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Thermal Comfort and Microclimate in Indoor Spaces of Low-rise Residential Buildings in Dry Tropical Climate

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Abstract

The aim of this research is to analyze thermal comfort and microclimate for indoor spaces in low-rise residential buildings in dry tropical climate. The study area is the municipality of Palmar de Varela in northern Colombia. The experimental methodology is based on measuring three microclimatic parameters: air temperature (T_a), relative humidity (RH) and natural ventilation (W). The study assessed the thermal sensation in indoor spaces based on Thermal Sensation Vote (TSV) and Predicted mean vote (PMV). Data gathered from surveys were analyzed with data mining technologies. The findings suggest that suspended ceilings and ceramic tiles aid to the thermal equilibrium of the building, resulting in a 1.1 °C decrease in indoor air temperature. Likewise, the correlation between temperature and wind (r = -0.72; -0.56) indicates that natural ventilation in buildings can alleviate thermal discomfort. Based on the thermal sensation evaluation, the predominant feeling reported by interviewees in indoor spaces was *warm* (2) in S1 and S2, and *slightly warm* (1) in S3. In addition, the correlation between air temperature and comfort sensation in indoor spaces (r = 0.64; 0.44) suggests that temperature has a direct impact on thermal sensation votes.

1.0 INTRODUCTION

Housing demand in developing countries has contributed to the construction of housing - for middle and low-income population- of inadequate physical and spatial characteristics for the climatic environment in which they are located (Marincic, Ochoa and del Río, 2012; Bano and Sehgal, 2020). The use of materials with high thermal transmittance, such as concrete and clay blocks, cause unfavourable thermal variations in housing, particularly in tropical climates (Velez et al. 2014; Giraldo-Castañeda, Czajkowski and Gómez, 2021). This increases energy consumption due to the excessive use of air conditioning systems such as air conditioners in hot climates and heaters in cold climates (Bin Nadeem et al., 2022; Balter et al., 2021; Hermawan and Svajlenka, 2022). In addition, global warming is changing the microclimate of urban contexts, particularly in residential areas (Therán and Rodríguez, 2018; Pérez-Arévalo et al., 2023).

Microclimate refers to the local climatic conditions affected by thermophysical, geometrical features and heat sources in urban areas (Dimoudi et al., 2013). It is measured through such parameters as RH, T_a, W, and solar radiation (Therán Nieto et al., 2019). These are fundamental for the thermal behaviour, energy performance, healthiness and habitability of residential buildings (Hermawan and Svajlenka, 2022; Kumar, Singh, and Mathur, 2020). Studies of microclimatic variations in interior spaces of buildings located in tropical climates have demonstrated the influence of these parameters on the thermal comfort and health (Pan et al., 2021; López-Escamilla, Herrera-Limones and León-Rodríguez, 2022; Guzmán-Hernández, Franco-González and Zamora i Mestre, 2020).

According to Andreoni-Trentacoste and Ganem-Karlen (2021), there is a growing demand for the improvement of thermal conditions in residential environments. In recent years, extreme weather conditions in hot climates create an urgent need to adapt low-rise residential buildings (Molar-Orozco, Velázquez-Lozano and Vázquez-Jimánez 2020). Therefore, the design and construction of residential buildings in tropical climates should take into account thermal parameters and natural ventilation, as well as the outdoor microclimate. This is necessary to reduce energy consumption and to improve the thermal sensation of users, who spend most of their time indoors (Ma et al., 2017; Pérez-Arévalo and Caballero-Calvo, 2021; Toala Zambrano et al., 2022).

The purpose of this research is to analyze the microclimatic variations and thermal sensations in interior spaces of low-rise residential buildings in a dry tropical climate with high relative humidity conditions. The analysis considers three microclimatic parameters: T_a (°C), RH (%) and W ($m\ s^{-1}$). The case study is the municipality of Palmar de Varela (Atlántico) in the Caribbean region of Colombia. The methodology is experimental and is based on microclimatic measurements in three indoor spaces and the outdoor space of a low-rise residential building.

The measurements identified microclimatic variations between the interior and the exterior of the house, determining the possible elements (structural, material and spatial) that have an impact on the thermal behaviour and natural ventilation of the indoor spaces. Likewise, the thermal sensation in the interior spaces of the building was evaluated based on TSV and PMV using thermal comfort surveys. The findings of the surveys were used to determine the thermal sensation of 18 people (6 people per space), who were between 18-45 years oldThe results of the surveys were also used to study the thermal conditions of interior spaces and to determine whether the thermal sensation is directly or inversely proportional to T_a, RH and W. This enabled us to analyze whether T_a per space is in the range of acceptable or neutral temperature that contributes to user comfort and human occupancy as defined by Fanger (1970) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55.

This research, focused on thermal sensation measurements and evaluation, may contribute to the improvement in planning of future residential buildings in municipalities located in Dry Tropical Climate. Our study of thermal comfort in indoor spaces also adds to the scientific understanding of the influence of the indoor microclimate on the occupants' sense of satisfaction and thermal well-being.

2.0 LITERATURE REVIEW

2.1 Thermal performance and natural ventilation of buildings in tropical climates

“Hot and humid climate conditions have always been a challenge to building designers in tropical countries” (Nordin, Azzam-Ismail and Ariffin, 2019, p. 1). In recent years, various studies tackled the issue ot the thermal behaviour and natural ventilation of buildings in tropical climates. Qays-Oleiwi and Farid-Mohamed (2023) studied the effects of passive cooling strategies on the indoor temperature of buildings in a tropical climate. The case study was selected in Malaysia and the methodology implemented was based on computer simulation validated by measured data. In addition, the thermal comfort perception was evaluated based on different passive cooling strategies using IES-VE 2019 software. The cooling strategies implemented in the building design were shading devices, closing the curtains to reduce the amount of radiation entering from the windows, and using wood in the walls. The results show that the use of shading devices or closing the curtains contributes to the reduction of indoor temperature (Qays-Oleiwi and Farid-Mohamed, 2023).

