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Sustainability metrics for housing and thermal performance evaluation of a low-cost prototype made with PET bottles

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Abstract: The scope of work covers the proposal on the implementation of a sustainable, low-cost, environmentally affable, and affordable housing for low-income people. This paper aims to address the current housing issues, where many people lack decent housing and built houses usually are of low sustainable nature. The work consists in three main parts: Evaluation of the housing sustainability; measurement of parameters related to their internal comfort and simulating the thermal enclosure with the software COMSOL Multiphysics. An important objective is to propose a sustainability assessment format, which besides being explained in detail, it is presented in a percentage scale for easy understanding. This work seeks a methodology for evaluating the level or degree of sustainability for the construction and inhabitation stages of housing. In a prototype, constructed with PET bottles, temperature and humidity were measured. There was a contrasting behavior of these two parameters, which tends to have an inverse behavior, except on cloudy or rainy days. The roof of the prototype contained some waste materials that provided thermal insulation: galvanized steel, polyethylene bags for upcycling them as waterproofing, PET bottles, soil and endemic plants (green roof). The result obtained in the simulation was in accordance with the real internal behavior of the prototype.

Keywords: Sustainable housing; building materials; re

cycling; interior comfort; upcycling; endemic plants, green roofs.

1. Introduction

Housing is one of the primary needs of human beings and, is currently is a pressing need directly associated with population growth on both local and global scale. Also, it is a problem with high ecological impact, as much for the occupation of spaces for residential developments as for the use of large quantities of materials for construction. Moreover, there is a concern about the direct and indirect impacts by the extraction, processing, and transport of these materials. Constructive innovation is a major solution to the needs of the human organism who has by various means provided for by itself, starting from *homoerectus* about half a million years ago, according to Hadfield [1]. Later, the construction methodology was evolved and, currently, the sustainability tendency plead to use renewable materials available in the surrounding area and their life cycle as shown by Mun and Choi [2]. Nowadays, there is a boom in the use of building materials used in past times, such as stone façades, stucco, blocks of compressed earth and organic materials such as wood and bamboo [3-9]. The latter is rapidly renewable and has useful properties based on the weight-resistance relationship, in comparable with steel or new high-tech fibers [10-12]. Many other vegetal alternative materials have been used such as cork [13] and Arundo donax [14].

Another example is the use of adobe, which is no longer used in urban construction but is known to have properties of interest, such as its excellent coefficient of thermal conductivity that allows internal comfort. The disadvantage of adobe is its deterioration in the face of weathering factors such as the rain and the wind. There are a few innovations for adobe stabilization such as a cover of latex, lime or fermented fertilizer mixtures to provide greater resistance [15-17].

In this work, a prototype of a room for a house of social interest was built using some recycled materials. PET bottles (waste soft drink containers) were used to close the space of the room (walls). These bottles were not processed (mechanically or chemically) to avoid energy consumption in the recycling [18]. Several works have reported the use of PET as a recycled material in related research, to construction materials such as concretes, mortars, etc., adding it to mixtures of such materials [19-25]. In addition, this prototype served as a reference in the evaluation of sustainability in homes, according to different parameters that influence the sustainability metrics as proposed in this work.

This work proposes the evaluation of prototype characteristics, for both existing structures as well as those in planning, which includes, among others, thermal, acoustic and electromagnetic insulation, environmental and structural humidity, gases (volatile organic compounds, oxygen, methane, and carbon dioxide). This include as well, the affectation of these parameters by modifications made in the housing surfaces, either covered or not by painting or waterproofing. This work shows only the results of the consensual values assigned to the different factor for the metrics of sustainability and the thermal behavior of a housing prototype built using PET bottles. The evaluation of the rest of the indicated factors is relevant in the case of inhabited houses.

The work seeks to identify and improve practices that quantify the degree of sustainability that a construction may have. Finally, based on the information obtained from the prototypes, a COMSOL simulation of the thermal insulation was made for a prototype intended to be a sustainable housing. This software has the advantage of coupling different physical phenomena and integrally making the simulation by handling the thermal and the acoustic modules, among others.

