92% of the time monitored, similar to the bedroom (C) with 10.44%. In CON-01, the social area (B) and the bedroom (C) were within the limit of 48.56% and 46.48%, respectively. This result is due to the high thermal transmittance of the roofing materials used in the CON-01 house, specifically fiber cement and translucent sheets, which allow for the accelerated transmission of heat. This increases the indoor temperature at certain times of the day, thereby decreasing the relative humidity value.

During the entire monitoring period, the TRA-02 house remained within the RH limits. The social area (B) of the home CON-02 was only 12.53% of the time, unlike the bedroom (C), which was within the limits, 59.79% of the time. This is because the social area (B) of CON-02 is located on the ground floor, and due to the presence of a masonry enclosure and the absence of a glazed surface, no radiant heat is able to enter.

SURFACE TEMPERATURE MONITORING

In TRA-01, the floor and ceiling temperatures, with U-values of 1.53 W/m²K and 2.87 W/m²K, respectively (Table 2), exhibited minimum oscillations of 3.22°C and 6.28°C. The CON-01 house, with a roof U-value of 5.21 W/m2K, presented an internal surface temperature variation of up to 20°C. This marked oscillation could be associated not only with the roof's low thermal performance but also with high exposure to solar radiation during the day and the presence of translucent surfaces. The wall surface temperatures in the TRA-01 house, which have a U-value of 0.94 W/m²K despite having low temperature values, were maintained within a minimum and constant oscillation range (Figure 7). In the CON-01 house, the walls have a U-value of 3.10 W/m²K, as shown in Figure 8, indicating accelerated heat gain and loss.

As for the two-story houses, the TRA-02 house, with a U-value of 0.55 W/m²K in the floor and 0.45 W/m²K in the roof, remained in a constant oscillation range, despite the daily thermal amplitude of the exterior. However, the roof of the CON-02 house, which has a U-value of 4.02 W/m²K, exhibits significant heat gain and loss (Figure 7).

The same was seen in TRA-02, with a minimum and constant oscillation range in the walls, which has a U-value of 0.21 W/m2K. On the other hand, the temperature of the walls of the CON-02 house, whose U-value is 2.83 W/m²K, underwent an abrupt change of at least 20°C between 11:00 am and 3:00 pm.

EVALUATION OF THERMAL COMFORT

The houses TRA-01, TRA-02 and CON-02 presented a predominant average outdoor temperature value of 12°C and the CON-01, which is the house with the