On the other hand, Gou et al. (2018) conducted a study on the thermal performance and comfort of naturally ventilated residential buildings in tropical climates. The study was conducted on the campus of the National University of Singapore. The methodology was based on field measurements of thermal comfort and indoor environmental quality. The results showed that occupants of naturally ventilated buildings are exposed to operating temperatures higher than those recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) comfort standards for naturally ventilated spaces. The authors found that increasing indoor air velocity by turning on mechanical fans or opening windows contributes to improved occupant acceptance of the thermal environment (Gou et al., 2018).

In the Latin American context, Garcia (2020) analyzes the thermal environment and comfort of buildings in humid tropical zones in Colombia. This study shows that for a thermal acceptance of 96.5 %, based on the Griffiths method, the thermal comfort operating temperature is 23.57 ° C. In addition, Garcia (2020) defines that ventilation systems regulate the environment and thermal sensation in buildings. Callejas-Ochoa et al. (2023) studied the thermal performance of residential buildings in Colombia, focusing on low-income housing (VIS), using computer simulations. The authors conclude that most of these buildings do not provide thermal comfort conditions for the occupants, and therefore design strategies are needed in existing housing to adapt to climate change.

2.2 Thermal comfort

Thermal comfort pertains to the level of satisfaction with the indoor temperature. When designing a residential building, one must consider several factors, including thermal comfort (Yau and Chew, 2012). The thermal conditions in an indoor environment affect the productivity and thermal sensation of the occupants in indoor spaces (Zhang, de Dear, and Hancock, 2019). To provide thermal comfort in residential buildings, individuals have turned to the use of air conditioning systems. Nevertheless, these systems increase energy consumption (Wang et al., 2018).

Thermal comfort is a relevant element in personal protection, health and safety (Han et al., 2023). Also, the feeling of thermal comfort is subjective because it is influenced by individual physical and psychological characteristics (Zhang et al., 2023). One of these physical factors is environmental temperature: sudden temperature changes in indoor spaces of residential buildings affect thermal perception, both positively or negatively (Zhan et al., 2010). Therefore, thermal comfort is expressed as an interval in which humans tolerate or function in the environment (Mohammadzadeh, Karimi and Brown, 2023).

In the literature, the categories of thermal comfort studies include construction building technology, energy fuels, environmental sciences, thermodynamics, green sustainable science technology and materials science. In regions with Dry Tropical Climate, thermal comfort studies have focused on residential apartments, sleeping environments, naturally ventilated housing, compressed earth buildings and public space (Neya et al., 2021; Johansson et al., 2018; Ouedraogo et al., 2022; Djongyang, Tchinda and Njomo, 2012; Udaykumar, Rajasekar and Venkateswaran, 2015).

On the other hand, other studies in this area have used thermal assessment models such as PMV and TSV to determine the thermal comfort in indoor spaces. Specifically, predicted mean vote (PMV) is the most widely used thermal evaluation model for efficient and sustainable building management (Zhang et al., 2020). Fanger's PMV model considers six variables (air temperature, MRT, relative humidity, air velocity, metabolic rate, and clothing insulation) (Yau and Chew 2012; ASHRAE, 2017). However, PMV model does not fully account for thermal adaptations (Zhang and Lin, 2020). Both PMV and TSV scale a person's thermal sensation as very cold, cold, cool, slightly cool, neutral, slightly warm, warm, hot, hot and very hot. This scale was considered for conducting the thermal sensation assessments in this research.

3.0 METHODS

3.1 Study area

The study area is the municipality of Palmar de Varela - Atlántico (10.69613, -74.768969) located in the Caribbean region of Colombia (Figure 1). The area of the municipality is 94 km²; the total population is 31,969 inhabitants, with density of 340.1 inhab/km² (Departamento Nacional de Planeación, 2022). The climate of the municipality is dry tropical: average annual temperature of 26-28 °C, relative humidity of 80-85 %, wind speed of 3-5 m s^{-1}, solar radiation of 4.5 to 5.5 KWh m² and precipitation regime of 1000-1500 mm with a dry season during the winter months (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2010; Schubert et al., 2019).

