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Assessment of Vernacular Housing in the Dominican Republic Using Simulations

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Abstract: Dominican vernacular architecture, based on the Spanish-influenced indigenous bohio, is built with natural materials. This housing model has remained practically unchanged for five centuries, responding adequately to the tropical Caribbean climate. However, it is necessary to characterize this behavior to verify the indoor comfort conditions of this housing typology. The aim of this research is to evaluate the behavior of a vernacular house located in Villa Sombrero, Peravia Province, Dominican Republic, using a simulation model. For this purpose, a bohio was selected, which has a simple rectangular volume. Simulations were carried out using Design Builder software, considering the passive strategies incorporated in the bohio. The results indicate that indoor ambient temperature remains within the comfort range throughout the annual cycle. It was confirmed that the highest solar gain through exterior windows occurs in the warmer months. Lighting consumption varies between approximately 195 kWh and 220 kWh, with a more stable behavior during the middle months of the year. CO_2 emissions followed the same behavior as lighting consumption since it was the only energized element in the bohio. This research demonstrated that passive strategies implemented in the vernacular dwelling work correctly, except for the minimum illuminance level, which needs to be improved.

Keywords: vernacular housing; thermal performance; indoor comfort; solar gains; illuminance; simulation; Dominican Republic

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1. Introduction

Vernacular architecture is a response to the different climatic conditions that exist throughout the world and is conditioned by the natural resources found in its immediate surroundings using traditional techniques [1]. In addition, it is based on the cultural and historical background of the people and becomes a territorial reference and part of the rural landscape [2]. Thus, this type of architecture responds to the local climate to conserve energy and provide indoor thermal comfort by employing several passive design strategies [3]. This type of passive strategy implemented in vernacular architecture can provide solutions to the current architecture and contribute to the mitigation of environmental impacts such as greenhouse gas emissions, indiscriminate depletion of resources, and high energy consumption, among others. However, this architectural style is currently on the verge of extinction as it has been replaced by current constructions [1]. In this context, it is important to characterize the effect of passive strategies on the indoor comfort of vernacular housing, which can serve as a reference for decision making in the design of new buildings or in the improvement of existing buildings.

The importance of vernacular housing assessment has been highlighted by several authors. In this way, there is worldwide research on the study of vernacular dwellings, as is the case of Ding and Shu (2024), who studied the thermal characteristics of housing built with bamboo-woven mud walls in a hot and humid region of China during the summer season [4]. Also, in 2024, Cheng et al. assessed the indoor thermal comfort of vernacular dwellings in cold regions of China using a combination of parameters [5]. Meanwhile, in Iran, Heidari and Davtalab (2024) studied the effect of vernacular techniques on the indoor thermal comfort in an extreme climate of the Sistan region [6].

Furthermore, Bhaumik et al. (2023) simulated vernacular dwellings in Todas, India, to study the architecture and indoor space quality as a function of thermal comfort parameters such as indoor temperature and airflow [7]. Also, in 2023, Bustán-Gaona et al. analyzed the natural lighting of vernacular housing in Ecuador combining measurements and simulation during summer and winter solstices [8]. Costa-Carrapico et al. (2022) aimed to understand thermal comfort in vernacular dwellings in Alentejo, Portugal, by monitoring several variables during summer and winter [3]. Widera (2021) conducted a comparative analysis of user comfort and thermal performance of six vernacular housing types in West Sub-Saharan Africa, measuring temperature, relative humidity, indoor air quality, and daylighting [9]. Also in 2021, Chang et al. analyzed the influence of vernacular building spaces on human thermal comfort in arid climatic zones of China [10]. While Fernandes et al. (2020) analyzed the thermal behavior and comfort conditions of vernacular rammed earth architecture in southern Portugal [11], Zune et al. (2020) assessed passive design techniques used in vernacular dwellings located in Myanmar to achieve thermal comfort by conducting simulations [12].

In the Dominican Republic, research has been carried out on thermal comfort in vernacular housing, as in the case of Prieto-Vicioso et al. [13], where they evaluated the thermal behavior of two types of roofs of Dominican vernacular housing, one with a cana palm and the other with zinc sheets, using infrared thermography, surface temperature sensors, and measurement of environmental conditions. In this context, the majority of research on vernacular architecture has been carried out in Asia and Europe, with only a few studies in Africa, South America, and the Caribbean. However, conservation and energy efficiency are key components of vernacular architecture. Thus, it is essential to carry out further research on vernacular dwellings located in the Caribbean in order to learn about the effect of passive strategies on the indoor comfort. For this reason, this paper addresses this gap by evaluating the behavior of a vernacular house located in Villa Sombrero, Province of Peravia, Dominican Republic, through a simulation model, to verify the indoor comfort conditions of this housing typology.

2. Materials and Methods

The methodology used to carry out this research is presented in Figure 1, which comprises a description of the case study, local climatic conditions, a description of the model and simulation, and the results (air temperatures, relative humidities, solar gains through windows, lighting consumption, carbon dioxide emissions, illuminance and daylight factor).

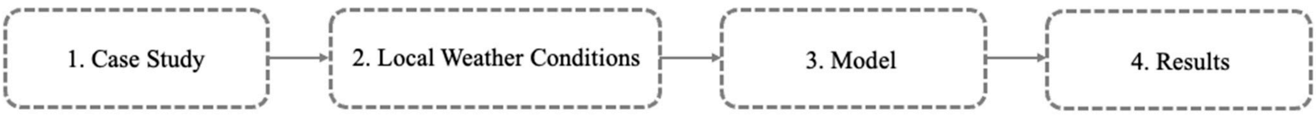


Figure 1. Methodology of the study.