Castañeda [26] argues that the construction industry is one of the sectors with the highest contribution to environmental pollution. Therefore, there is a growing concern in the field of construction and sustainable development. Various social groups have been consolidated with the purpose of proposing sustainable housing projects, from small groups to large companies that involve some sustainable character in their constructions. The present work, associated with this theme, seeks to provide quantifiable elements that can allow evaluation of different prototypes called "sustainable".

The Life Cycle Assessment (LCA) methodology is meant to assess the impacts of primary energy input (PEI) and greenhouse gas emissions throughout the whole life cycle of a product, which include buildings [27]. LCA follows the ISO 14040-14044 (ISO 2006a,b) and it can be calculated with a software such as *SimaPro*® [28]. A cradle-to-grave LCA applied to buildings is a complex process, where some prioritize the evaluation of carbon dioxide-equivalent emissions [29] and possibly include others such as Land Use, Acidification, Eutrophication, Ozone Depletion, Resource Depletion and Human Toxicity [30-32]. Some works were extended to include life cycle assessment (LCA), life cycle energy analysis (LCEA), and life cycle cost analysis (LCCA) studies [33]. There are absence of common criteria for the reported studies such as methodological structure, parameters for construction, transportation, consumption of water and energy, maintenance, waste destination and the practical application of LCA in different regional typologies [29,34].

Currently, there are few quantitative systems to adequately assess the sustainability of homes throughout their life cycle [35], especially for the actual circumstances and regional interest. This is because the design of the buildings does not consider the operating costs and the environmental impact of the systems associated with the operation in the life cycle of the buildings. Usually, the measurement of sustainability could be conducted in great building projects such as Leadership in Energy and Environmental Design (LEED®) in the United States [36] or for real state developments, by CONAVI, in the case of the Mexican institution [37]. Therefore, this work seeks a methodology for evaluating the level or degree of sustainability.

2. Materials and Methods

2.1. Materials used in construction

The prototype room had an area of about nine square meters. In building the walls of the prototype, 5000 PET bottles of 600 mL filled with sand of the site were used (Figure 1). These were placed on the conventionally constructed foundations. The bottles have a mooring with annealed mesh (Figure 2). Then there is a layer of mortar repellant. Finally, a coat of white cement and marble powder was applied to confer a white aesthetic finishing appearance, to avoid an extra finish like paint or waterproof. The roof has six sheets of galvanized steel overlapping in their extremes, followed by a cover of recycled high-density polyethylene bags commonly used in supermarkets. In this case, they were used in the sense of upcycling them as a waterproof layer. The polyethylene bags constitute a high pollution source and they were overlapped to form a continous plastic layer on the roof. The prototype roof includes a double layer of about one thousand PET bottles uncovered and empty; all the other PET bottles with irregular shapes and different sizes, which were not suitable for the walls were used. As a third layer, there was another layer of used bags. A fourth layer used the cardboard waste from the packages of construction materials. The next layer was made with the site soil. The top layer was generated using endemic vegetation from the site of construction. The latter was intended for two purposes, first, for conferring a cover that provides shade and second, the original idea of not altering the landscape from a top view, an aerial view or a satellite perspective.

