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Hydrothermal Evaluation of Vernacular Housing: Comparing Case Studies of Waste PET Bottles, Stone, and Adobe Houses

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Abstract: This work shows the humidity and thermal evaluation of different case studies of houses. The analyses focused on room prototypes and houses built in different regions of Querétaro, México. Three different climatic zones were included with the evaluations of houses and prototypes. The assessments of internal and external parameters in residential buildings are also shown. The internal parameter measurements were done with hydro-thermometers and thermography images. Six structures were evaluated, one of the conventional housing materials and five of alternative or vernacular materials. The predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) were determined using the average temperature and relative humidity values, and they were considered to be dynamic because they can change depending on many factors. The six dwelling insulating properties were associated with their construction materials, design, location, and other factors. The six houses have many differences, but considering their behavior in their location, the two floor porous stone house got the best results. On the contrary, the flagstone house with a gabled roof of galvanized sheets had a cold perception despite many advantageous elements, failing to provide comfort in such a cold location. Contrasting these with other adobe constructions, the analyzed one had low thermal insulation, which was explained by its characteristics. PET and adobe uninhabited prototypes had medium to cold perceptions. The PET prototype has excellent and adjustable insulations, both on temperature and RH, considering the passive illumination and ventilation of its glass bottle skylights.

Keywords: concrete; mortar; PET; reuse; waste treatment; sustainability; rural

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1. Introduction

Housing is one of the primary needs of human beings, and, at present, locally and worldwide, it is a pressing need that is directly associated with population growth. The construction of comfortable housing today is a human need that is not satisfied with the pace of population growth and affects the environment through the building of new urban developments. It is also a problem with high ecological impact, both because of the occupation of land for housing developments and because of the use of large amounts of construction materials, in addition to the direct and indirect impact of their extraction, processing, and transportation of construction materials [1].

It is undeniable that the problems generated by population growth are corrective and non-preventive. These bring other inherent problems, such as the need for food, water, and energy supply, with the consequent contamination of air, water, and soil. It is increasingly becoming an individual and collective obligation that each home takes environmental considerations into account, and this is not just a luxury reserved for those who can afford it and want to pay for it. There is a high lag in the supply of comfortable and secure housing, and those constructed are not consistent with the care of the environment necessary for sustainability.

The construction industry is one of the driving forces of the world's and the country's economy. Construction is a necessary daily activity for the people and the economy. The goal of construction is to build with environmental responsibility, sustainability, dignifying housing, reducing costs, and to build homes that are affordable for everybody [2–5].

Currently, there is a progressively growing interest in the society that new constructions, and ideally pre-existing ones, increase their degree of sustainability in the three stages: throughout construction, inhabitation, and demolition. Sustainability and the circular economy converge in construction from the environmental, economic, and social dimensions of buildings up to the model of production and consumption [6]. Buildings and construction materials involve, along their lifecycle, making, using, repairing, reusing, and recycling as many times as possible.

From large buildings, especially in developed countries, to houses of social interest, to a greater or lesser extent, seek to incorporate practices and materials considered sustainable [3,4]. Among these, there are countless construction materials, such as bamboo [7], polyethylene terephthalate (PET) bottles [8], adobe [9], fly ash [10,11], recycled wood [12], rice husks [13], straw bales [14,15], date palm [16], soil as solid rammed earth walls [17], hemp [18], rocks in the surroundings of the construction site [19–21], and others.

Incorporating the term "sustainable" in industrialized housing construction is currently desirable. However, it is arbitrarily used and there is no estimation of the actual degree of sustainability. An emerging societal goal seeks to identify and improve practices that quantify the degree of sustainability that has a construction [4,22]. There are sustainability indicators established in various building environmental certifications, such as the methodology used by LEED (Leadership in Energy and Environmental Design), which is highly recognized and implemented for buildings [23,24]. According to the score obtained in the LEED rating system, four levels of construction certification are offered and they are certified, silver, gold, and platinum [25]. The Green Building Council (USGBC) evaluates five green design categories: sustainable sites, water, energy and atmosphere efficiency, quality indoor and environmental materials, and resources [26]. Other certifications, such as BREEAM® (Building Research Establishment Environmental Assessment Methodology) and WELL consider the inhabitant's health and well-being [6].

LEED emerged in 1994 to provide a set of standards for green construction. LEED has grown to encompass over 6000 projects in 28 countries, covering one billion square feet of the development area. The hallmark of LEED is that it is an open and transparent process where the technical criteria proposed by the LEED committees are publicly reviewed for approval by the more than 8500 member organizations that currently make up the USGBC [27,28].

Nowadays, the serial construction of houses prevails with prefabricated and cheap materials. Various housing developments opt for this idea without considering the drawbacks of this type of construction since construction materials are used interchangeably in different regions, causing contrasts and extreme temperatures inside the dwelling. This type of analysis inside and outside the house observes different thermal insulation [29] depending, among other factors, on the wall thickness and the construction materials, such as waste concrete [11], fly ash [11], straw bale [14,15], date palm [16], solid rammed earthwalls [17], hemp [18], and so forth.

When talking about thermal comfort, after temperature, a second factor needs to be considered: relative humidity (RH). The RH influences the interior thermal behavior. Usually, there is low relative humidity at high temperatures and vice versa, which occurs in non-extreme climates or away from the coastline. A series of studies have been done to link these two factors with the construction materials and the external environment [16].

P.O. Fanger proposed one of the most widely used methods today for measuring thermal comfort, now registered in ISO 7730:2005 [30,31]. The following parameters are considered in the proposed equation: clothing, metabolic rate, air temperature, average radiant temperature, relative airspeed, relative humidity, or the partial pressure of water vapor. With this, the indices of estimated average vote (PMV-predicted mean vote) and percentage of dissatisfied people (PPD-predicted percentage dissatisfied) were established [31].

In this work, some parameters (mainly hygrothermal) were evaluated in prototypes and dwellings that integrate some sustainable features. These consist of new prototypes and traditional or vernacular dwellings [32–40]. The objectives of this work include evaluating the thermal and RH performances of these constructions in three different weather conditions and considering the marked differences in building materials. The evaluation of their PMV and PPD indices considers their specific characteristics, without or with inhabitants. Some of these constructions are vernacular homes with inhabitants for many years, facing extreme weather conditions. The research aims to show how these cases behave in temperature and relative humidity in view of the materials in roofs and walls and their designs. Sustainability as well as the circular economy are important, but the ulterior purpose of dwellings is to offer shelter, health, and comfort to the inhabitants. This comparative study aims to demonstrate this point.

2. Materials and Methods

The temperature and humidity measurement was carried out with *Thermotracker*® brand sensors, an internal sensor installed inside the prototypes and a reference sensor located in the area surrounding the prototypes. The only restriction was to avoid direct solar radiation to any of the sensors since this alters the results. This restriction did not affect the results, it only avoided recording data related to heating the sensors.