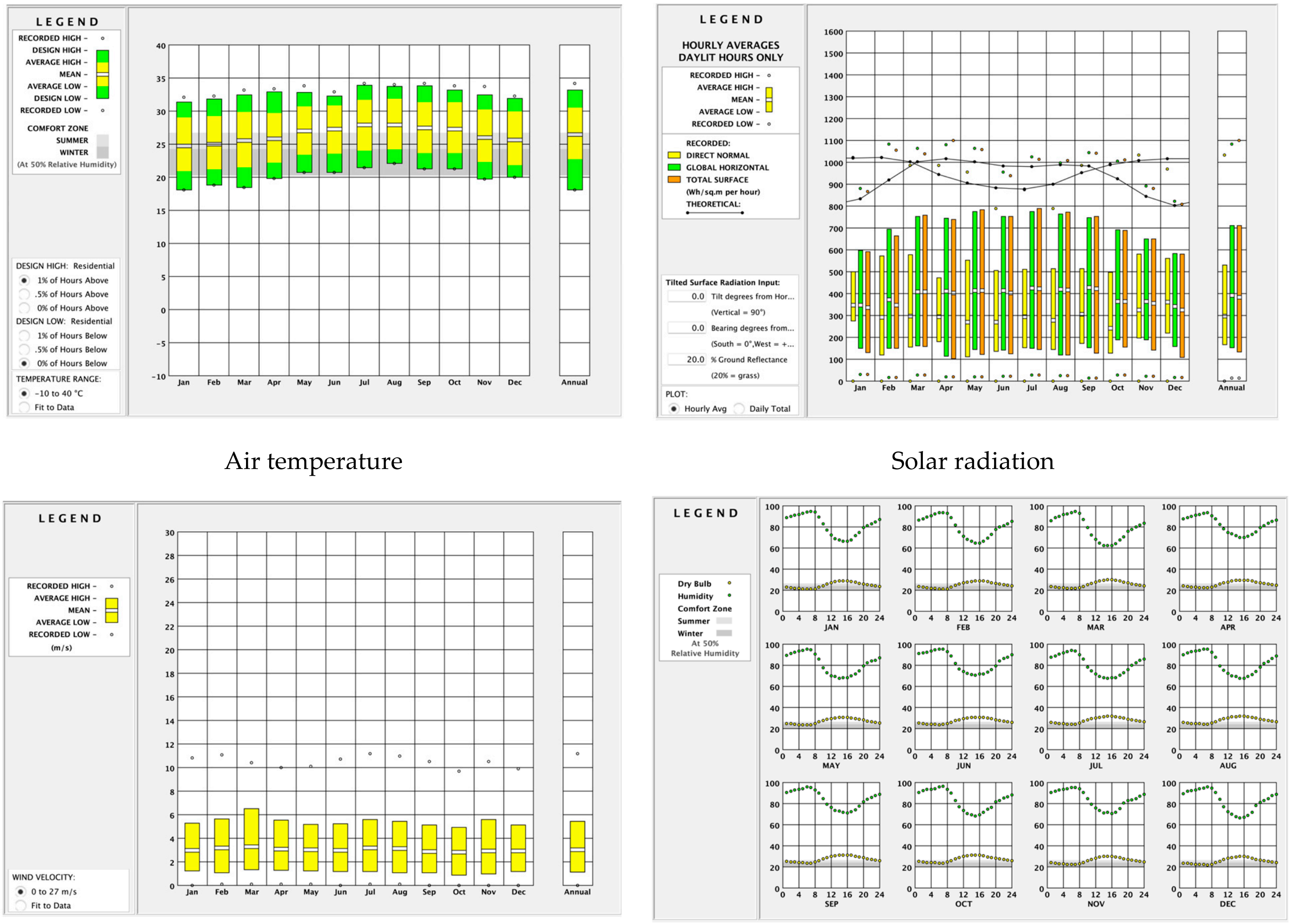
2.1. Case Study

The bohio studied was built at the end of the 19th century and represents the typical Dominican dwelling. It is located in Villa Sobrero, Bani, and belonged to General Faustino Ortiz, a personage of Dominican history. Originally, it had a simple volume with a rectangular floor (9.8 × 5.8 m) plan and a hipped roof; the walls have a height of 2.5 m and the ridge height is approximately 4.15 m. Spatially, it is composed of three spaces; in the center is the social space, fragmented by a handrail that is a division made of two low walls, with a passage between them framed by three arches and four columns, all made of wood. On one side is the master bedroom, and on the other, two bedrooms. The kitchen, pantry, and latrine were originally located outside. The structure of the hut consists of thick mahogany and oak forks driven directly into the ground, topped by the sleepers or sills and the keys, which form the upper perimeter frame of the structure of the walls, on which rests the frame of the roof, which supports the thick layer of palm leaves (*Sabal domingensis*). The boards of royal palm (*Roystonea hispaniolana*), used as enclosure material throughout the house, are nailed to the forks. These boards, which emerge from the bark of the palm trunk, are normally 10 to 12 cm wide and about 2.5 cm thick and are placed with the epidermis facing outwards. The inner walls do not reach the ceiling, which allows air to flow over them. Some wrought iron nails can still be found on the walls, which certifies the age of the bohio. The bohio has a door in the middle of its main facade and four windows, two on each side of the door. On the rear facade facing the courtyard, it also has a door placed in the middle and four windows, two on each side of the door. The windows are hinged, with wood and with metallic knockers, although some have already been replaced by windows with wooden lattices. The floors are of cement mosaic and polished cement. At present, the house has some annexes built of cement blocks and a wooden roof and corrugated zinc sheets [14]. Figure 2 shows the bohio selected as a case study.

Figure 2. Bohio selected as a case study.

2.2. Local Weather Conditions

The Dominican Republic is in the intertropical zone, at 19° north latitude and presents characteristics of a subtropical climate that varies from place to place, due to the topography and the northeast trade winds. The climatic variations are marked, ranging from arid to very humid [15]. The province of Peravia, located in the southern region of the country, approximately 60 km west of the city of Santo Domingo, belongs to the Caribbean Coastal Plains and has a climate that varies from dry subtropical to very dry subtropical, with vegetation that is mostly cacti [16]. According to the Köppen–Geiger climate classification, it is Aw, or tropical savanna climate, where in winter there is much less rain than in summer [17]. On average, the annual average temperature is 26.6 °C, with July being the hottest month (31.0 °C) and January the coolest (25.0 °C). Average temperatures vary during the year by 3.0 °C. Average annual precipitation is 952 mm, with February being the driest month (25 mm) and October the rainiest (138 mm) [15,17]. Figure 3 shows the annual ranges of outside temperature, solar radiation, wind speed and relative humidity of the city of Baní, which is located less than four kilometers from Villa Sombrero. These meteorological files were obtained using the Climate Consultant 6.0 program.



Air temperature

Solar radiation

Wind speed

Relative humidity

Figure 3. Range of weather conditions in Peravia Province [18].

2.3. Model Description

For this research, a simplified model of the bohio described in Section 2.1 was made, which has a surface of 56.84 m^2. As for the orientation of the bohio, the major axis is oriented from east to west. Figure 4a shows the floor plan of the bohio divided by the thermal zones, while Figure 4b presents an isometric of the model of the bohio made in Design Builder.