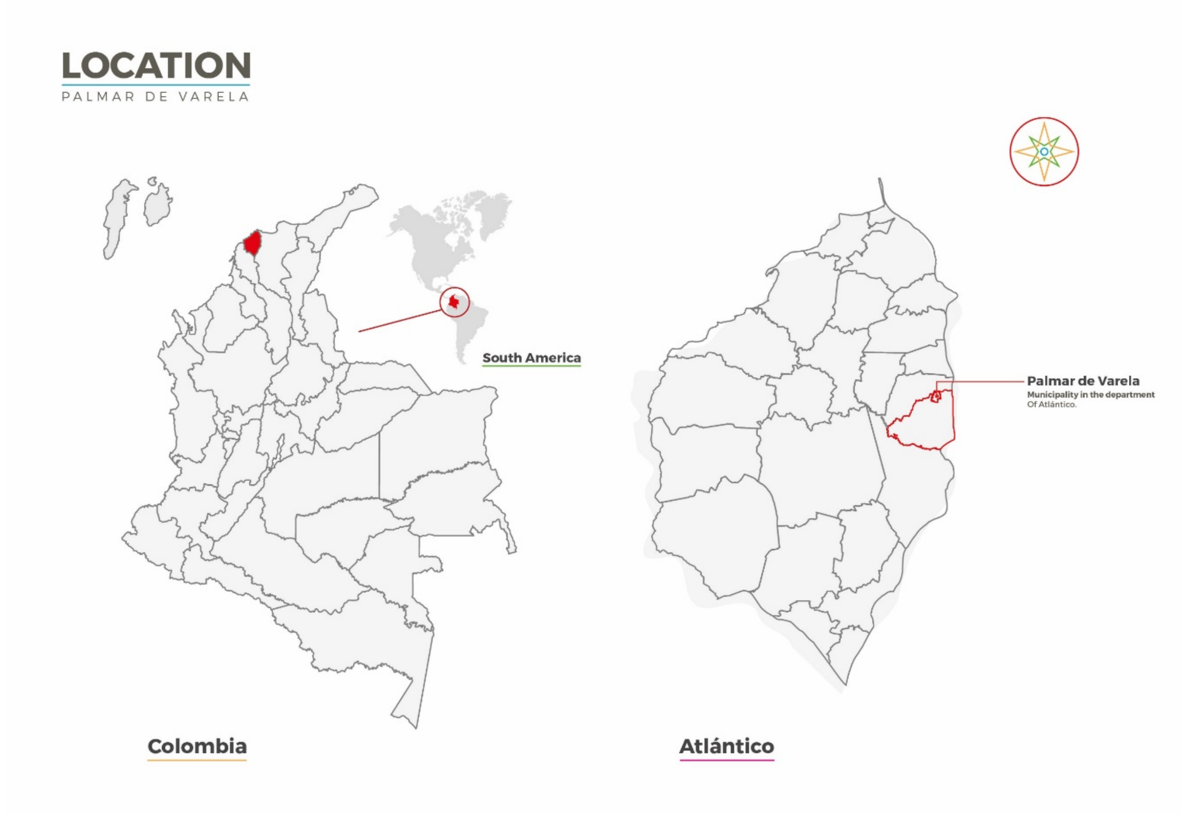

Figure 1. Palmar de Varela, Colombia

3.2 Study techniques and tools

3.2.1 Low-rise residential building selection

According to the Departamento Nacional de Planeación (2020), the municipality of Palmar de Varela has 6,357 housing units. Of these, 93.5% are houses and 3.64% are apartments. The most common materials used in the floors of the houses are ceramic tiles (36.46 %) and cement or gravel (55.73 %), while the predominant material in the exterior walls is block or brick (94.88 %). Most of the residential buildings in the municipality are low-rise (1-2 levels). Therefore, a low-rise single-family house (one level) located in a local climatic zone of open fabric in the centre of the municipality was selected for the study (**Figure 2**). The residential building has 82.4 m² of constructed area. The predominant materials in walls and floors are concrete brick, ceramic tiles and concrete, while the roof is constructed with asbestos cement sheets.

For the microclimatic measurements, in addition to the outdoor space, three indoor spaces (Space 01 – S1; Space 02 – S2; Space 03 – S3) corresponding to the living room and two bedrooms were selected (**Figure 3-Figure 4**). These spaces have similar characteristics in terms of size and occupied area but differ in materials, coverings and use of suspended ceilings. **Table 1** shows the characteristics of the selected indoor spaces.