Records of an annual cycle were taken and the results were subsequently interpreted with the help of the *Thermotracker Pro 2.0 software* (Creator: José Ismael Beltrán Zamora, Culiacan, Sinaloa, México).

Thermographic images were taken with the PCE-TC 3 thermal imager, which shows contrasts in temperature and the behavior of the materials used. Thermographs show the maximum temperatures reached externally on walls. These were taken at peak hours of heat concentration, that is, between 12:00 p.m. and 3:00 p.m.

The absolute humidity on the surface was carried out with the absolute humidity meter from the PCE brand, model WP21 (PCE Ibérica S.L., Tobarra, Albacete, Spain). Measurements were taken on the external walls of the prototype, the upper, lower, central, and lateral parts, with a distance of 50 cm between each one.

2.1. Prototype of PET

The prototype built with PET bottles is in *CIDETEQ S.C.*, in *Sanfandila*, *Pedro Escobedo*, *Querétaro*, *México* and the coordinates of the site are $+20°29'26.78''$, $-100°13'19.98''$. The foundations were built conventionally. PET bottles filled with earth from the site were used. These bottles had a horizontal arrangement in the construction. Mortar and cement were applied to stack them using a metallic mesh formwork. They were then hammered traditionally and finished with marble.

Galvanized sheets were placed in the upper part to condition a green roof. After the sheet layer, the construction waste materials were used, such as cardboard for the material packages, empty and open PET bottles, plastic bags, and the site's soil was placed on top. This soil came from the scratched foundations.

The walls were 33 cm thick and the construction dimensions were 3 m wide $\times$ 3 m long, which gave an internal height of 2.45 m and an external height of 3.15 m. It has an 83 cm high $\times$ 93 cm long window on its right front. The left front side has a 2.14 m high $\times$ 60.5 cm wide door. The prototype has three rows of skylights located at a height of 1.95 m. These skylights were situated on the left, rear, and right sides of the building. The primary characteristic of the skylights is that they were made of waste glass bottles, which were upcycled as a skylight product. They have a thickness of 7 cm.

In the case of PET, its recycling involves mixing with pure materials since its polymer chains are broken in the recycling process, and mixing with new PET is necessary. Mixing PET and melting it again involves an energy expenditure that leads to an economic expense. It was decided to use the entire waste PET bottles to avoid this problem [8]. Figure 1(a1,a2,a3) show the PET prototype in three different views.

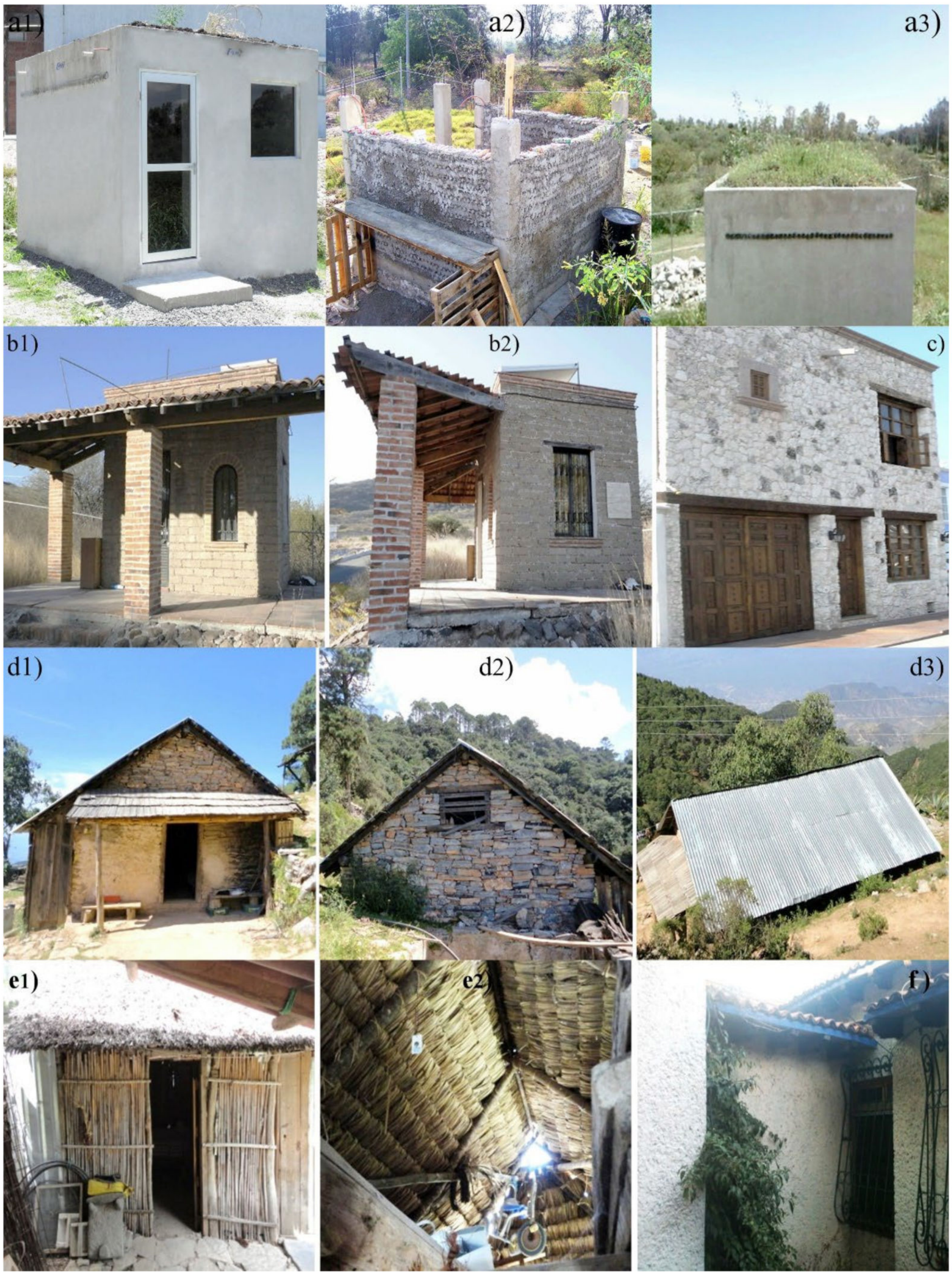

Figure 1. Images of the studied constructions. (**a**) Waste PET bottles prototype in three different views (**a1**) façade view and right side, (**a2**) rearview and left side during the construction stage, and (**a3**) green roof view. (**b**) Photographs of the adobe prototype, (**b1**) front and (**b2**) side views. (**c**) Façade of the house built with porous stones from the *Peña de Bernal* region. (**d**) Flagstone country house located on the slopes of a hill, (**d1**) front view, (**d2**) rearview, (**d3**) rooftop view. (**e**) Bamboo and date palm leaves-thatched roof construction, (**e1**) front view, (**e2**) internal view of the roof. (**f**) Red bricks and cement urban house used as a reference.