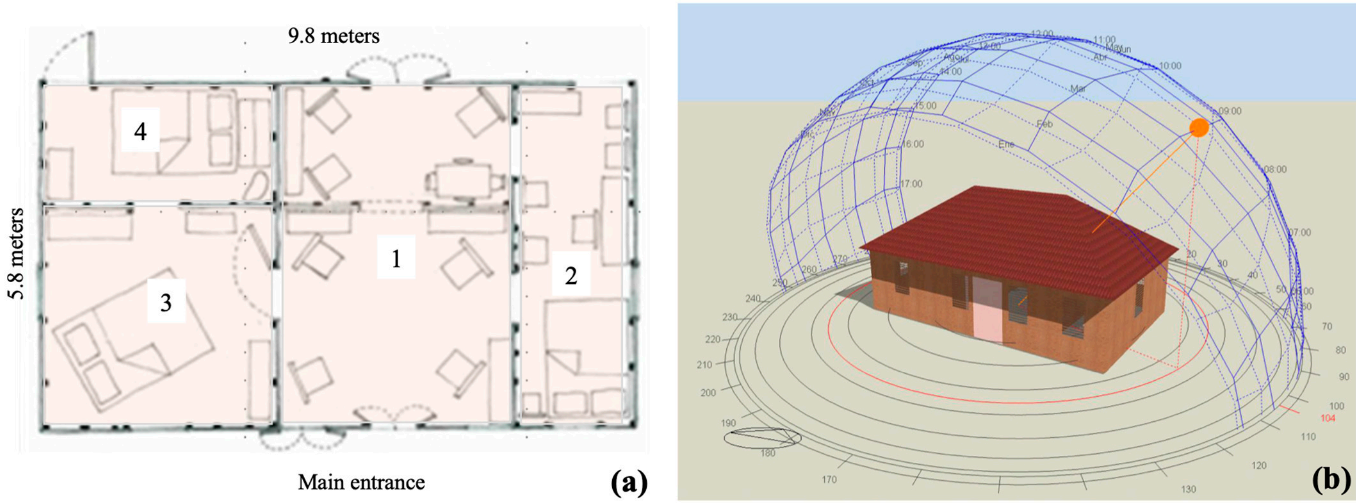


Figure 4. (**a**) Floor plant with the four thermal zones created for the model; (**b**) isometric of the model.

The model of the bohio includes the following construction systems: the roof is made of cana palm leaves, which has a thermal transmittance of 0.198 W/m^2·K; the walls are made of real palm board with a thermal transmittance of 3.633 W/m^2·K; and the floor is made of polished cement, which has a thermal transmittance of 4.392 W/m^2·K. The doors and windows are made of wood, the latter being of the lattice type. Table 1 shows the thermal properties of the materials that make up the hut, indicating their thickness, conductivity, density and specific heat.

Table 1. Thermal properties of the materials [19,20].

	Thickness m	Material	λ Conductivity W/m·K	ρ Density Kg/m^3	Specific Heat J/kg·K
Roof	0.3	Exterior Cana palm leaves Interior Thermal transmittance (W/m^2·K): 0.198	0.061	148.30	1600
Walls	0.02	Exterior Palm sheet Interior Thermal transmittance (W/m^2·K): 3.633	0.19	700	2390
Floor	0.02	Polished cement Thermal transmittance (W/m^2·K): 4.392	1.13	2000	1000
Doors	0.025	Wood	0.19	700	2390
Windows	0.006	Wood	0.19	700	2390

2.4. Simulation

The software Design Builder v.5.0.2.3 [19] was used to carry out the simulations. This is a well-known and widely used tool in the development of environmental, energy and air movement simulations. This software allows dynamic simulations to be performed through the Energy Plus numerical engine [21]. In this study, Design Builder was used to generate indoor air temperatures, relative humidities, solar gains through windows, lighting consumption, and carbon dioxide emissions using 2002 meteorological data obtained from Meteonorm [22]. These variables will be presented for the annual cycle and for one day of a cold month (1 January) and for one day of a warm month (1 August). Meanwhile, to calculate the illuminance and daylight factor, the Radiance calculation engine was used, which provides multi-zone calculations of illuminance levels in the working surfaces of the building. The illuminance and daylight factor results will be presented for a day of a cold month (1 January at 10:00 am) and for a day of a warm month (1 August at 10:00 am).

The simulation was carried out as a passive, naturally ventilated system (no mechanical cooling). In addition, several authors [23–25] have reported on the validation of Design Builder for related studies. ASHRAE 55-2017 [26] was used to perform the simulations. It is important to point out that in the Dominican Republic, there is no standard for thermal comfort and daylight; in this context, the results for thermal comfort will be compared to ASHRAE 55-2017 [27] and those for daylighting will be compared to Leadership in Energy and Environmental Design (LEED) requirements [28]. The model was divided into individual areas called "zones". In total, four thermal zones were created: (1) living room, (2) bedroom 1, (3) bedroom 2, (4) bedroom 3 (Figure 4). These zones were configured according to the following parameters: activity, occupancy and lighting consumptions. The configurations of the thermal zones and daylight conditions are shown in Table 2.

Table 2. Model configuration.

Zone's Properties	Description
Standard	ASHRAE 55-2017
Zone	1A
Activity	Residential
Surface	56.84 m^2
Occupation	5 people
Occupational density	0.088 people/m^2
Occupational programming	Weekdays: 18:00 h–7:30 h./Weekends: 24 h.
Summer clothing	0.50 clo
Interior doors	Openings: 100% open, 66% of the day
Windows	Louvered wood. Opening area: 80%
Lighting	5 W/m^2–100 lux
Sky conditions	1-CIE clear sunny day
Height working plane	0.75 m

3. Results and Discussion

3.1. Air Temperature

Figure 5 shows the comparison of the indoor and outdoor ambient temperature of the bohio for one year. The indoor temperature remains below the outdoor temperature throughout the year, with a smaller difference in the cold months and a greater difference in the warm months, which means that the indoor temperature remains in a comfortable range, between 23 °C and 25 °C, considering that the temperature can fluctuate between approximately 19.44 °C and 27.77 °C according to ASHRAE 55-2017 for optimal thermal comfort of building occupants. The greatest difference between the two temperatures was 1.43 °C in January and 3.44 °C in August, while the average over the annual cycle was 2.47 °C. This behavior is due to the cross-ventilation that occurs in the bohio, in addition to the cana palm leaf roof, which allows the interior to maintain a cooler temperature. This vegetal roof works as a natural insulation system, regulating and reducing the ambient temperature, improving indoor comfort for the occupants. It is important to note that in tropical climates, indoor thermal comfort is highly dependent on natural ventilation and passive cooling systems [12].