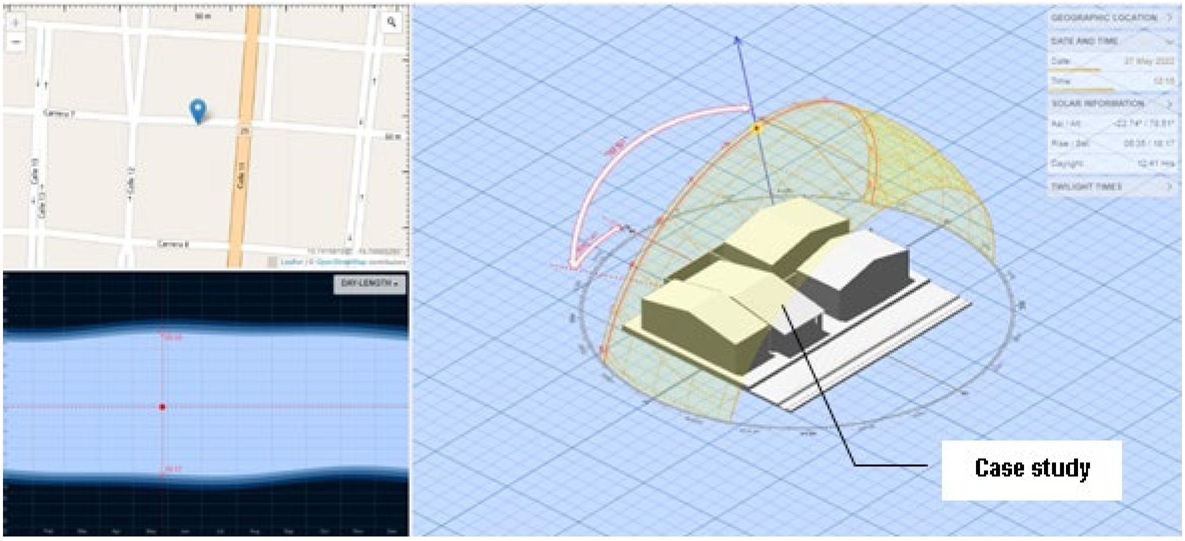

Figure 2. Location of the building in the Heliodom

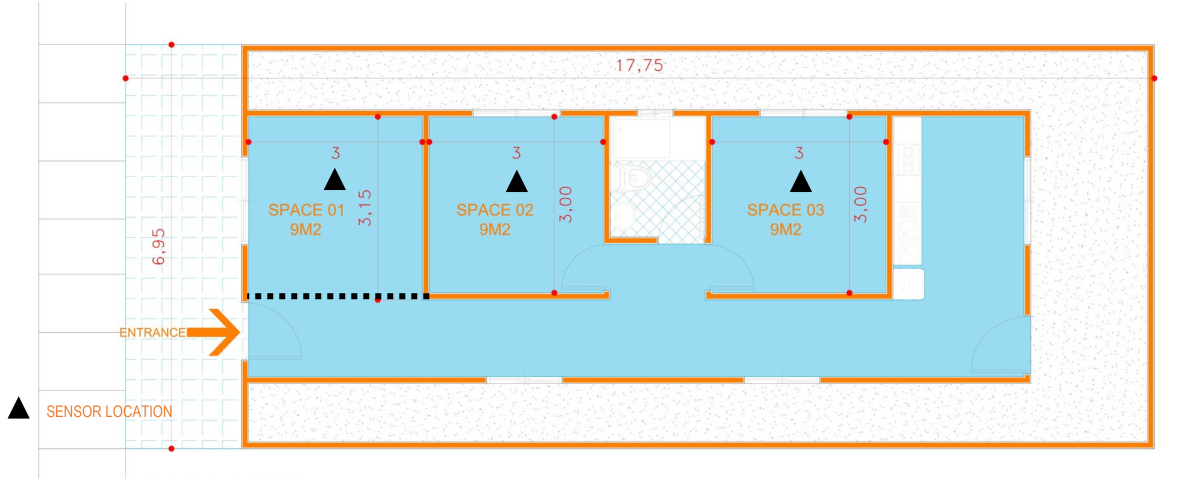

Figure 3. Architectural drawing of the selected low-rise residential building

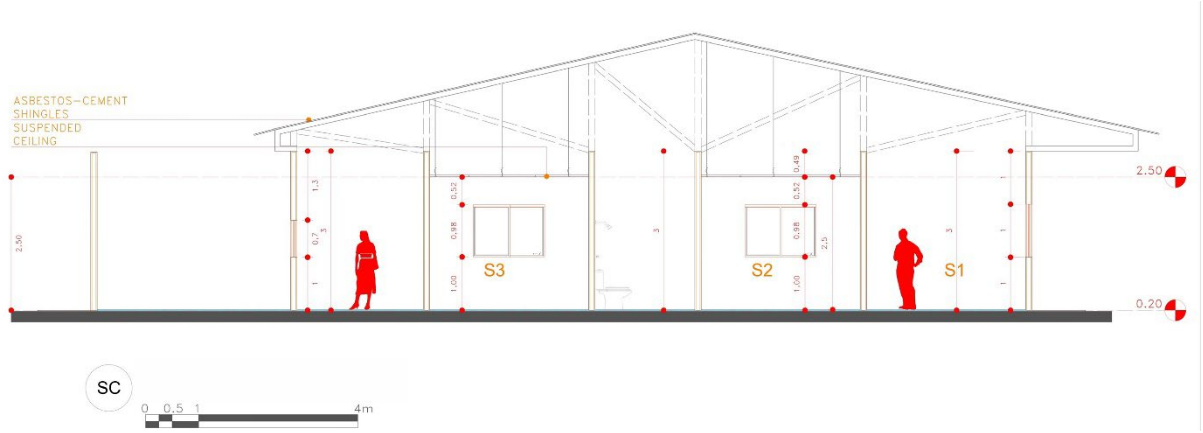

Figure 4. Building design cross-section

Table 1. Characteristics of the indoor spaces

Area		Internal wall material	Floor material	Window	Window area	Use of suspended ceiling
S1	9.45 m²	Concrete	Concrete	Open	1.5 m²	No
S2	9.00 m²	Concrete	Ceramic tile	Open	1.0 m²	Yes
S3	9.00 m²	Ceramic tile	Ceramic tile	Open	1.0 m²	Yes

3.2.2 Microclimate measurements

The in-situ measurements were carried out during 31 consecutive days in May 2022 from 08:00 to 18:00 in the indoor spaces and outdoor spaces of the building. The measurements considered that May is one of the three months of the year with high humidity levels and average temperatures (29 °C) in the municipality and the region (Weather Spark, 2022; Rodríguez-Potes and Villadiego, 2020). According to data provided by IDEAM in May 2022 the average maximum and minimum temperatures in the municipality were 35.3 °C and 22.0 °C (**Figure 5**).