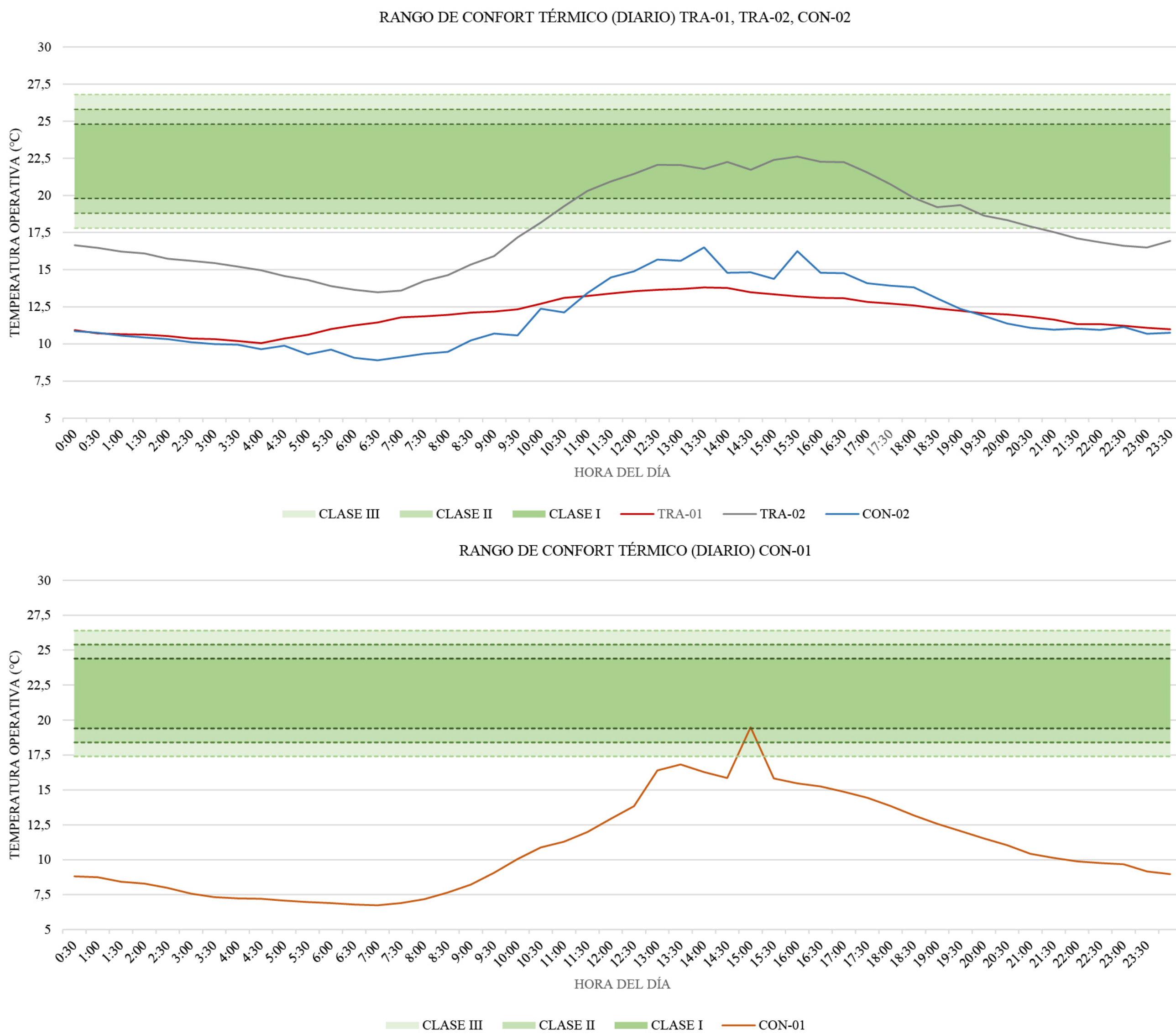


Figure 8. Thermal comfort of case studies. Source: Preparation by the Authors.

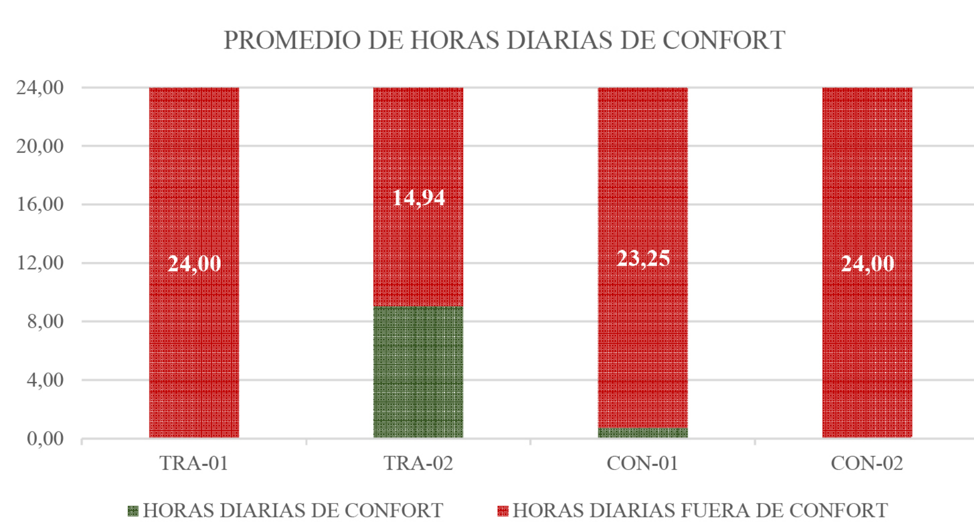


Figure 9. Average number of hours of daily thermal comfort. Source: Preparation by the Authors.

highest altitude, had a value of 10.95°C, so 3 of the 4 houses will be evaluated with the same comfort range and CON-01 will be evaluated with a slightly lower range (Table 4).

The TRA-01 and CON-01 dwellings are located below the comfort zone, as shown in Figure 8. However, TRA-01 has a more constant temperature than CON-01. In the latter, the higher temperature peaks caused it to reach, on average, a daily comfort period of 0.75 hours (Figure 9).

In TRA-01, the operating temperature ranged from 4°C to 8°C, which is outside the thermal comfort range, compared to CON-01, where there are hours during the day when the outdoor temperature reaches 12°C, also outside the thermal comfort range.

Regarding the TRA-02 house, with extreme temperatures outside, it is barely 4°C outside the thermal comfort range and has 9 hours of comfort per day on average (Figure 9). This is due to the use of insulating materials in the envelope and the use of glazed surfaces with a U-value of 2.75 W/m2K. For CON-02, despite having an average of 0 hours of daily comfort, there are hours during the day that it is barely 1°C outside the comfort range, and in the most extreme temperatures, it is 10°C outside the thermal comfort range.