Figure 6a shows the indoor and outdoor air temperature for a day in January and Figure 6b shows a day in August. From sunrise, both temperatures start to increase until sunset, when the temperatures start to decrease, as expected. The highest difference between the two temperatures on the cold-month day was 4.71 °C; the lowest was 2.52 °C, while the average was 3.87 °C. In the case of a warm-month day, the largest temperature difference was 4.22 °C, the smallest was 1.72 °C and the average was 3.06 °C.

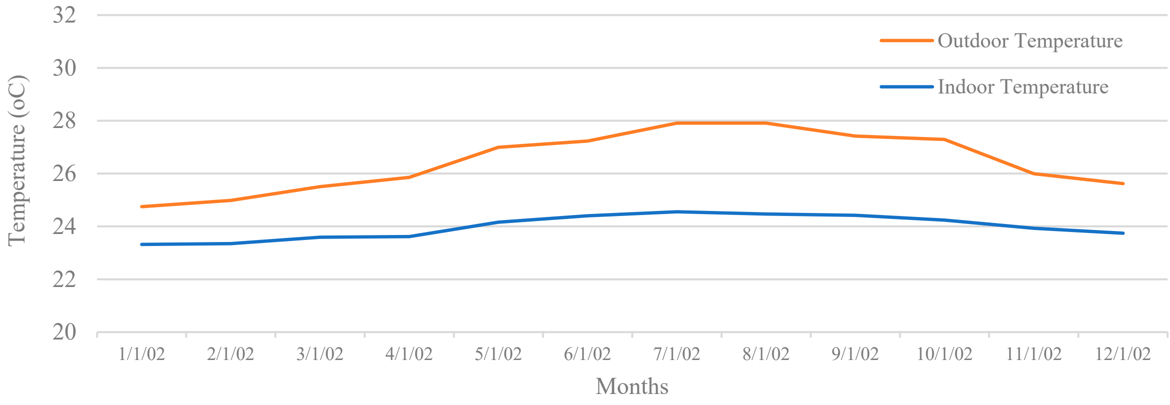


Figure 5. Yearly ambient temperature.

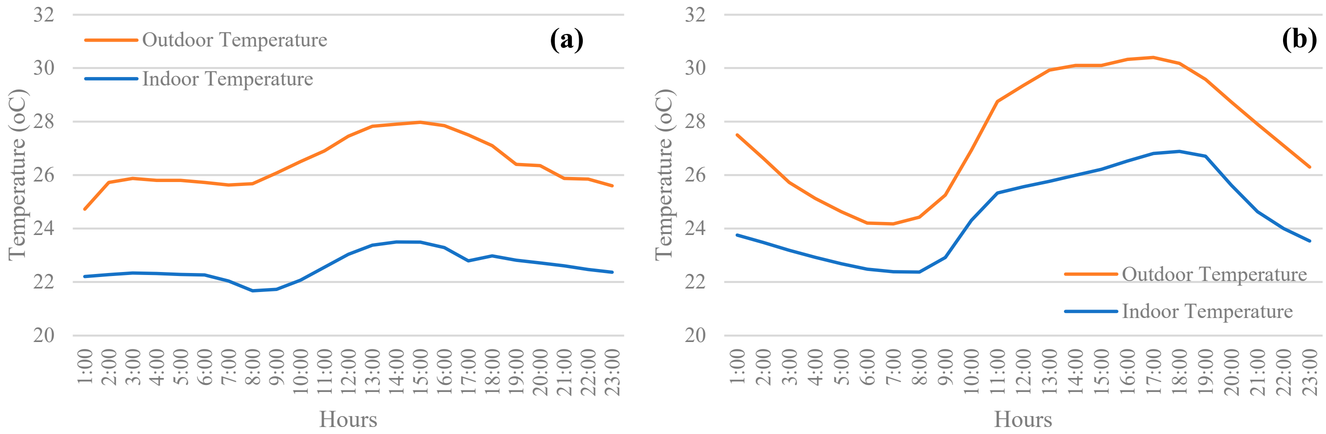


Figure 6. (**a**) Daily air temperature of a day in January (cold month) and (**b**) August (warm month).

Similar studies confirm this behavior, such as the case of a hot and humid region of China where vernacular dwellings showed thermal stability, especially during nighttime [4]. Also, during summer in cold regions of China, the average indoor temperature is much lower than the average outdoor temperature [5]. Meanwhile, in an extreme climate in Iran during summer, the average indoor temperature with vernacular techniques was lower than that of a space without vernacular techniques [6]. Also, in vernacular houses in India, Portugal and China, the indoor temperatures remain lower than outdoor temperatures during the summer season, providing comfort for the occupants [3,7,10].

3.2. Relative Humidity

Figure 7 shows the relative humidity inside the bohio throughout the annual cycle, where it can be observed that from March to September, it increases with the passing of the months, and in September, the humidity inside the bohio begins to decrease. The highest percentage of relative humidity was 95.63% and occurred in September, while the lowest humidity was in January and was 89.49%, with an average of 92.79%. It is important to note that in the bohio, being located in a tropical climate, the humidity throughout the year is generally high. This behavior was also confirmed in a study conducted in a hot and humid region of China, where the relative humidity in the vernacular dwelling was significantly higher than the recommended comfort range of 40–60% [4]. Additionally, this type of house is optimal for a warm tropical Caribbean climate, since the vegetal roof forms an "air cushion" that does not let heat pass through via conduction and the palm board walls let air currents pass through, changing the interior environment. This behavior keeps the bohio very cool even when there is sun or humidity.