2.2. Adobe Prototype

The adobe construction was carried out in *CINVESTAV-Unidad Querétaro* (Figure 1b1,b2). The coordinates of the location are +20°43′36.98″, −100°20′11.36″. The adobe used has different characteristics since it was reinforced with polymeric resins. Its thermal conductivity was approximately 0.6 W/m °C, and the blocks used had a resistance of about 47.54 kg/cm^2. The dimensions of the room were a height of 3.13 m, and the front of the building was 3.30 m wide and 3.75 m long. The building has a vaulted ceiling with fired red bricks.

The blocks used have a dimension of 35.5 cm long, 23.5 cm wide, and 10 cm high. It has a front window located on the left side of 52 cm × 115 cm. There is another window on the right side of the building, measuring 95 cm × 142 cm. The door was made of aluminum at the bottom and glass at the top and measures 0.93 m wide × 2.13 m in high. The construction has a brick dome in the central part. The upper part was built with an adobe base like the rest of the building. Figure 1b1,b2 shows the adobe prototype, façade, and side views.

2.3. Porous Stone House

The house is located at the following coordinates +20°35′20.26″, −100°24′56.15″. It is a house built of porous yellow stones. The stone was extracted from the region of the monolith that is called "*Peña de Bernal*". It is a two-floor house having a ceiling height of about 2.40 m. The width of the walls is 0.4 m on all walls. It should be noted that the stone is also used inside the house, not only on the façade. The doors and windows are made of wood. The roof was built on a cement basis. Figure 1c shows the type of stone used in construction and the house's façade can be seen in the same image.

2.4. Other Buildings

Three other houses were monitored, which were (a) a flagstone house with a gabled roof (Figure 1d1–d3); (b) a house of bamboo and a date palm leaves-thatched roof (Figure 1e1,e2); (c) housing built with conventional materials (Figure 1f). In the case of Figure 1f, used as a reference, this house was within the urban area. Consequently, it is in a block with other houses around its three sides with the façade towards the street.

The flagstone country house is located on the slopes of a hill (Figure 1d1–d3) and it has a gabled galvanized sheet roof [41,42]. This construction is located in the community of "*La Barranca*", in the municipality of *Pinal de Amoles*, *Querétaro*, *México*. In this mountainous area, low temperatures and high humidity prevail. The coordinates of the site are +21°8′42.01″, −99°38′52.81″. The construction was of flagstone stone [43–47]. The walls are 55 cm wide and the ceiling height is 1.87 m. The front of the house is 4 m high and the length is 5.4 m. The construction has a loft used as a cellar. The loft height to the ceiling is 1.5 m, giving a total height of 2.37 m. The gabled roof [48,49] was in two layers, the first layer had a material named "*tableta*" and the top layer consisted of galvanized sheets. In this construction, galvanized sheets were used because the local people are prohibited from using timber products because it is a natural reserve region of the biosphere. Also, they use an attic, locally named "*tapanco*" and "tejamanil", thin boards cut into strips that are placed as tiles on the shed over the door.

The house of bamboo and date palm leaves-thatched roof is located in the "*Sierra Gorda*" of Querétaro, at the entrance to the municipality of *Jalpan*. The coordinates of the site are +21°11′51.18″, −99°29′54.65″. It should be noted that it is a place where the jungle climate predominates, with high temperatures and high humidity. The construction was made with reed sticks between 3.5 and 4.5 cm in diameter. The dimensions of the house are 3 m wide by 3.5 m long. It has a height of 1.80 m to the loft and from the loft to the ceiling 1.2 m, giving a total of 3 m high. The photographs of the date palm leaves-thatched roof dwelling [50,51] are shown in Figure 1e1 (façade view) and Figure 1e2 (thatched roof, internal view).

A house built with conventional materials, such as red brick and cement, was evaluated for comparison. The housing built with conventional materials is located in the downtown area of Querétaro City, México, a few blocks from the stone house. Its coordinates are $+20°35'20.23''$, $-100°24'56.19''$. This house has a height of 3 m and it has a 120 m^2 area of construction on only one level.

3. Results

3.1. Measurement of Internal and External Parameters

3.1.1. PET Prototype

Temperature and humidity measurements were taken throughout an annual cycle (December to December). The sensors recorded these data every 20 min, and extreme daily temperature and humidity measurements were taken. There are 72 daily temperature and humidity measurements. Figure 2a shows the temperature results of the external and internal medium of the PET prototype over 365 days. The gray shadowed area represents the temperature results outside the construction and the black area shows the internal behavior of the prototype. This type of graphs is not analyzed with daily maximum and minimum points; therefore, the graphs present many fluctuations, which are not noise, but the temperature changes along the days and nights. It is important to note that to have a good analysis of the graphs and data shown, an exhaustive work of the data analyzed was carried out: four graphs, 72 data/day, 365 days, and there were duplicated sensors (hygrothermometers) in each room.

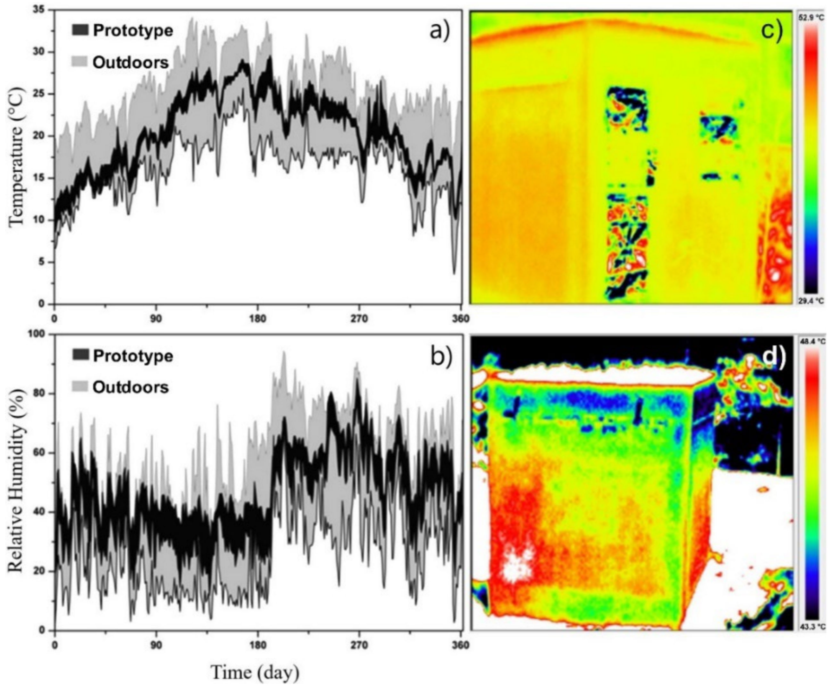

Figure 2. (**a**) Temperature and (**b**) relative humidity of the waste PET bottles prototype and outdoor environment. Thermographic images of the PET prototype showing (**c**) the right side and façade of the room and (**d**) the backside of the building.