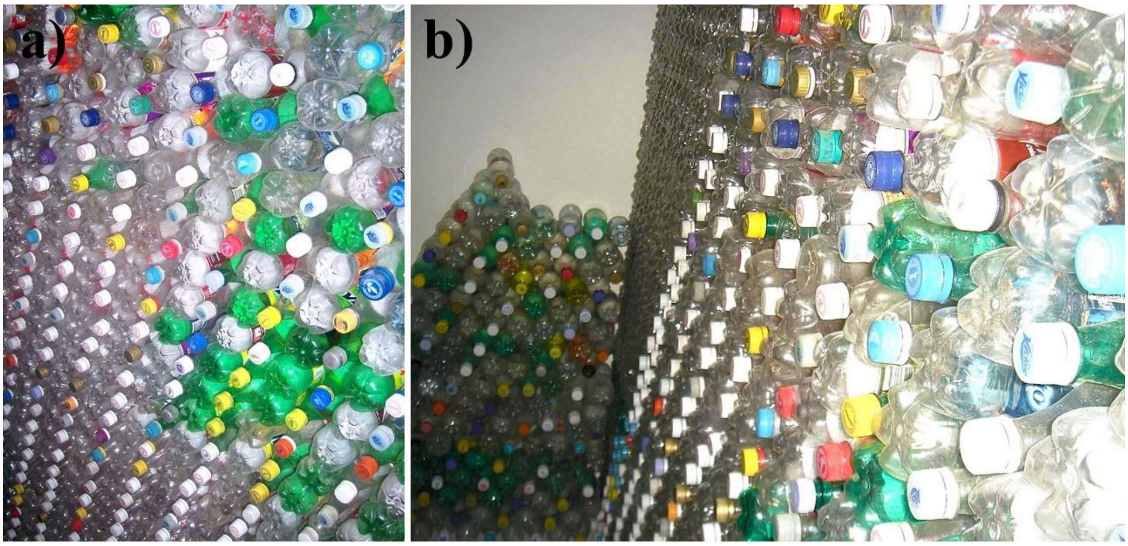


Figure 1. a) and b) images of the collected PET bottles, under storage, before building the prototype.

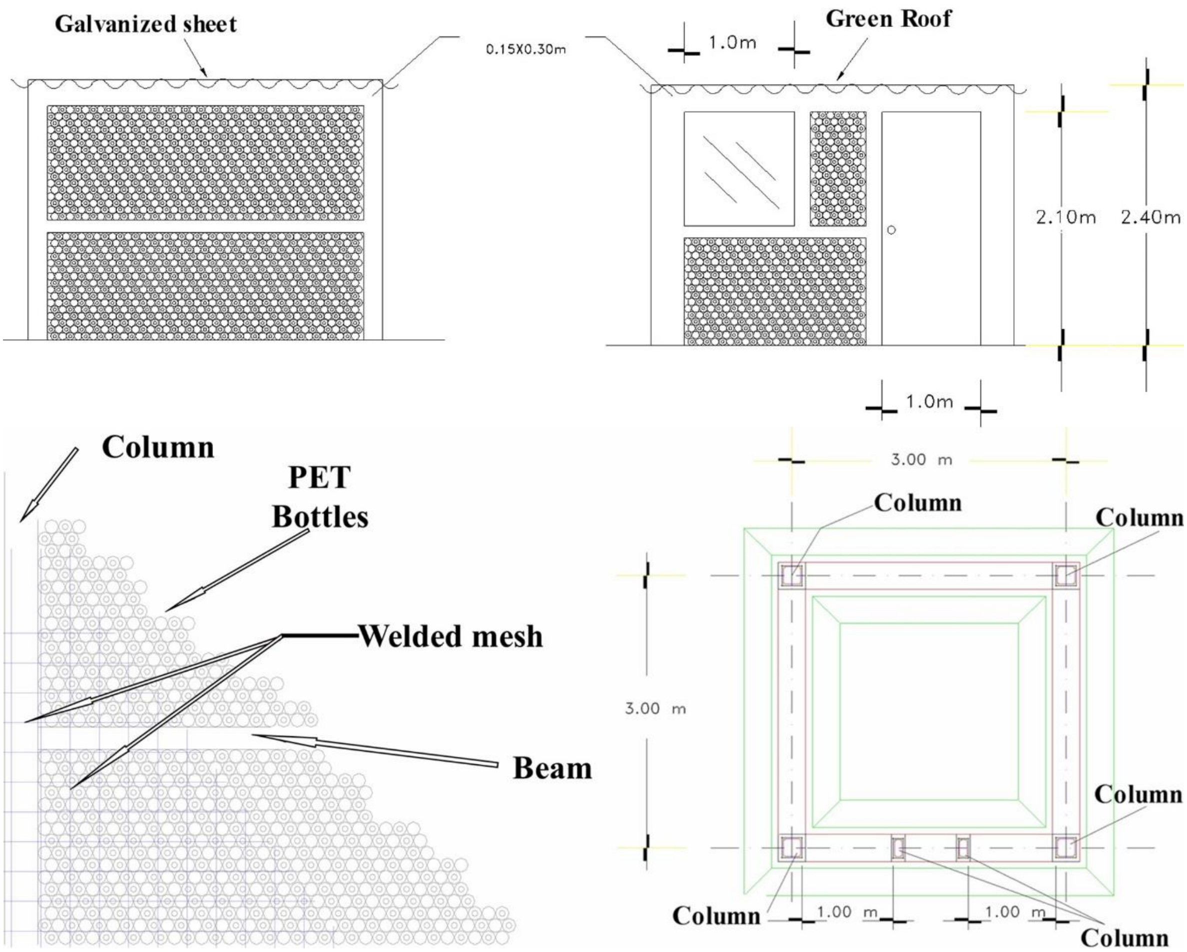


Figure 2. The structure planes proposed before constructing the housing.