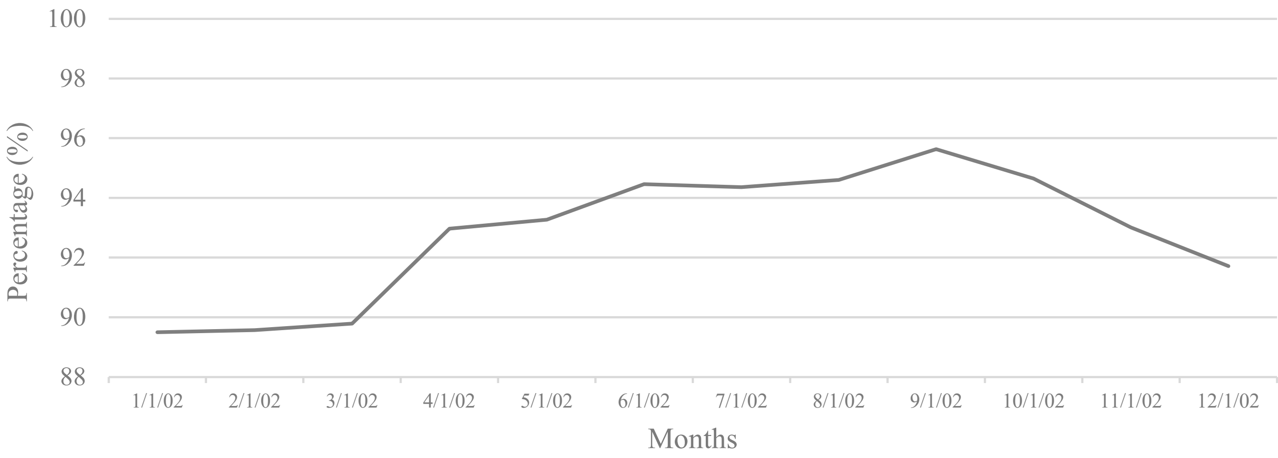


Figure 7. Yearly indoor relative humidity.

Figure 8a shows the indoor relative humidity for a day in January and Figure 8b shows that for a day in August. It can be observed that on a cold day, the humidity starts to decrease at around 8:00 h until 13:00 h, reaching almost 94%, and then it starts to increase until it reaches 100%, while in the case of a warm day, the humidity starts to decrease at 8:00 h and then reaches 100% again around 21:00 h; in this period, the percentage drops to almost 90%. The average on the cold day was 99.34%, while on the warm day it was 96.58%.

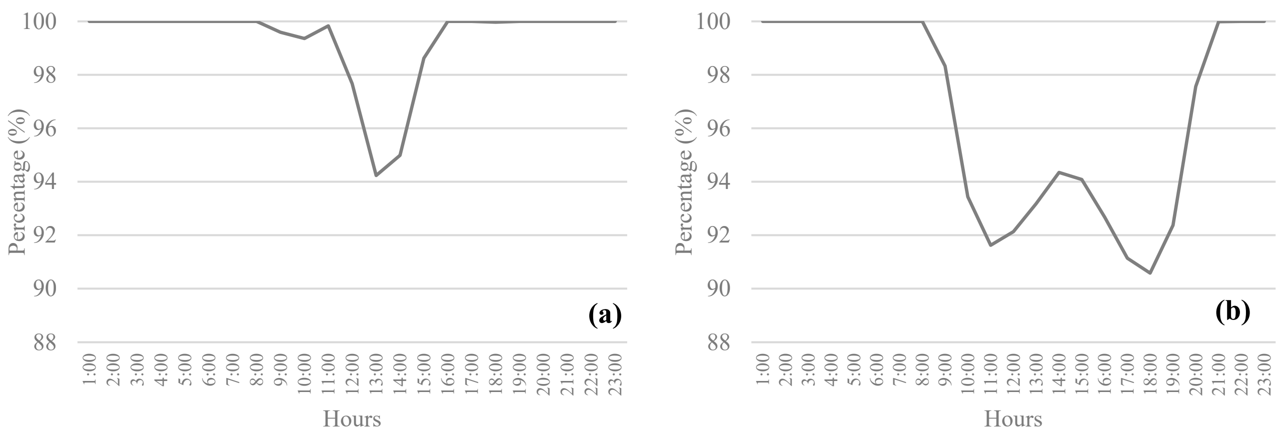


Figure 8. (**a**) Indoor daily relative humidity of a day in January (cold month) and (**b**) August (warm month).

3.3. Solar Gain through Exterior Windows

Figure 9 presents the yearly solar gain through exterior windows inside the bohio. It can be observed that in the warmest months (from March to October), the gains fluctuate between approximately 275 kWh and 325 kWh; meanwhile, in the coldest months (from November to February), the solar gain increases from around 350 kWh to 400 kWh. The yearly average solar gain through exterior windows is 331.26 kWh. It can be observed that the impact of the external climate is significant, affecting the internal gains of the vernacular house as well as the indoor comfort. In this context, it is important to keep in mind that the increase in outdoor temperature due to climate change affects the indoor behavior of this type of housing, and the passive strategies currently implemented will probably have to be improved [12].

Figure 10a shows the solar gain through exterior windows for a day in January and Figure 10b shows that for a day in August. It can be observed that the solar gains during a day in January were produced from the first hours of the morning (8 h) and reached their highest value in the midday hours before decreasing until 18 h, with the maximum value reached being 0.52 kW. In comparison, on an August day, the solar gains are longer than in January, starting from 6 h to 20 h, reaching the highest value around 17 h with 1.27 kW.

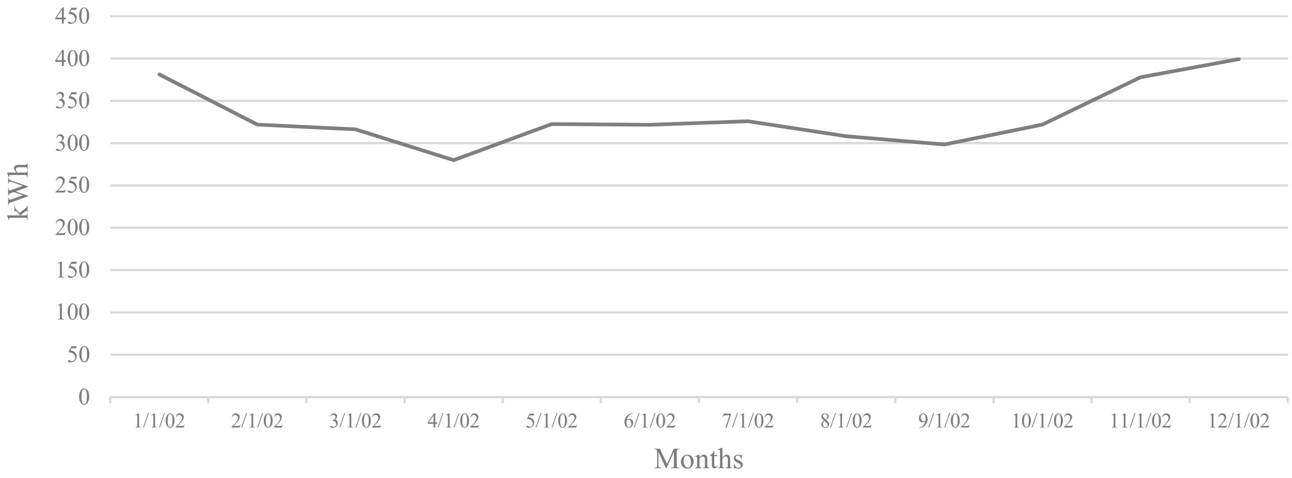


Figure 9. Yearly solar gain through exterior windows.