The average daily temperature insulation inside the prototype was 8.08 °C. Regarding high thermal conditions, there was an insulation of 4.64 °C and, at low conditions, there was an average insulation of 3.44 °C. It is important to highlight the Gaussian behavior shown by the internal environment of the PET prototype in an annual cycle (Table 1), whose equation is Equation (1) (normal or Gaussian distribution function).

$$y = y_0 + \frac{A}{w\sqrt{\frac{\pi}{2}}} e^{-2\sqrt{\frac{x-x_c}{w}}} \quad (1)$$

where, y is the *y*-axis value (temperature, °C), x is the *x*-axis value (time, day), y_0 is the displacement from zero on the *y*-axis, w is the standard deviation, x_c is the mean, and A is a constant factor.

Table 1. Gaussian behavior parameters of the PET prototype.

	1	**2**	**3**	**4**
	P-T_{max}	**P-T_{min}**	**R-T_{min}**	**R-T_{min}**
y_0	7.03	5.43	17.17	−25.02
x_c	186.74	186.69	179.59	183.22
w	246.14	241.34	220.64	515.07
A	6076.7	5862.9	3528.1	28714.3
Area	7743.8	7028.1	9367.1	5799.4
Center (days)	182.8	183.0	180.3	181.6
Height (°C)	26.7	24.8	29.9	19.4

The areas for the maximum temperature of the prototype P-T_{max} (1) and the minimum temperature of P-T_{min} (2) were 7743.8 and 7028.1, respectively. Meanwhile, the maximum reference temperature P-T_{max} (3) behavior and the minimum temperature of P-T_{min} (4) were 9367.1 and 5799.4, respectively. The comparison can be made by subtracting these areas as (Zone 1–Zone 2) = 715.7 and (Area 3–Area 4) = 3567.7. Therefore, the ratio (1–2)/(3–4) = 0.2. This implies that the attenuation between fluctuations of the PET prototype and the external medium is approximately a fifth.

Figure 2b shows the PET prototype's relative humidity. Similar to the temperature graphs, the gray shadowed area represents the outdoors relative humidity and the black area represents the internal one. There was a difference of 9.27% humidity at high humidity conditions and a difference of 14.97% humidity in lower humidity environments, giving average insulation of 24.24% of relative humidity.

It should be noted that in the autumn-winter periods, the ventilation of the prototype was kept open. In spring-summer, the ventilation was closed to achieve extreme results in the internal environment. If ventilation had been reversed, an even more stable internal behavior could be expected.

Thermographic images were taken and a stable external behavior was observed in the different areas of the latter. In Figure 2c, a thermographic image of the front of the house and its left part is shown. The coldest parts represented with dark colors were the window and the glass part of the door. Aluminum foil was used on the glass to prevent the direct entry of solar radiation, maintaining the temperature on the external glass walls at around 47 °C. Figure 2d shows a thermographic image taken from the right, also showing the rear section of the prototype. The average temperature was observed at about 45 °C, similar to the front that received the most solar radiation. Some red and white spots with the highest temperatures can be seen in this image. This was because, in the construction stage, the materials of the coating mixture were different in that area. On the other hand, the green roof has a higher temperature, reaching 71 °C. It should be noted that these temperatures are superficial since very stable temperatures remained at around 25 °C, d inside the green roof. A thermography is shown in Figure 2d. Thermographs were taken in May, a hot month in the area. In this month, a maximum internal temperature of 30 °C was recorded. Then, isolation of about 15 °C from the external and internal walls can be assumed. Figure 2c,d shows the shape and parts of the prototype.

Figure 2d shows unevenness in the left lateral zone. A study of superficial humidity was carried out and it did not show any differences between the different zones of the prototype. Therefore, the temperature differences in this zone cannot be related to the superficial humidity of the prototype walls. The absolute humidities varied between 0.5% and 1.3%, which is not an alarming figure and does not indicate the influence of moisture on the temperature changes registered by thermography. Measurements were taken in constructions near the prototype, where the humidity varied between 4% and 13.5%. These figures if they could alter external temperature conditions in walls.

3.1.2. Adobe Prototype

Figure 3 shows the results regarding the adobe prototype. The adobe prototype had inadequate insulation at high temperatures, approximately 2.3 °C. At low ambient temperatures, better insulation was presented, around 5.3 °C, giving a total thermal insulation of 7.6 °C. The average temperature of the prototype was maintained between 15 and 25 °C (Figure 3a). The data in this figure were obtained from September to February.