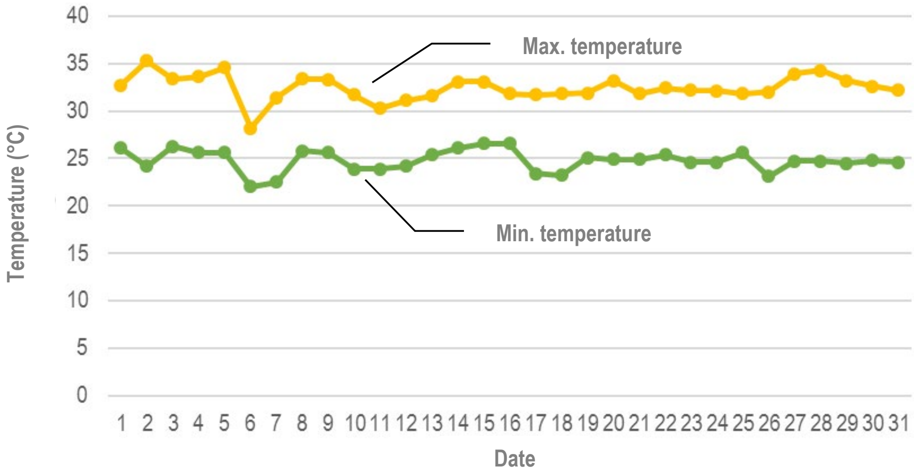

Figure 5. Palmar de Varela Weather: Average Temperature in May 2022

The measurements assess the variations presented in three microclimatic parameters that affect thermal comfort: W (m s^{-1}), RH (%) and T_a (°C) (Borowski, Zwolinska, and Czerwinski, 2022; Azad et al., 2018; Novia-Bramiana et al., 2022). In the thermal analysis, the roof and ceiling used in the building were considered, as these elements modify the thermal conditions of the indoor spaces and protect from external weather conditions (Ortiz-Zambrano, Torres-Quezada and Véliz-Párraga, 2021). Measurements were taken at one-hour intervals using a thermo-anemometer (**Figure 6**), which is installed in the selected spaces at 1.5 m and the data were collected manually.

Figure 6. Thermo-anemometer installed in the rooms

For the measurements, a member of the research team was present in the selected spaces and manually activated the thermo-anemometer to identify and collect the thermal data and wind speed in all the spaces. These data were manually recorded on characterization sheets, which were printed spreadsheets that collected data such as date, time of measurement, T_a, RH, and wind speed. These data were then tabulated in Excel spreadsheets to obtain the averages of the collected data.

On the days of measurement, windows were open, and the spaces were naturally ventilated. No mechanical fans or air conditioners were used. This ensured that the thermal sensation of the occupants was assessed according to the natural conditions of the spaces. In addition, to ensure that the occupants did not alter the thermo-anemometers, these devices were removed after the last measurement of the day (19:00) and reinstalled the next day at 6:30 before the start of the daily measurements. Similarly, to monitor the meteorological conditions of the municipality during the study, the daily data published by the meteorological station of the municipality of Soledad, located 18 km from the case study, were reviewed.

On the other hand, measurements of the microclimatic conditions in the outdoor space of the building are applied, presenting a comparison of the thermal and natural ventilation differences between the indoor and outdoor space, considering that the thermal conditions of the environment determine the microclimate in a building (Hong et al., 2021). The data obtained were systematized in characterization sheets by space and quantitatively compared to obtain the correlation coefficient [*r*] between the parameters. Minitab software was used to obtain the correlation coefficient. The correlation coefficient indicates that if the value of *r* is close to

-1 the covariation is extreme. In contrast, if *r* is equal to -1 the correlation is perfectly negative. The values presented in the results tables correspond to the quantitative hourly average of the 31 days measured.

3.2.3 Thermal Sensation Assessment

Thermal sensation surveys based on Thermal Sensation Vote (TSV) and Predicted Mean Vote (PMV) were applied in the research. The Fanger's predicted mean vote determines the thermal comfort in a space, however, the application of thermal comfort surveys in field studies provides more accurate tests and captures the actual thermal sensation of a person taking into consideration aspects of microclimate, physical activity, age and body mass (kg) (Djongyang, Tchinda and Njomo, 2010; Kim, Schiavon and Brager, 2018; Zhang et al., 2019). Therefore, the survey aimed to assess the thermal sensation of building occupants in indoor spaces. This served to analyze the correlation coefficient between air temperature, relative humidity and natural ventilation concerning the thermal sensation of a person in a resting state in each selected space.

It is important to consider that the resting state represents the minimum physiological effort of regulation (Broday et al., 2019). Another variable considered was the type of clothing people wear at home. The type of clothing (thermal insulation of clothing) and the metabolic rate also affect the thermal sensation (Yau and Chew, 2012).

The surveys were applied to 18 people (occupants of the building and research team), between 18-45 years old (50% male and 50% female; 6 people per space). In addition, the survey was administered during the 31 days of measurement and adapted the PMV and TSV thermal sensation scale: -3 (very cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), and 3 (very hot) (Zhang et al., 2010; Luo et al., 2023). Interviewees selected an option according to the sensations they had in the space (at different times: 8:00 - 18:00) (Rodríguez-Potes and Villadiego, 2020).

For the systematization and assessment of the thermal sensation votes, data mining technologies were used to establish the correlation between the thermal patterns of the spaces (temperature and humidity) with the thermal sensation (Song et al. 2020). The results tables present the thermal indicators (-3, -2, -1, 0, 1, 2, 3) with the highest vote (%) per day and time. For the general analysis per time, two reliable statistical variables Mode_1 and Mode_2 were established. Mode_1 refers to the most frequent TSV in the data set per time over 31 days, whereas, Mode_2 refers to the most frequent TSV in the space during May 2022. In this sense, Mode_2 represents the overall thermal sensation in the indoor space.

4.0 RESULTS AND DISCUSSION

For the period analyzed, S1 presented an average air temperature of 31.9 °C and maximum and minimum temperatures of 34.4 °C and 26.5 °C, respectively (**Table 2**). S1 presents high temperatures due to the amount of heat received by the canopy (Yuliani et al., 2021). The average relative humidity value is 72.3 %, with maximum and minimum values of 91.5 % and 62.8 %. The findings show that the correlation coefficient between temperature and relative humidity in S1 is $r = -0.9$ (extreme inversely proportional covariation). That is, if the air temperature increases, the relative humidity values decrease. The use of asbestos cement sheets (thermal inertia of 0.8 $W\ m^{-1}\ K^{-1}$) in the building envelope does not contribute to the thermal optimization of S1 (Calderón Uribe, 2019).