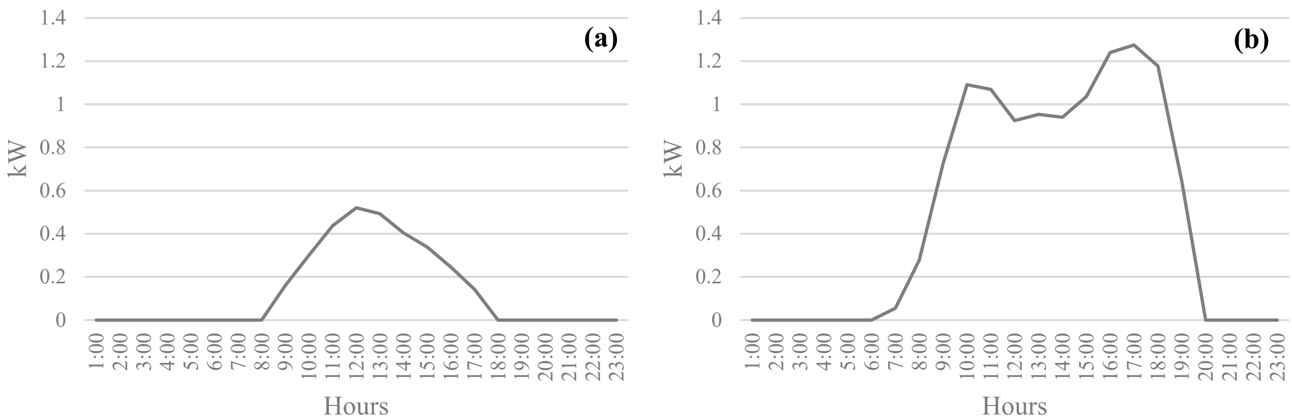


Figure 10. (**a**) Daily solar gain exterior through windows of a day in January (cold month) and (**b**) August (warm month).

3.4. Illuminance and Daylight Factor

Figure 11 presents the illuminance (LUX) and the percentage of daylight factor (FLD) map which shows the distribution of daylight levels available inside the bohio, according to the sky conditions set (in this case, clear sky). The minimum illuminance level presented in zone 1 was 101.91 lux; that of zone 2 was 64.71 lux; that of zone 3 was 121.61 lux; and that of zone 4 was 46.9 lux; the total average was 83.78 lux, which, for almost all the zones, is a value below the suggested minimum (108 lux) recommended by Leadership in Energy and Environmental Design (LEED). Meanwhile, the maximum illuminance level obtained in zone 1 was 36,176.33 lux; that in zone 2 was 803.12 lux; that in zone 3 was 17,635.26 lux; and that in zone 4 was 17,687.22 lux, with the total average being 18,075.48 lux. This behavior could be due to the few openings to the outside and to the compact typology of the bohio. In addition, it is important to point out that by extending the entrance of natural light into the vernacular house, the indoor temperature could increase, since Bani is in a hot climate and the sun's rays are very intense. Similar performance was obtained in vernacular housing in Ecuador, where some indoor spaces presented insufficient levels of natural light with levels between 42 lx and 250 lx [8]. Also, in the vernacular houses located in Sub-Saharan Africa, the amount of daylight inside was small or very small due to the presence of small windows partially covered with shutters [9].

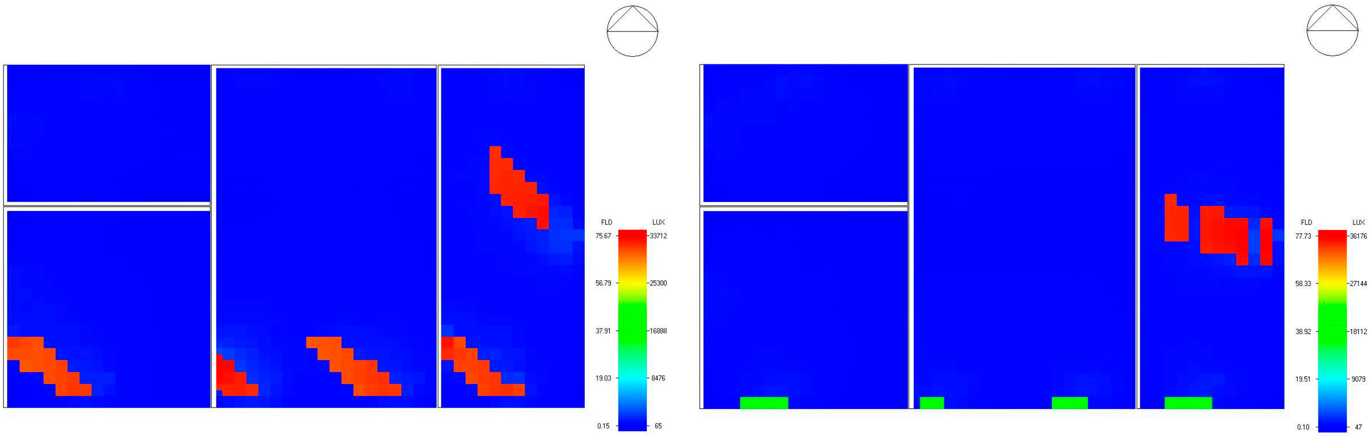


Figure 11. Left image: illuminance and daylight factor of a day in January—cold month; **right** image: August—warm month.