2.2. Instruments and software

- Thermographic camera, PCE-TC 3, PCE-Group Ibérica SL.
- Temperature and humidity sensors, Thermotracker.
- COMSOL Multiphysics Software versions 3.5 and 4.2.

2.3 Methods

2.3.1. Thermic simulation

The simulation was done using COMSOL Multiphysics software version 3.5 and 4.2, employing the thermal transfer module and the earth science module. The methodology followed in this simulation consisted of:

1. A compatible file extension of the desired structure was imported to the software or a direct drawing of the structure to be simulated.
2. The specific conditions of the structure and the type of material were specified in walls, windows, doors, ceiling, and foundation.
3. The border and the initial conditions were established of the entire structure, sectioning the parts of the house, if necessary, to set different circumstances.
4. The simulated system was solved.

2.3.2. Measurement of internal and external parameters

Temperature and humidity measurements were carried out with "Thermotracker" sensors, located in strategic areas of the evaluated prototypes.
With the PCE-TC 3 thermal imager, thermographic images were taken, showing the temperature contrasts and the behavior of the materials used.

3. Results and discussion

3.1. Assessment of the degree of sustainability

Below is the proposal for sustainability indicators or metrics. It should be noted that this proposal was applied to the prototype in its construction phase, but not in the performance of the house, because it is not an inhabited construction. The life of a building consists in three stages: construction, operational phase, demolition and waste treatment [38]. In this work, the first two stages were considered. No measurement indicators of the demolition stage were raised due to the short period of the evaluation process. However, it has been reported in other literature that during this stage, a ratio of 80/20 solid waste is generated in proportion to that of construction [18].

Each stage contains important aspects and these, in turn, are sectioned assigning values that allow us to obtain a total score, as shown in Table 1 and Table 2.

FIRST STAGE. Construction stage

Table 1. The weight for the evaluation of the degree of sustainability for the construction stage of the housing.

A) Site selection and ecological impact	B) Building materials	C) Construction design and bioclimatic	D) Backyard and green areas	E) Generation of waste

Respect the surrounding flora and fauna	**10**	Materials adjacent to the site	**10**	Ceiling height	**5**	Vegetation around the house	**5**	Minimize the amount of waste	**25**
The ground meets the construction characteristics	**5**	Recycling materials	**15**	Roof tilt	**5**	Consumable vegetables using composting	**15**		
There is permission for the use of land for housing construction	**5**	Rapidly renewable materials	**15**	Orientation of housing	**10**				
		Vernacular materials	**10**	Ventilation	**10**				
				Natural lighting	**10**				
Total	**20**		**50**		**40**		**20**		**25**

The score assigned to each item was established based on information from existing sources (LEED® [36-40], CONAVI [41], Martija Martínez [43], Rodriguez [44], Masera [45], MESMIS [46-48]) and by consensus of several collegiate works. Sustainability indicators are shown in Table 1 and Table 2. Using the score obtained from the evaluation of each prototype, a ratio was made in the percentage of sustainability, thus obtaining a comparable figure.

SECOND STAGE. Performance of the inhabited house

Table 2. The weight for the evaluation of the degree of sustainability for the inhabitation stage of the housing.

A) Energy efficiency		**B) Care for the water resource**		**C) Separation, disposal, and exploitation of waste**		**D) Internal comfort**		**E) Fuel used and emissions generated**	
Use of solar or other renewable energy	**35**	Rainwater harvesting and reuse	**15**	Composting	**5**	Acoustics	**10**	Natural Gas or LP Gas	**10**
		Separation of gray water and sewage	**15**	Separation of PET, glass, paperboard, paper, aluminum	**15**	Temperature	**10**	Biogas	**15**
		Water-saving devices	**15**			Humidity	**10**		
						Air quality	**10**		
Total:	**35**		**45**		**20**		**40**		**25**

Incises A and E are related to energy and, together, the points are 60 that are higher than the 45 points for water given more importance to energy. Energy was split in A and E to differentiate efficiency and emissions related to energy consumption.