The average wind speed in S1 was 0.59 m s-1, with maximum and minimum speeds of 1.2 $m\ s^{-1}$ and 0.2 $m\ s^{-1}$. During the day the wind flow is constant. This is due to two factors: wind flow from the southeast (3-5 $m\ s^{-1}$) that occurred during May in the municipality and the use of a window that allows natural ventilation. The correlation coefficient between wind speed and air temperature in the space was $r = -0.7$ (inversely proportional). The flow of natural ventilation in S1 optimizes indoor air quality and contributes to thermo-physical well-being (Yarke, 2005).

Table 2. Thermal variation and natural ventilation in S1

S1			
Time	T_a (°C)	RH (%)	W (m s^{-1})
08:00	26.5	91.5	1.2
09:00	31.2	75.1	0.7
10:00	34.3	62.8	0.3
11:00	34.4	65.1	0.3
12:00	30.5	80.8	0.6
13:00	33.0	64.4	0.3
14:00	32.2	72.3	1.1
15:00	32.9	68.6	0.4
16:00	32.9	68.7	0.7
17:00	32.3	71.4	0.2
18:00	31.7	74.3	0.7

On the other hand, in S2 the average air temperature was 32.0 °C, with maximum and minimum temperatures of 34.4 °C and 27.4 °C (Table 3). As for relative humidity, the average value was 74.0 %. Maximum and minimum RH were 90.3 % and 65.8 %. During the afternoon, the relative humidity increases due to the decrease in air temperature. Thus, the relationship between both parameters was inversely proportional according to the correlation coefficient (r = -0.969).

In S2 the natural ventilation flow was deficient, the average wind speed for May was 0.03 m s^{-1}. Likewise, between 11:00 and 18:00 the wind speed was 0 m s^{-1}. In addition, the correlation coefficient between T_a and W (r = -0.568) indicates that there was an inversely proportional relationship between the parameters. The space must have more ventilation by enlarging the area of the openings. In tropical climates, users of naturally ventilated spaces are susceptible to thermal discomfort generated by heat and relative humidity. Consequently, these spaces need greater wind circulation to improve people's thermal sensation (Buonocore et al., 2018).

Table 3. Thermal variation and natural ventilation in S2

S2			
Time	T_a (°C)	RH (%)	W (m s^{-1})
08:00	27.4	90.3	0.2
09:00	31.1	76.9	0.0
10:00	34.3	66.0	0.1
11:00	34.4	65.8	0.0
12:00	30.8	77.4	0.0
13:00	32.3	74.0	0.0
14:00	32.6	74.7	0.0
15:00	32.5	73.6	0.0
16:00	33.0	66.4	0.0
17:00	32.3	73.1	0.0
18:00	31.7	76.1	0.0

In S3 the average air temperature was 31.8 °C and the maximum and minimum temperatures were 34.1 °C and 27.8 °C (**Table 4**). The average relative humidity was 73.8 %, with maximum and minimum variations between 65.0 % and 77.8 %. In this space, the average air temperature was lower than in the rest of the building. This may be related to two factors: the material of the walls and floors that function as thermal insulators and the use of suspended ceilings. This contributes to the decrease in the use of air conditioners since the use of air conditioning systems represents 41 % of the total energy consumption of a building (Lopez-Perez, Flores-Prieto and Rios-Rojas, 2021).

The relationship between T_a and RH in this space is inversely proportional since the correlation coefficient was r = -0.4. It was observed that the type of window with sliding panels and the area of the openings (≥ 0.5 m^2) in S2 and S3 do not allow good natural ventilation flow to the interior. Although in these spaces the use of suspended ceilings contributes to thermal regulation, a greater wind flow would dissipate the excessive heat gains caused by the expulsion of metabolic heat from the users and the accumulation of solar radiation on the walls of the building (García-Chávez and Fuentes-Freixanet, 2005). Wind circulation would contribute to the thermal comfort of users exposed to hot and humid conditions that affect work performance and the development of their daily activities (Zhai et al., 2017; Bin Nadeem et al., 2022).

Table 4. Thermal variation and natural ventilation in S3

S3			
Time	T_a (°C)	RH (%)	W (m s^{-1})
08:00	27.8	75.5	0
09:00	31.2	68.5	0
10:00	34.1	65.0	0
11:00	34.1	69.0	0
12:00	30.5	72.5	0
13:00	31.8	77.8	0
14:00	31.8	77.5	0
15:00	32.2	77.0	0
16:00	32.6	75.1	0
17:00	32.2	76.5	0
18:00	31.5	77.3	0

In the outdoor space, the averages of air temperature, relative humidity and wind speed were 32.9 °C, 69.3 % and 1.2 m s^{-1} (**Table 5**). The correlation coefficient between T_a and RH was -0.9 and -0.14 for wind speed and T_a. Therefore, the covariation between T_a and wind speed indicated that, in the outdoor space, the wind had less influence on the decrease of air temperature. In the outdoor space, the thermal environment is influenced by the characteristics of the space and the configurations of the surrounding dwellings or buildings (Huang and Jie, 2022; Wattanachai et al., 2021).

Table 5. Thermal variation and natural ventilation in the outdoor space

Outdoor space			
Time	T_a (°C)	RH (%)	W (m s^{-1})
08:00	28.5	85.0	0.5
09:00	31.5	73.3	0.3
10:00	34.3	65.8	0.8
11:00	34.1	64.5	0.5
12:00	34.0	68.5	1.6
13:00	35.2	60.1	1.3
14:00	33.6	68.0	1.1
15:00	35.5	65.5	1.2
16:00	34.2	62.7	1.8
17:00	31.3	72.5	2.5
18:00	30.7	76.0	1.8

In the comparison of measurements by space, it was observed that humidity changes were strongly related to air temperature and outdoor conditions. This parameter varies according to the season, thermal conditions, precipitation levels or time of day (Vellei et al., 2017). In turn, the use of ceramic tile on the walls of S3 acted as a thermal insulator. In this space, the air temperature was lower compared to S1 and S2, where the interior wall covering is cement (Figure 7). It should be noted that traditional materials such as cement and concrete increase energy consumption, heat retention and thermal variations in buildings (Liang, Tan and Jiang, 2022; Gondal, Syed-Athar and Khurram, 2021). In addition, incorporation of a green roof in buildings tends to improve the thermal environment in the indoor spaces and, consequently, the feeling of thermal comfort (Rahman, Zaid and Shuhaimi, 2022).