In the case of the daylight factor, the minimum percentage obtained in zone 1 was 0.22%; that in zone 2 was 0.14%; that in zone 3 was 0.26%; and that in zone 4 was 0.1%, with the total average being 0.18%. In comparison, the maximum percentage of daylight factor in zone 1 was 77.77%; that in zone 2 was 1.73%; that in zone 3 was 37.93%; and that in zone 4 was 38.03%, with 38.87% being the total average. In the study conducted in Ecuador, the daylight factor ranged from 0.5% to 1.5%, confirming the need to improve natural light in vernacular housing [8].

3.5. Lighting Consumption

The few openings to the outside and the compact typology of the bohio did not allow the minimum illuminance levels in the interior to be reached, which led to the use of electric lighting. In this context, Figure 12 shows the yearly lighting consumption in the bohio. It can be observed that throughout the year, lighting consumption fluctuates from around 195 kWh to 220 kWh, with the lowest value in February and the highest value in December. In the other months, lighting consumption is more stable. The yearly average presented was 210.37 kWh. This consumption can be reduced by replacing the type of windows used in the bohio with ones that allow in more natural light.

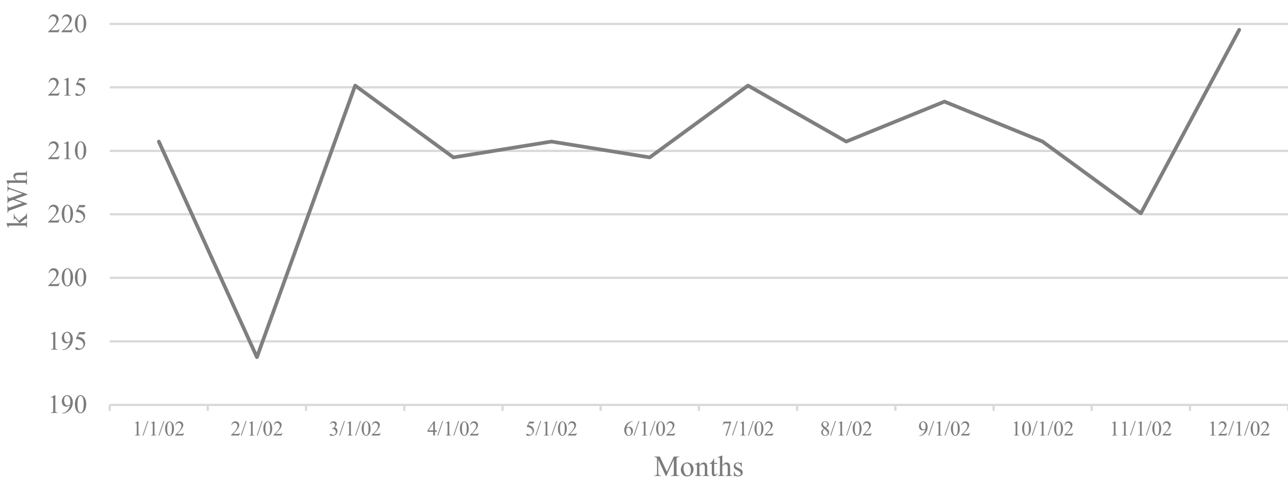


Figure 12. Yearly lighting consumption in the bohio.

In the case of Figure 13a,b, on days in cold and warm months, the lighting consumption obtained was the same for both months due to the same lighting demand. The maximum value reached was 0.42 kW and was presented in January from 17 h to 8 h, while in August, it was from 18 h to 9 h.

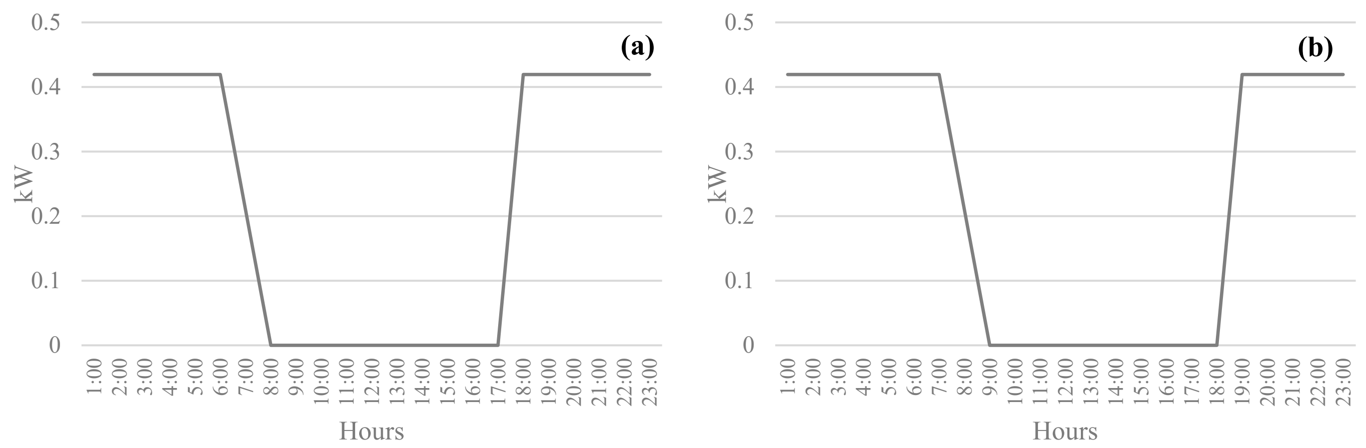


Figure 13. (**a**) Daily lighting consumption of a day in January (cold month) and (**b**) August (warm month).

3.6. Carbon Dioxide Emissions

Carbon dioxide emissions have been produced due to energy consumption for electric lighting in the bohio. In this context, Figure 14 shows the yearly carbon dioxide emissions of the vernacular house. The behavioral pattern of CO_2 emissions follows the same behavior of the lighting consumption because it is the only energized element in the bohio. The range of annual CO_2 emissions goes from 117 kg to 133 kg, with the lowest value occurring in February and the highest in December. These emissions can be reduced by improving the entrance of natural light into the vernacular dwelling and ensuring minimum illuminance levels.