The quantitative assessment of sustainability is shown in Figure 3, in which the weight of the different characteristics of a sustainable nature can be seen in the evaluation of housing. In this work, the sustainability assessment methodology was applied, considering only the first stage (construction stage), because the house is not inhabited and does not meet all the requirements of a house.

3.2. Sustainability Indicators

Figure 3 shows in detail the importance of each section in the contribution of the degree of sustainability to housing, having a total of 320 points, which is equivalent to 100% sustainability. Through this evaluation proposal, there is a format of evaluation of sustainability in housing and with the antecedents of methodologies previously proposed in the literature.

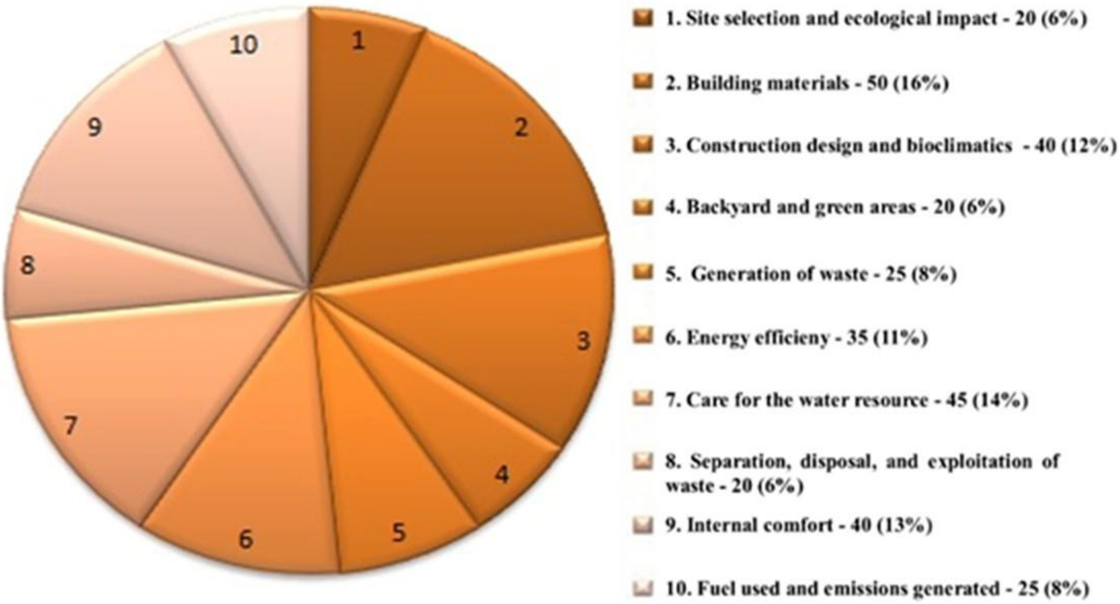
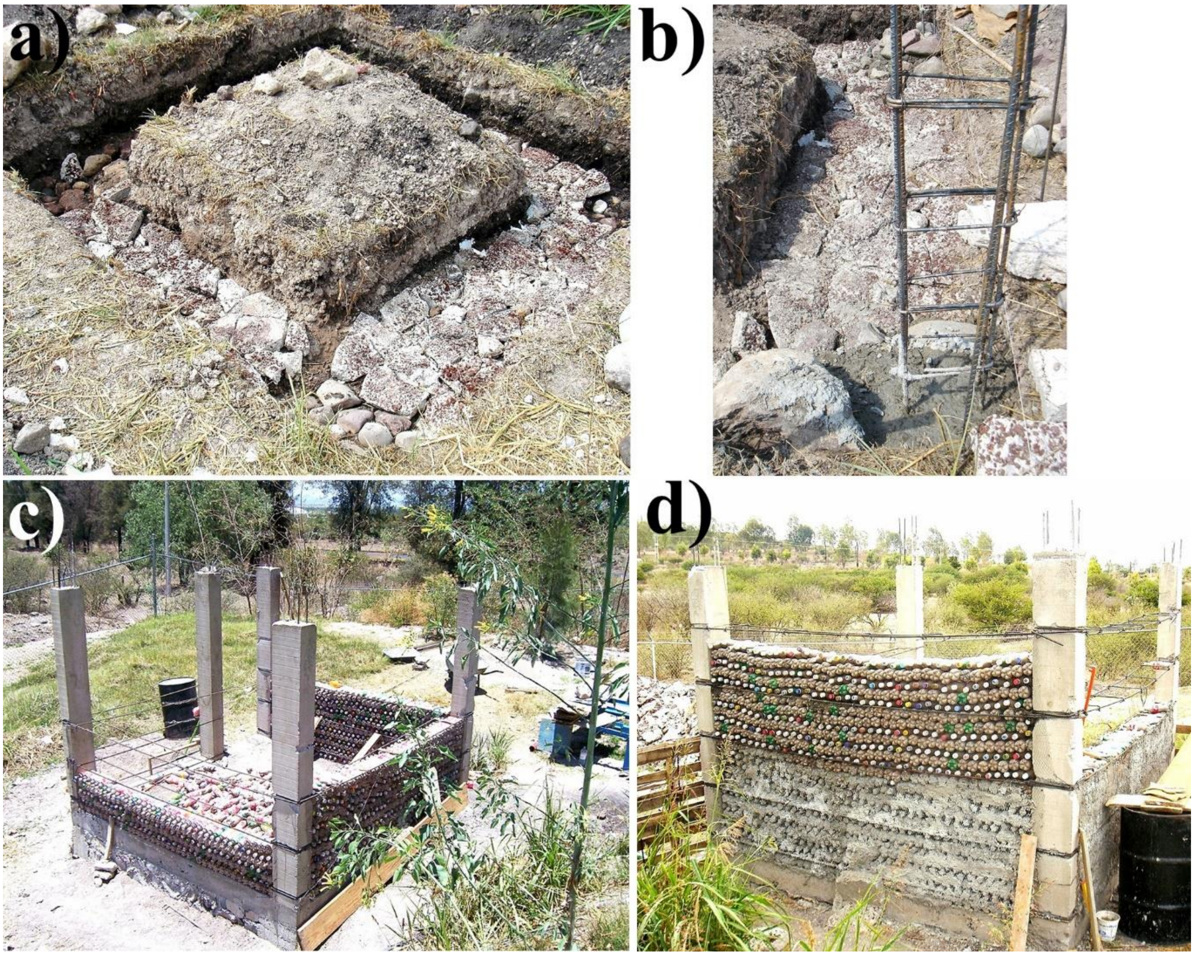