IDENTIFICATION OF PASSIVE STRATEGIES

The passive air conditioning strategies identified in the different houses were the following: (TRA-01) the orientation concerning the predominant wind, the thermal mass and the attached greenhouse, (TRA-02) the search for the optimal orientation, the perimeter vegetation barrier, the facade and roof color, the thermal mass and the correct selection of the type of glass and carpentry, and in the house (CON -02) the thermal mass on the roof, the color of the facade and the existing enclosure.

Due to the low night and morning temperatures, it is necessary to capture the heat in the morning. The sector's vernacular architecture uses regular shapes, is small, of low height, and has minimal openings. The TRA-02 house divides the space into several volumes that capture sunlight from the east and west. The bedrooms can face east with vertical windows to capture the early morning heat.

Insulation is indispensable in all components of the envelope, including the floor, walls, and roof. Components with U-values above 3 W/m²K are not very efficient at maintaining thermal comfort inside. For a cold climatic zone 5, the envelope requirements according to the NEC-HS-EE (Ministry of Urban Development and Housing, 2018) are U-2.8 on roofs and U-2.35 on walls of non-air-conditioned housing. It is suggested to replicate the wall and roof solutions of TRA-01 and TRA-02, as well as the roof of CON-02, whose pumice block lightening becomes a thermal insulator.

It is necessary to avoid overheating of the spaces due to solar radiation between 12:00 p.m. and 4:00 p.m. Glazing can be minimized or supplemented with solar protection on the west and north facades. Passive ventilation is possible during the middle of the day to regulate the temperature and renew the air. However, the openings should avoid being oriented in the direction of the prevailing winds.

LIMITATIONS OF THE STUDY AND FUTURE RESEARCH

Regarding the study's limitations, the in situ monitoring of temperatures and humidity for the four case studies was recorded asynchronously and over a limited period. Future research may include more extended periods of monitoring to record potential moisture effects during the rainy season of the year. Full-year digital simulations could also be conducted to compare the data recorded in this research.

On the other hand, a methodological limitation is the absence of data on the interior height and vertical location of the sensors, as well as the volumetric and morphological differences between the houses, which limits the comparability between the cases. However, lessons can be learned from passive strategies for achieving adequate thermal comfort inside housing units located between 3,000 and 5,000 masl.

CONCLUSIONS

This study contributes to the field of sustainable habitats, with an empirical focus on dwellings located in cold, high-mountain climates in the Andean region. The context is poorly researched, and thermal comfort becomes important due to the limited availability of active air conditioning systems in the local market. The information obtained from the censuses indicates a growing tendency to replace traditional construction systems with modern solutions, which, in most cases, have inferior thermal performance and also result in a significant loss of built heritage. Therefore, it is essential to explore passive conditioning strategies rooted in traditional knowledge.

To identify passive strategies to improve the thermal comfort conditions of homes located above 3000 masl in the Andean region, the temperature and humidity of 4 homes, two neo-vernacular (TRA-01 and TRA-02) and two homes with modern materials, were described and monitored. (CON-01 and CON-02).

The results showed that the neo-vernacular dwellings maintained a stable indoor temperature, with an average oscillation of 2.13°C for TRA-01 and 5.29 °C for TRA-02. However, TRA-01 is outside the comfort range 100% of the time, and TRA-02 stays within the comfort range 37.75% of the time. This difference in comfort shows that using low thermal transmittance materials, such as straw and the double-glazed system in the windows, allows the interior temperature to be raised. For future research, it is recommended to expand upon the analysis of this typology and explore the potential of using straw as a sustainable construction material with high thermal properties.

In the case of the modern house, CON-01, it is observed that the indoor temperature presents a daily trend similar to that of the outdoor temperature, with a thermal oscillation of up to 11.22°C inside. As for the modern CON-02 house, it shows a more stable thermal behavior, with fewer variations throughout the day. This difference is mainly attributed to the roof's constructive characteristics: while the CON-02 roof incorporates materials with a higher thermal mass, which favors the damping of thermal fluctuations, the CON-01 roof has a lower thermal inertia capacity, which facilitates heat gains or losses, for example when there was an absolute minimum temperature of 7.52°C inside, there was 4.73°C outside, that is, the envelope at the most critical moment of the day only produced an increase of 2.79°C in temperature inside compared to outside.