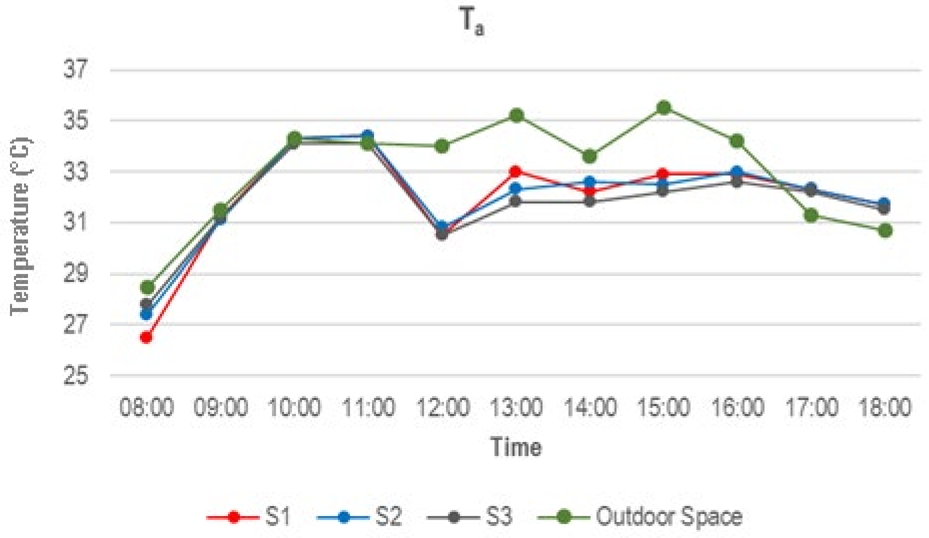

Figure 7. Comparison of indoor and outdoor air temperatures

In terms of wind speed, S2 and S3 presented deficiencies in natural ventilation flow. This was caused by the roughness of the surface and the orientation of the buildings, which have changed the wind circulation patterns and obstructed the passage of natural ventilation to indoor spaces (Mendes, Romero and Ferreira da

Silva Filho, 2020). In turn, the results identified that the thermal behaviour of the building on dry days with clear or partially overcast skies differs from days with precipitation. On rainy days the air temperature tends to decrease in the indoor spaces. The thermal differences during dry days were 1.98 °C in S1; 2.34 °C in S2; 2.48 °C in S3; and 2.93 °C in the outdoor space. Solar radiation tends to be weak during rainy days or periods, causing differences between indoor and outdoor air temperatures (Lu, Hu and Zhong, 2022; Kubilay, Derome and Carmeliet, 2018).

As discussed by Gou et al. (2018), in naturally ventilated rooms, the use of mechanical fans or air conditioners allows the occupants to adapt to the thermal environment. However, to improve the thermal environment in the building, passive design strategies can be implemented, such as the use of sunscreens or closing the curtains on the windows to reduce the amount of radiation entering the rooms from the windows. Also, wood or ceramic tiles can be installed on the walls (Qays-Oleiwi and Farid-Mohamed, 2023).

4.1 Thermal Sensation

In S1 and S2 for $Mode_2$ data, the most frequent thermal sensation response was 2 (warm). That is, the thermal sensation in S1 and S2 for May was warm. In $Mode_1$ the thermal sensation between 8:00 - 9:00 and 18:00 was 1 (slightly warm), while in the rest of the time, the respondents' sensation was 2 (warm). Likewise, the results of the surveys per day in S1 indicate that between 8:00 and 18:00 the thermal sensation of some respondents was 0 (neutral) or -1 (slightly cool). In S2 the interviewees never reported feeling "slightly cool" during 8:00 and 18:00. This is due to the temperature differences between the two spaces at the analyzed times.

The assessment in both spaces indicated that in the early morning hours and at sunset the thermal sensation of people tends to decrease (1, 0, -1), due to the reduction of temperature and cooling of the spaces. In fact, according to the analysis of the variables in S1 and S2, the correlation between Ta and TSV was directly proportional (r = 0.6488, S1; r = 0.6637, S2), i.e. if T_a decreases the thermal sensation also decreases. In contrast, the correlation between RH and TSV (r = -0.6553) indicates that if RH decreases the thermal sensation increases.

According to the data obtained with $Mode_2$ in S3 the most frequent thermal sensation was 1 (slightly warm). Between 8:00 and 9:00 the most voted thermal sensation indicator was 0 (neutral), i.e. thermal comfort. According to the $Mode_1$ indicator, the thermal sensation between 16:00 and 18:00 was 1 (slightly warm), i.e., as the air temperature decreases during the sunset, the thermal sensation improves. Unlike S1 and S2, no votes for indicator 3 (very hot) were present in this space (**Figure 8**). In addition, the findings indicate that S3 is the indoor space with the best thermal conditions both in air temperature behaviour and in the thermal sensation of the interviewees.