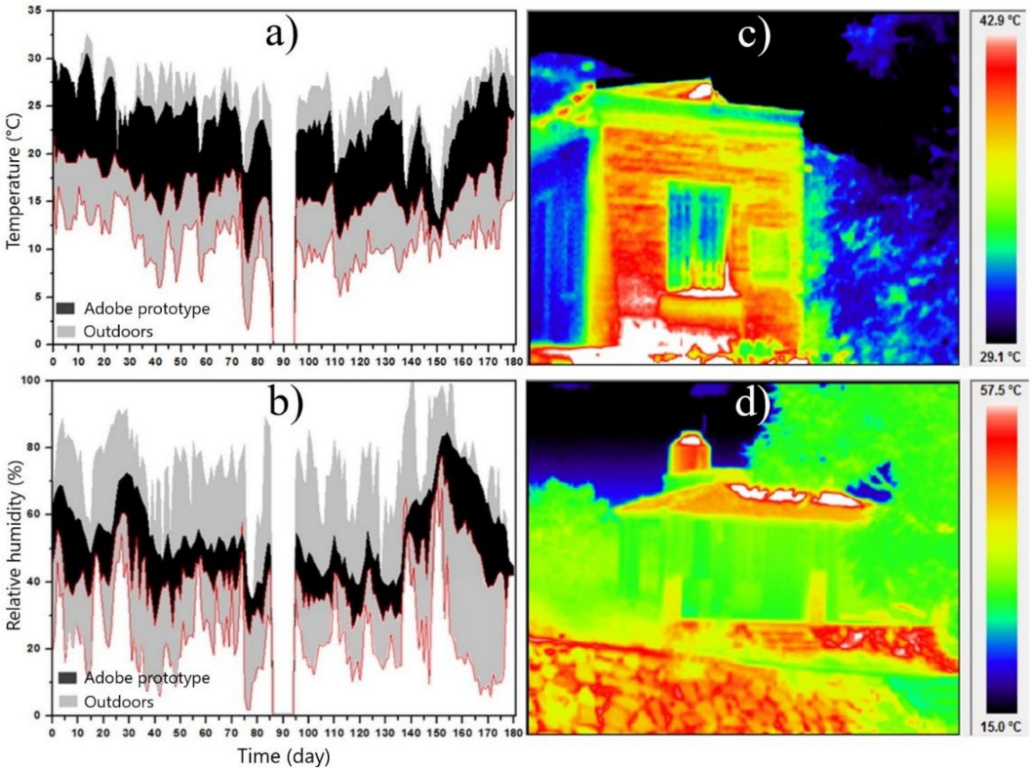

Figure 3. (**a**) Temperature and (**b**) relative humidity of the adobe prototype and outdoor environment. Thermographic images of the adobe prototype showing (**c**) the right side of the building, and (**d**) the facade of the building.

Figure 3b shows the Relative Humidity graph inside and outside the adobe prototype. Regarding relative humidity, a uniform behavior was observed. This was attributed to the self-regulating properties of adobe. Adobe is a material that has the characteristic of absorbing and returning moisture to the environment. An average humidity of 55% RH was maintained. The highest humidity registered was about 80% RH inside the prototype, while, at the time, total relative humidity (100% RH) was reached in the external environment. The lowest humidity recorded inside was 28% RH, while the external environment came to have only 5% RH.

Figure 3c shows a thermographic image of the south side of the adobe prototype. Figure 3d shows a thermography of the north side and façade. The right part of the image represents the front protected by the shed and did not directly receive solar radiation, therefore its lower temperature. The hottest parts in white represent the red tile roof covering the front of the construction. In these images, there were average wall temperatures of 38 and 40 °C, respectively.

3.1.3. Porous Stone House, Two-Floor

The stone house presented excellent thermal insulation in the evaluated period. The daily temperature variation inside the house is 2 °C. It was maintained between 17 and 24 °C from November to January. Outside the house, data of around 4 °C was recorded. These figures show this room's excellent insulation because of its materials and construction design. Figure 4a shows the graphs of the evaluated period.

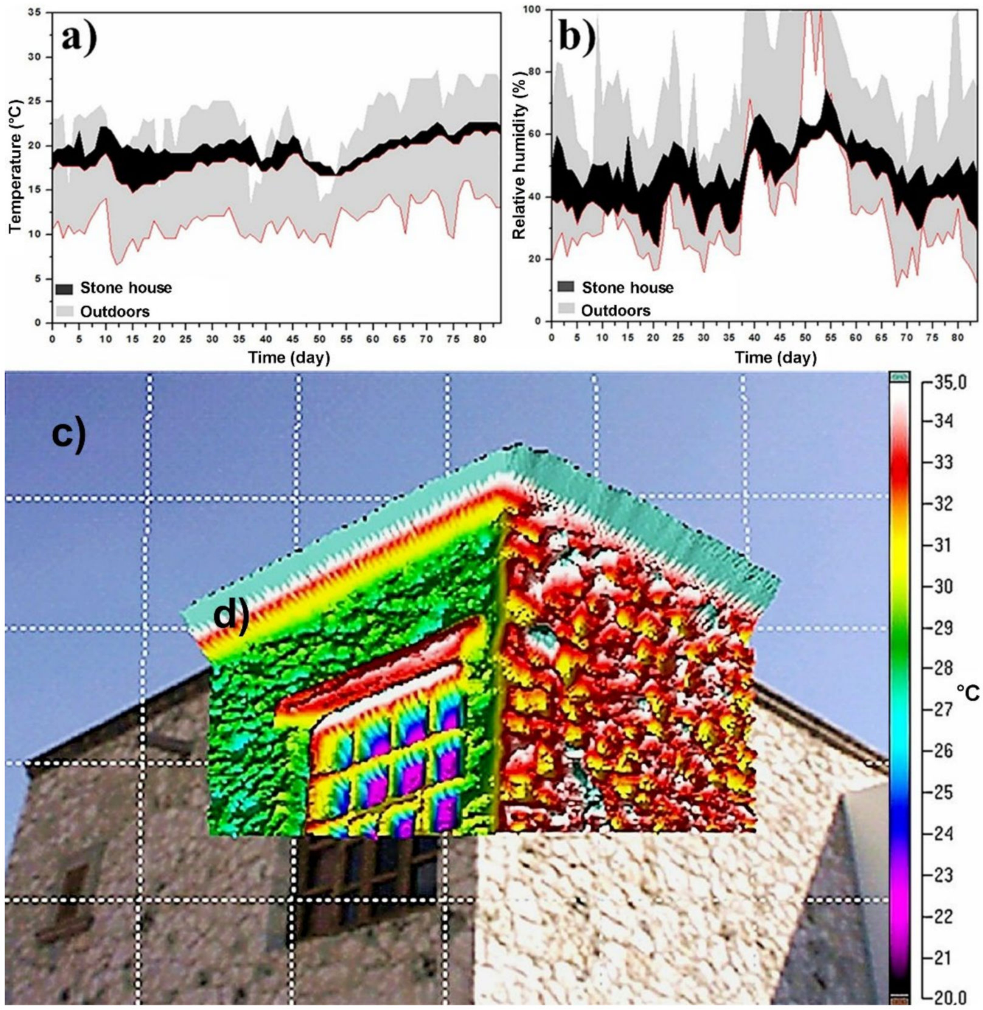

Figure 4. Quarterly graphs of the behavior of the stone house for (**a**) temperatures and (**b**) relative humidities. (**c**) Porous stone house, two-floor and (**d**) inserted thermographic image of the stone house.

The relative humidity in the stone house remained between 30 and 65% RH (Figure 4b); it showed excellent performance and insulation at high humidity, but at low humidity it has around 13% RH from the external environment. The recorded external humidity ranges between 15 and 99% RH. Figure 4b shows the previously mentioned behavior.

The thermographic image in Figure 4d shows the contrast between the surface of a side directly illuminated by sunlight and the shaded façade. Even under similar lighting conditions, there are some areas on each side with differences in temperature due to the topography and characteristics of the materials. The direct sunlight illuminated side shows surface temperatures between 30 and 35 °C. The façade without direct sunlight illuminated shows surface temperatures between 26 and 29 °C. These stones are porous and their behavior was a higher insulation effect.