Taking into account the envelope requirements for opaque elements and windows in non-air-conditioned living spaces of climatic zone 5, according to NEC-HS-EE, even though the standard has a low requirement, only the housing envelope of TRA-02 meets these values. These values are the result of using insulating elements throughout the house's envelope. TRA-01 does not comply with the roof envelope requirement, and CON-01 and CON-02 do not comply with the roof and wall envelope requirements. It is worth mentioning that the four houses meet the window and floor envelope requirements.

These results indicate that a house's thermal response does not depend exclusively on the thermal transmittance value of the materials used, but also on their ability to store and release heat, that is, their thermal inertia. Similarly, it is suggested that other factors, such as orientation and the proportion of glazed surface, among others, may have a significant impact on the indoor thermal behavior. Therefore, it is recommended that these aspects be addressed in future research to achieve a more comprehensive analysis of the thermal performance of homes in Andean areas above 3000 m.a.s.l.

On the other hand, it was seen that in the vast majority of traditional homes in San Juan, parts of the deteriorated vernacular materials have been replaced by modern materials that are more affordable, easier to install, and cheaper, which in some cases has led to a decrease in the quality of the indoor climate. In other cases, the hybrid nature of the solutions demonstrates that the coexistence of traditional materials with contemporary bioclimatic architectural design supports research that has shown the importance of incorporating vernacular architecture to achieve sustainability in modern architectural practices (Moscoso-García & Quesada-Molina, 2023). In this sense, the documentation and analysis of the vernacular architecture of the sector and province are recommended.

Finally, a significant limitation of the study was the inability to conduct simultaneous monitoring between dwellings, which affects the direct comparability of the results. Additionally, it was not possible to take measurements at different heights inside the house to account for the vertical thermal gradient. Therefore, it is recommended that more exhaustive measurements, calibrated thermal simulations, and a more in-depth analysis of the hygrothermal behavior of vernacular materials be incorporated into future research.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, A.N.M.A., V.F.G.M.; Data Curation, A.N.M.A.; Formal analysis, A.N.M.A., V.F.G.M.; Acquisition of A.N.M.A. financing; Research, A.N.M.A.; Methodology, A.N.M.A.; Project management, A.N.M.A.; Resources, A.N.M.A.-N.M.S.H.; Software. A.N.M.A.; Supervision, V.F.G.M.; Validation, A.N.M.A., V.F.G.M., N.M.S.H.; Visualization, A.N.M.A.-N.M.S.H.; Writing - original draft, A.N.M.A.; Writing -revision and editing, A.N.M.A.-N.M.S.H.

ACKNOWLEDGMENTS

Article developed under the Master's Thesis "COMPARATIVE ANALYSIS OF THERMAL COMFORT BETWEEN HOUSING UNITS WITH DIFFERENT CONSTRUCTION SYSTEMS LOCATED OVER 3000 M.S.N.M."

BIBLIOGRAPHIC REFERENCES

ASHRAE Standard 55 (2020). *Thermal Environmental Conditions for Human Occupancy*. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

Atecyr (2010). *Fundamentos de climatización*. Atecyr, Ed.

Cerrón Contreras, A. (2022). Sistemas de calefacción pasiva para lograr el confort térmico en viviendas alto andinas de Perú. *Cátedra Villarreal*, *10*(1), 37–48. https://doi.org/10.24039/cv20221011379

Chang, S., He, W., Yan, H., Yang, L., y Song, C. (2021). Influences of vernacular building spaces on human thermal comfort in China's arid climate areas. *Energy and Buildings*, *244*, 110978. https://doi.org/10.1016/j.enbuild.2021.110978

Cojocaru, A., y Isopescu, D. (2021). Passive Strategies of Vernacular Architecture for Energy Efficiency. *Bulletin of the Polytechnic Institute of Iași. Construction. Architecture Section*, *67*(2), 33 - 44. https://doi.org/10.2478/bipca-2021-0013

Dhaka, S., Mathur, J., Brager, G., y Honnekeri, A. (2015). Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India. *Building and Environment*, *86*, 17–28. https://doi.org/10.1016/J.BUILDENV.2014.11.024

Gallardo, A., Palme, M., Lobato-Cordero, A., Beltrán, R. D., y Gaona, G. (2016). Evaluating thermal comfort in a naturally conditioned office in a temperate climate zone. *Buildings,* 6(3), 27. https://doi.org/10.3390/buildings6030027

Guillén Mena, V., Quesada Molina, F., López Catalán, M., Orellana Valdés, D., y Serrano, A. (2015). Eficiencia energética en edificaciones residenciales Energetic efficiency in residential Buildings. Estoa. Journal of the Faculty of Architecture and Urbanism, 4(7), 59-67. https://doi.org/10.18537/est.v004.n007.07

Harman, L. (2010). *Confort térmico en viviendas altoandinas un enfoque integral*. Balcari Editores.