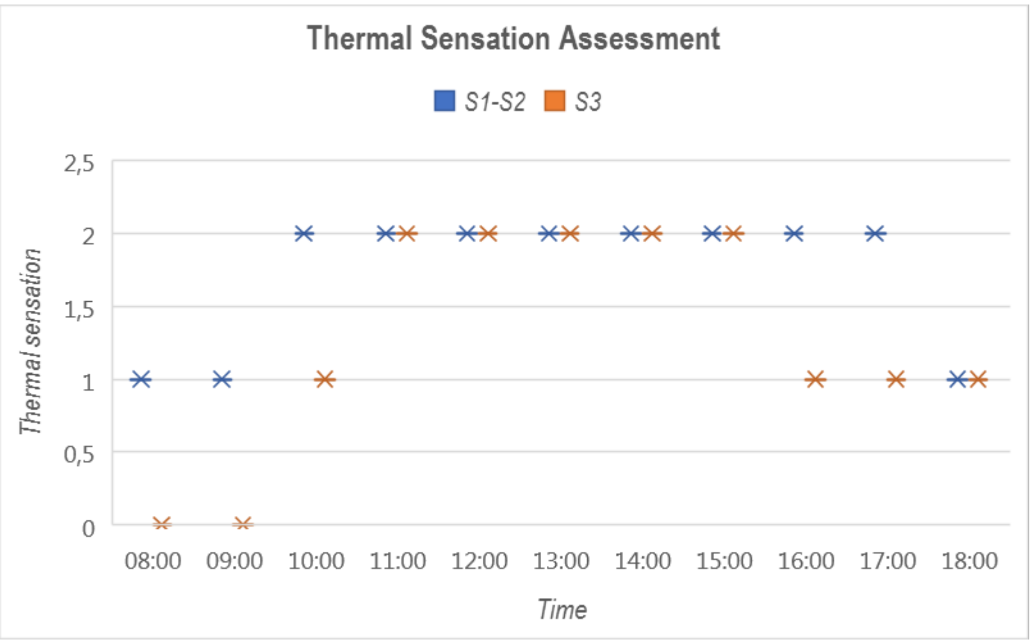

Figure 8. Thermal sensation per room and time in May 2022

In S3 the correlation coefficient between RH and TSV ($r = 0.2431$), Ta and TSV ($r = 0.4429$) is directly proportional. RH has a positive correlation or direct impact on thermal sensation only in S3. Therefore, in the design of indoor spaces, it is necessary to ensure microclimate conditions (temperature, relative humidity and natural ventilation) suitable for the occupants (Bonefacic, Wolf and Frankovic, 2015). Fanger (1970) defines that the acceptable air temperature for neutral thermal sensation (comfort) in space should range between 21 °C to 25 °C, regardless of the climate. ANSI/ASHRAE Standard 55 (2020) states that the acceptable temperature range varies between 23 °C and 26 °C. Thus, in the spaces analyzed, the average T_a has an impact on the thermal sensation of the occupants at rest.

The thermal sensation of occupants in S1, S2 and S3 is determined not only by the temperature and relative humidity conditions of the space but also by the heat flow and heat exchange between the human body and the environment (Croitoru et al., 2015), which is related to various factors including the materials of which the space is constructed. Similarly, proper natural ventilation and indoor air quality would improve the thermal sensation and heat exchange of occupants in indoor spaces (Lei et al., 2017).

Overall, it was found that 53% of the male respondents' thermal sensation responses were 2 (warm), while 57% of the female respondents' responses were 1 (slightly warm). According to the regression results obtained with Minitab, it was determined that the relationship between age is not statistically significant ($p > 0.05$).

5.0 CONCLUSIONS

The design of indoor spaces should pay more attention to the use of passive strategies that optimize the thermal balance and natural ventilation of buildings. Therefore, it is necessary to prioritize the use of materials with low thermal transmittance and ceilings to protect from excessive heat and solar radiation accumulated on the roof and walls. Likewise, using other types of windows or increasing the size of the inlets (amount of air) can contribute to the thermal regulation of the spaces. S2 and S3 present deficiencies in natural ventilation: the size of the entrances and the use of sliding windows do not contribute positively to air circulation.

According to the correlation coefficient between wind and air temperature, natural ventilation should be prioritized in the design of indoor spaces for two reasons: it helps thermal balance and improves indoor air quality. In low-rise residential buildings, a greater flow of natural ventilation to the interior should be guaranteed, optimizing the thermal comfort of the occupants. The research identified that the air temperature of the indoor spaces until 16:00 is lower compared to the outdoor space. Whereas, outdoors the air temperature drops by 1 °C between 17:00 and 18:00. This is because in the evening the wind speed increases, contributing to the thermal regulation of the outdoor space.

In terms of thermal sensation, interviewees felt different levels of thermal comfort depending on the time and day of the month, as well as the air temperature and relative humidity conditions of the indoor space. The state of rest also had an impact on thermal sensation, since another level of physical activity would increase the occupants' comfort level at any time of the day. The correlation coefficients indicate that there is a linear relationship between air temperature and the thermal sensation of the occupants. The thermal sensation vote indoors is lower, when Ta decreases. Other factors can influence the comfort of the occupants such as the use of suspended ceilings, the orientation of the indoor spaces, the amount of radiation accumulated on the walls and the outside temperature.

On the other hand, the methodology and results of the study may be useful for other research on thermal behaviour, natural ventilation and thermal comfort in indoor spaces in low, medium and high-rise residential buildings in tropical and other climates. Future research should analyze the relation between thermal variations and natural ventilation with the thermal sensation of comfort of users in buildings located in tropical climates, using the Fanger scale, PMV and TSV. The effective implementation of the results of this research can help to improve the design of low-rise residential buildings and, therefore, increase the thermal comfort of their occupants.

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