3.1.4. Flagstone House with Loft

Figure 5 shows the graphs of temperature (Figure 5a), relative humidity (Figure 5b), and thermographies (Figure 5c,d). The house has a uniform thermal behavior, varying indoors by 5 °C on average, and maintains low but constant temperatures. It should be noted that it was a highly cold area with high relative humidity. The capping acts as a thermal damper, maintaining lower temperatures than the external environment in the case of high-temperature conditions and, in turn, higher at lower temperature conditions. In terms of humidity, the loft plays an inverse role to that observed in terms of heat, and it was expected so since these two factors usually maintain an inversely proportional relationship. The humidity kept in this house was not entirely suitable for a room, attributed mainly to the conditions of the area and the ventilation of the house.

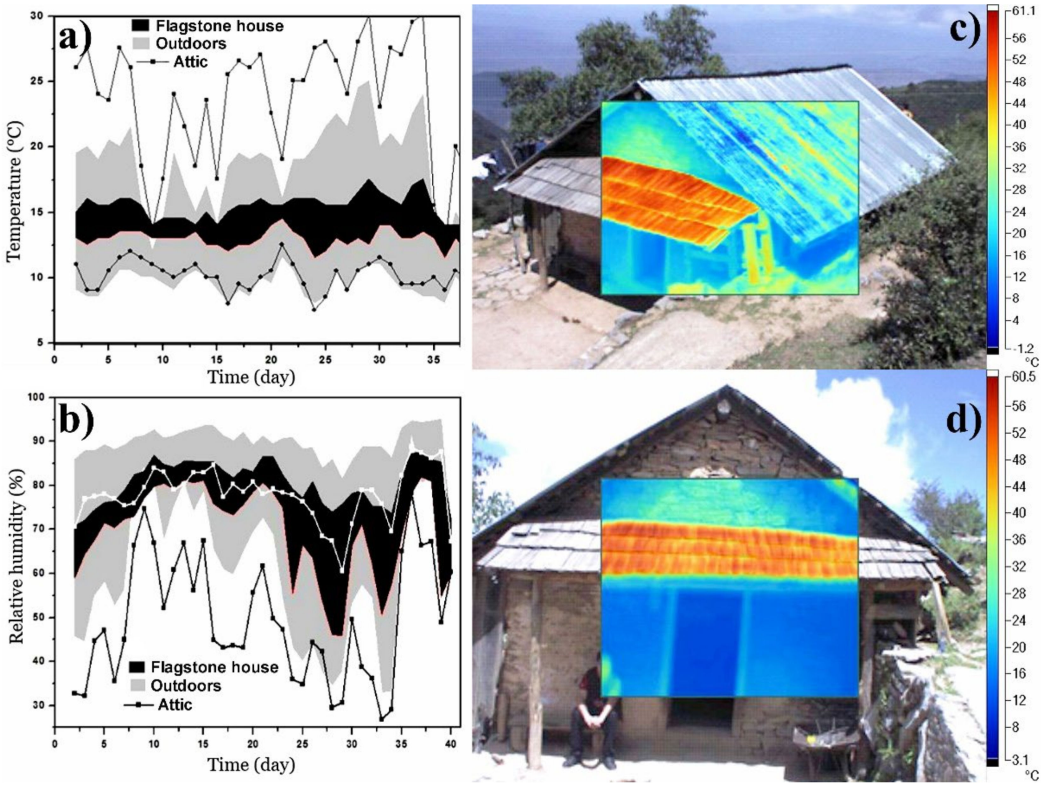

Figure 5. (**a**) Temperature and (**b**) relative humidity of the flagstone construction and outdoor environment. Lines show the values of the attic, locally named "*tapanco*". Thermographic images of the flagstone construction in the *Sierra Gorda* of Querétaro, México. (**c**) Frontal view and (**d**) "*tejamanil*" shed over the door.

The simulations vary from the thermal images taken when talking about the roof of the house, around 8 units in °C. However, they are similar in terms of walls and maintain a close relationship.

3.1.5. House of Bamboo and Date Palm Leaves-Thatched Roof

Figure 6 shows the graphs of temperature (Figure 6a), relative humidity (Figure 6b), and thermographies (Figure 6c,d) of the dwelling made of bamboo and the date palm leaves-thatched roof. In this construction, there were higher variations within the interior of the house, directly caused by the temperature fluctuations of this region. These materials had low thermal insulation, which, together with the construction design, becomes a construction with low thermal insulation.

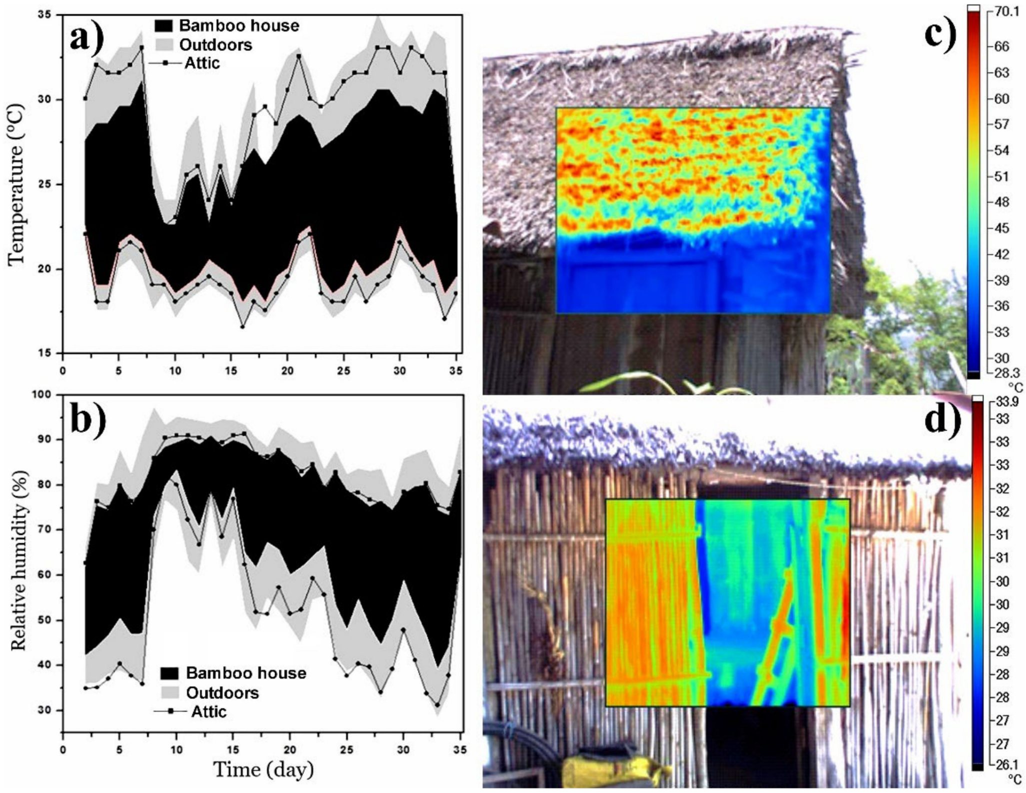

Figure 6. (**a**) Temperature and (**b**) relative humidity of the Bamboo (*Bambusa oldhamii*) house and outdoor environment. Lines are showing the values of the attic, locally named "*tapanco*". Thermographic images of the bamboo house in the *Sierra Gorda* of Querétaro, México. (**c**) Roof view and (**d**) façade view.