INAHMI. (2023). Datos de estación meteorológica San Juan. https://servicios.inamhi.gob.ec/

INEN-ISO 7730. (2014). Norma Técnica Ecuatoriana [NTE] - Servicio Ecuatoriano de Normalización [INEN], Sobre ISO 7730: Ergonomía del entorno térmico.

Indraganti, M. (2010). Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India. *Energy and Buildings*, *42* (7), 1019–1025. https://doi.org/10.1016/J.ENBUILD.2010.01.014

Instituto Nacional de Estadística y Censos [INEC]. (02, abril de 2024). Censo Ecuador Resultados. https://www.censoecuador.gob.ec/resultados-censo/#historicos

Ministerio de Desarrollo Urbano y Vivienda (2018). NEC *Norma Ecuatoriana de la Construcción. Eficiencia-Energética en Edificaciones Residenciales (EE) (código NEC-HS-EE).* https://www.habitatyvivienda.gob.ec/wp-content/uploads/2023/03/4.-NEC-HS-Eficiencia-Energetica.pdf

Ministerio de Vivienda y Agenda Urbana (2022). Documento Básico HE- Ahorro de energía. https://www.codigotecnico.org/pdf/Documentos/HE/DBHE.pdf

Mino-Rodríguez, I. (2021). *A thermal comfort model for high-altitude regions in the Ecuadorian Andes* [Tesis de Doctorado, University College London]. UCL Discovery. https://discovery.ucl.ac.uk/id/eprint/10139857

Moscoso-García, P., y Quesada-Molina, F. (2023). Analysis of Passive Strategies in Traditional Vernacular Architecture. *Buildings*, *13*(8), 1984. https://doi.org/10.3390/buildings13081984

Quesada Molina, F., y Bustillos Yaguana, D. (2018). Indoor environmental quality of urban residential buildings in Cuenca-Ecuador: Comfort standard. *Buildings, 8*(7), 90. https://doi.org/10.3390/buildings8070090

Suasaca Pelinco, L., Apaza Mamani, A., Flores Alfaro, J. A., Perca Chura, O. A., y Quinto Machaca, W. (2020). Influencia de las pacas de avena en la temperatura y humedad en las viviendas en zonas altoandinas. *Revista Investigación & desarrollo*, *20*(1), 215–227. https://doi.org/10.23881/idupbo.020.1-15i

Tapia, W. E. (2017). *El confort térmico en las edificaciones de arquitectura vernácula de la ciudad de Loja y Malacatos* [Tesis de Magíster, Universidad de Cuenca]. Repositorio Institucional de la Universidad de Cuenca. https://dspace-test.ucuenca.edu.ec/handle/123456789/97/simple-search?query=&sort_by=score&order=desc&rpp=10&filter_field_1=subject&filter_type_1=equals&filter_value_1=Arquitectura+tradicional&filter_field_2=subject&filter_type_2=equals&filter_value_2=Dise%C3%B1o+arquitect%C3%B3nico&etal=0&filtername=author&filterquery=Tapia+Chocho%2C+Wilson+Eduardo&filtertype=equals

Tartarini, F., Schiavon, S., Cheung, T., y Hoyt, T. (2020). CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX*, *12*, 100563. https://doi.org/10.1016/j.softx.2020.100563

UNE-EN 16798-1 (2020). Asociación Normalización Española [UNE]. Eficiencia energética de los edificios. Ventilación de los edificios. Parte 1: Parámetros del ambiente interior a considerar para el diseño y la evaluación de la eficiencia energética de edificios incluyendo la calidad del aire interior, condiciones térmicas, iluminación y ruido. Módulo 1-6. Asociación Española de Normalización. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0063261

UNE-EN-ISO 7726 (2002). Asociación Normalización Española [UNE]. Ergonomía de los ambientes térmicos- Instrumentos de medida de las magnitudes físicas. Asociación Española de Normalización. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0026478

Villacís, D. (2010). Construcciones patrimoniales de Chimborazo. En Instituto Nacional de Patrimonio Cultural (Ed.), *Guía de bienes culturales del Ecuador-CHIMBORAZO* (pp. 39-45). Ediecuatorial. https://www.patrimoniocultural.gob.ec/wp-content/uploads/2023/05/14_CHIMBORAZO.pdf