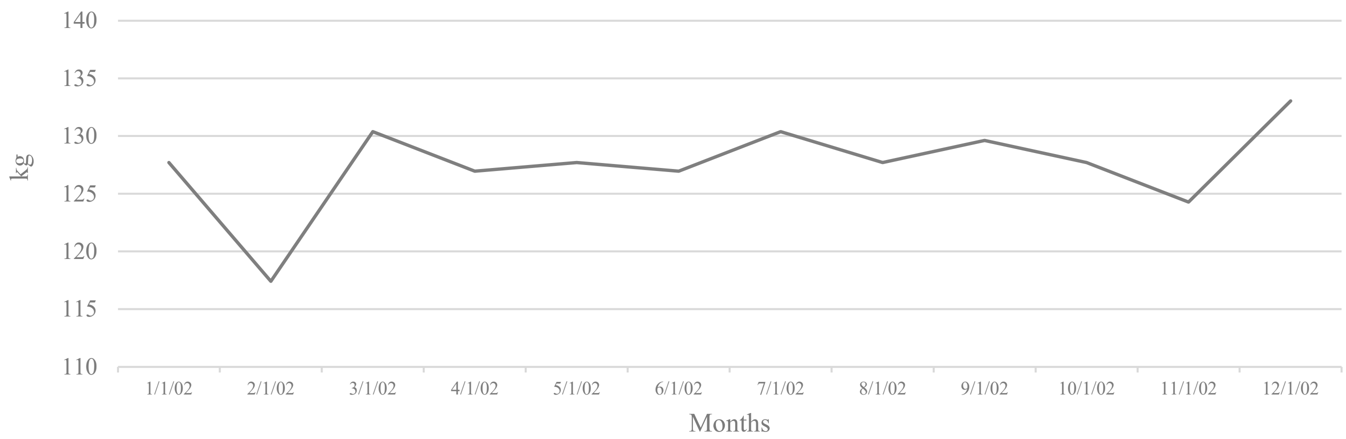


Figure 14. Yearly carbon dioxide emissions.

Figure 15a,b show the daily carbon dioxide emissions of a day in January (cold month) and August (warm month). Both graphs show the same pattern of performance following the behavior of lighting consumption. The maximum value obtained for CO_2 emissions for one day was 0.25 kg.

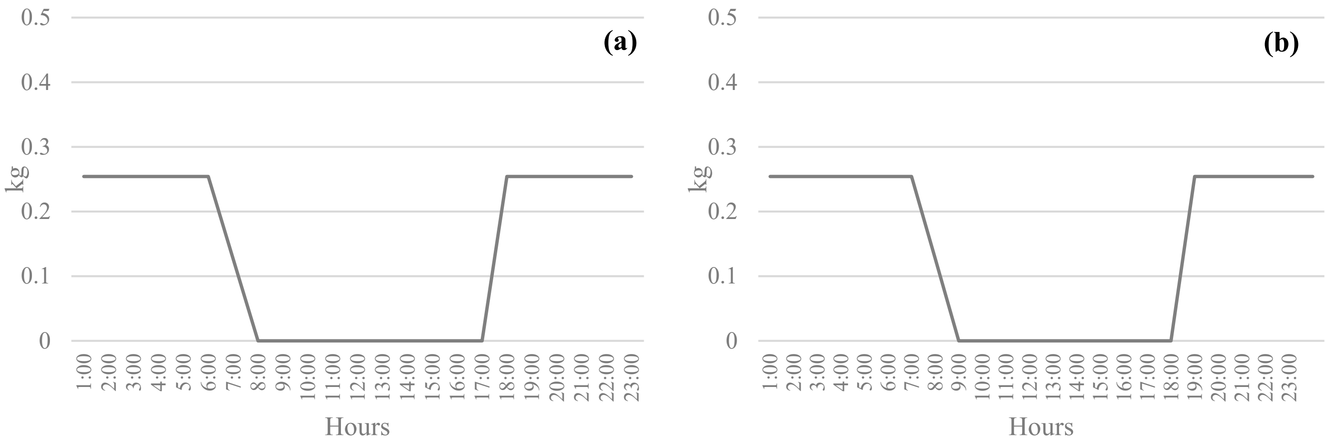


Figure 15. (**a**) Daily carbon dioxide emissions of a day in January (cold month) and (**b**) August (warm month).

4. Conclusions

The objective of this research was to evaluate the thermal performance of a vernacular house located in Villa Sombrero, Peravia Province, Dominican Republic, to characterize its behavior and to respond to the lack of research on vernacular houses in the Caribbean. For this purpose, a model of a bohio was simulated using the Design Builder software during an annual cycle.

The main finding is the indoor ambient temperature is maintained in a comfortable range between 23 °C and 25 °C throughout the year, demonstrating that the passive strategies implemented in the vernacular dwelling, such as natural ventilation and roof shading, work correctly, since there is no need to implement air conditioning systems. The greatest difference was 1.43 °C and 3.44 °C with respect to the outside temperature in the coldest and warmest month, respectively. With respect to indoor relative humidity, it was observed that from March to September, it increases with the passing of the months, presenting an annual average of 92.79%.

It was confirmed that the highest solar gain through exterior windows occurs in the warmer months, as expected. Additionally, lighting consumption varies between approximately 195 kWh and 220 kWh, with a more stable behavior during the middle months of the year. CO_2 emissions followed the same behavior as lighting consumption since it was the only energized element in the bohio. The minimum illumination values obtained in all the zones of the bohio were lower than the suggested minimum, which does not correspond to the current standard of living, and the occupants should limit certain activities indoors. Therefore, the occupants have chosen to use electric lighting during some hours of the day, increasing their energy bills.

Among the limitations of this paper are the fact that due to the version of Design Builder software used, it was not possible to calculate the annual Spatial Daylight Autonomy (sDA) or the Useful Daylight Illuminance (UDI), presenting data only for a cold day and a warm day. Thus, the illuminance and daylight factor results cannot be generalized to the annual cycle. Also, since the vernacular house is located in a tropical climate, the results can serve as a reference for similar climates but not for other latitudes and different climatic conditions.

The findings of this research help to supplement the lack of studies on vernacular dwellings in tropical climates and confirms that the passive strategies incorporated in the bohio maintain the interior comfort of the users, with the exception of natural light. These passive strategies, especially cross-ventilation and roof shading, should be mandatory in the design of new buildings to maintain indoor comfort without contributing to energy cost, especially in buildings located in tropical climates. However, the research presented in this paper can be further developed by performing additional simulations in other locations and monitoring over an annual cycle to compare results and validate the model. In addition, it is important to conduct additional research on this type of architecture, taking into account the future climate scenario to validate if current passive strategies maintain indoor comfort or need to be improved.

Furthermore, the results of this research serve to establish baselines for current sustainable housing based on the implementation of passive design strategies to create resilient housing adapted to local climatic conditions.

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