The relative humidity inside the house was highly variable. It was attributed to the open ventilation that the construction has since the bamboos were not totally joined and allowed the airflow between the external and internal environments. The date palm leaves-thatched roof has a high surface temperature, reaching 58–76 °C. These temperatures can be observed in Figure 6c, as well as the bamboo walls, whose values were approximately 35 °C. This is due to the shed provided by the date palm leaves-thatched roof.

3.1.6. Housing Built with Conventional Materials

It was considered important to compare the buildings with a house constructed with conventional materials. Figure 7 shows the behavior of a house built with conventional materials with temperatures of 20 to 28 °C, while in the external environment, temperatures of the order of 17–32.5 °C were recorded (Figure 7a). The evaluation was carried out in the June–August period. The house showed average isolation of 4.5 °C.

The construction with conventional materials showed poor thermal insulation and a variable internal behavior between day and night.

Regarding humidity, high variations were observed (Figure 7b). However, it adheres to the recommendations for room houses following the trend of the exterior environment but limited to comfortable room conditions.

3.2. Determination of the PMV and PPD Indices

The indices of Estimated Average Vote (PMV-predicted mean vote) and PPD-predicted percentage dissatisfied were determined using the average values obtained for temperature and relative humidity [52]. The other factors were set as follows (a) the relative air velocity equal to 0.15 m/s, (b) thermal insulation of clothing equal to 1 (average clothing–full suit), (c) metabolic energy production equal to 1.1 met (0.262 kcal or 63.965 W/m^2–equivalent to a rest-activity, person sitting comfortably). The Average Radiation Temperature was considered equal to the average air temperature in the house.

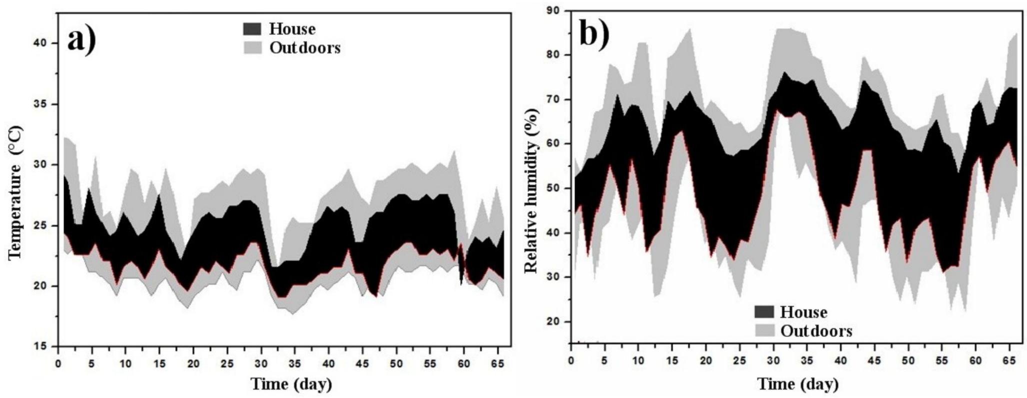

Figure 7. Bimonthly graphs of the behavior of the conventional house for (**a**) temperatures and (**b**) relative humidities.

Figure 8 shows the six graphs of the monitored dwellings corresponding to the indices of Estimated Average Vote (PMV-predicted mean vote) and the PPD-predicted percentage dissatisfied with the studied buildings.

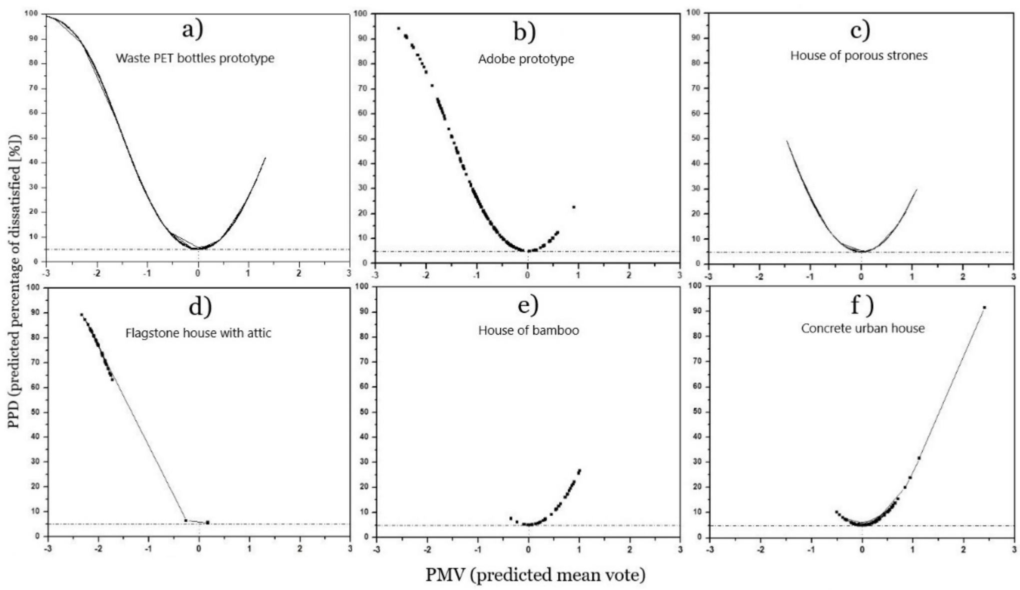

Figure 8. Graphs of the indices of Estimated Average Vote (PMV-predicted mean vote) and PPD-predicted percentage dissatisfied of the studied buildings.

The results shown in Figure 8 are consistent with the information previously described for each dwelling and prototype. The PET and adobe prototypes (uninhabited) showed comfort indices with medium to cold thermal perception. The dwellings with conventional materials and that of bamboo and date palm leaves-thatched roof showed comfort indexes with thermal perception from medium to warm. In the case of the flagstone house with a gabled roof, it only showed comfort indices with cold thermal perception. The porous stone house showed comfort indexes with average thermal perception.

4. Discussion

4.1. PET Prototype

Regarding the exterior behavior of the PET prototype, it can be concluded that it had a uniform external behavior, maintaining a temperature of approximately 45 °C in walls.

However, the maximum internal temperature was 30 °C, which is bearable and shows suitable insulating properties. The temperature rose to 30 °C because the ventilation was intentionally blocked to know the extreme values. Otherwise, the internal temperature would have been lower.

The green roof showed temperatures of up to 70 °C, considering that has black clay from the surrounding area. It should be noted that it is only superficial since, inside the roof, it maintains temperatures of about 22.5 °C, with average variations of 5 °C. The roof was shown to have a higher temperature because it directly receives more solar radiation [53].

The inconsistent behavior of the walls located on the right side of the prototype is attributed to non-uniform mixtures of materials in the construction process since the study of absolute humidity that was carried out showed no relationship between the range of temperatures located in the marked area and absolute surface humidity.

High temperatures can be observed during the March–May period. However, the prototype maintained pleasant temperatures and proved to have good thermal insulation comparing the internal and external environments. The internal variations of the prototype were in the range of 0.5 to 3.4 °C, while external variations of up to 16.5 °C were shown, considering the highest and lowest daily temperatures.

4.2. Adobe Prototype

The adobe prototype turned out to have low thermal insulation of around 7.5 °C. In this, adequate insulation at low temperatures was observed. In the case of high temperatures, there was less insulation compared with the case of low temperatures. The indoor relative humidity in the adobe prototype was very close to the ideal internal humidity conditions. It remains very stable, which is attributed to the humidity-regulating properties of the adobe [54–57].

The adobe prototype turned out to have low thermal insulation of around 7.5 °C. In this prototype, adequate insulation at low temperatures was observed. In the case of high temperatures, there was less insulation compared with the case of low temperatures. This observation differs from other adobe buildings that are usually reported as the best insulation [54–57]. Nonetheless, the insulation depends, among other factors, on the roof characteristics. In this case, the building has a vaulted ceiling, with fired red bricks. Moreover, the metallic door and three windows are large relative to the prototype construction size. Also, the adobes are made of a composite with an epoxy polymeric resin. All of these factors contribute to such thermal behavior.

The indoor relative humidity in the adobe prototype was very close to the ideal internal humidity conditions. It remains very stable, which was attributed to the humidity-regulating properties of the adobe. This agrees with the reported performances of adobe constructions as an outstanding humidity regulator [54–57].

4.3. Porous Stone House, Two-Floor

The best thermal insulation presented was that of the stone house on two floors, maintaining minimal variations inside the house of about 2 °C, and it shows a comfortable temperature. This was due to the excellent thermal insulation of the material used and the construction design, especially the thickness of its walls. The relative humidity was kept within the recommended limits (35–65% RH). It should be noted that one person inhabited the house and the time spent at home was short. No heater or humidifier was used in the period of evaluation that could affect the measurements.

4.4. Flagstone House with Loft

Located on a hill with low temperature, high humidity, and higher wind speed, this house had a stable average indoor temperature of about 14.5 °C but it was considered too low for the inhabitants [52]. Even more, considering the high average relative humidity of about 80%, the low temperature and the higher wind speed, the apparent temperature was even lower. This house has a gable roof made of galvanized sheets and this acts as a thermal damper, maintaining higher temperatures than the external environment. The insulating behavior was excellent with an average temperature of about 2 °C when the external value changed by about 15 °C. Also, the RH had average fluctuations of about 7% when the external value changed about 15–40%.

4.5. House of Bamboo and Date Palm Leaves-Thatched Roof

This house is located in a local tropical-like environment with high temperatures and relative humidity. It is constructed with a single line of bamboo without any construction material that blocks the empty spaces on the wall. The house has an attic covering half of the inner area. The results showed the lowest insulation. The attic has a very close performance to the external weather conditions, both in temperature and relative humidity. The indoor conditions were a temperature in the range of 20–30 °C and a RH of 40–85%. This construction has a better performance in reducing high than lower temperatures and the opposite in the case of RH. The overall sensation indoors was a middle to hot temperature, night to day period, with a high RH.

4.6. Housing Built with Conventional Materials

This house is located within an urban area. Differently from the others, it has neighbors on both sides and its backside. The façade is south facing a street. Used as a reference, this house has low insulation reducing the low and high extreme temperatures in a night/day interval to only about 4.5 °C. The RH has fluctuating behavior.

4.7. PMV and PPD Indices for the Six Dwellings

The PMV and PPD indices were in accordance with the above described results for the six dwellings considering some fixed values for their determination. PET and adobe uninhabited prototypes had medium to cold perceptions. The reference house of conventional materials and the bamboo/date palm leaves-thatched roof dwelling had medium to warm perceptions. The case with a cold perception was the flagstone house with a gabled roof. Contrarily, the two floors of the porous stone house got the best thermal perception.

5. Conclusions

Six cases of the study of dwellings with contrasting characteristics were analyzed on their thermal and RH performances. Their insulating properties were associated with their construction materials, design, location, and other factors. The PMV and PPD indices were concordant with the individual results but considering the possible general perceptions of inhabitants.

The six houses have significant differences, but considering their behavior in their location, the two floors of the porous stone house got the best results, not only on the bare analyzed results, but in concordance with the opinion of the inhabitants considering the annual period, rainy and dry or hot and cold seasons. On the contrary, the flagstone house with a gabled roof of galvanized sheets conforming to an attic had a cold perception considering the PMV and PPD indices, but also according to the opinion of the inhabitants and the visitors. This dwelling has many elements that are advantageous, such as low fluctuations in both temperature and RH. The house uses local traditions in construction, such as "*tapanco*" (attic) and "*tejamaní*" (woody shed over the door). It incorporates local materials, such as flagstones and mud to block the gaps between them, but reduces the use of wood from the surrounding forest because of local conservation restrictions. Nonetheless, it fails to provide comfort in such a cold location.

Contrasting with other adobe constructions, the one analyzed in this work has low thermal insulation. Some factors explain such performance, such as the characteristics of the fired red brick roof, a vaulted ceiling, metallic door, and three large windows relative to the prototype size. Even considering that the adobe bricks have a polymeric resin, the humidity was regulated by absorption in the walls.

PET and adobe uninhabited prototypes had medium to cold perceptions. The PET prototype has excellent and adjustable insulations, both on temperature and RH considering the passive illumination and ventilation through and in between the glass bottle skylights.

The reference house of conventional materials and the bamboo/date palm leaves-thatched roof dwelling had medium to warm perceptions. The last one is in a hot weather location, and despite the fact that it mitigates the direct exposure to sunlight, rain, and wind, as well as extreme temperatures, this is not enough to provide a comfortable perception to the inhabitants.

Among the many factors to consider in houses, materials and design require to be chosen to offer security and comfort, according to its location, environment, risk of natural events, inhabitants number, traditions, habits, and so forth. The PMV and PPD indices are valuable factors to be considered in the construction and inhabitation of dwellings, but they are dynamic, they fluctuate even within the same house at different times or in different rooms with the number of persons, the furniture, and changes resulting from renovations, etc.

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