Figure 3. Indicators of sustainability and percentage contributed by item.

3.3. Building the prototype with PET bottles


a)
b)
c)
d)


e)
f)
g)
h)
i)
j)
k)
l)

Figure 4. a)-s) Images of the building process for the prototype housing using PET bottles.

Figure 4 shows the images of the building process for the housing prototype where PET bottles were used for both the walls and the roof. There were other waste materials employed in the construction. The foundations have concrete pieces obtained from the demolition of a building. The bottles were filled with sand obtained from the excavation of the foundations but the façade wall was installed using empty PET bottles without screw caps. This was to avoid deformations by temperature changes along the year, which happened in stacked PET bottles. This resulted in a greatly simplified work because, the filling of the bottles was tough. There was no significant difference between the façade and the other three walls in terms of stability, humidity accumulation or temperature transference.

The tubes for the electric cables were inserted under the metallic mesh. The ceiling was built with steel bars and galvanized sheets. Steel rebars were used every 1.2 m around the building to truss the mesh and the columns.

The multilayered roof was made of different waste materials and finished with a vegetation coverage (Green roof). This roof fulfilled the desired characteristics as thermal insulation, waterproof in rainy seasons, and a top view similar to the surrounding area.

In addition, recycled glass bottles were placed on the inside top under the roof along the perimeter of the room, to function as skylights. The space between the placed bottles was not sealed with the objective of ventilating the lower part of the roof, this is because in this area the temperature is higher and the air renewal cups would help in the reduction of the internal temperature.

3.4. Simulation

A first thermal simulation was performed considering only extreme conditions of external temperature, and it was coupled to the one observed in the real prototype related to the wall temperatures. It should be noted that the solar radiation phenomenon was not applied for this preliminary simulation. The temperature of the external medium was taken as 42 °C, establishing, in turn, a ceiling temperature of 60 °C. The walls reached outside temperatures of about 30 °C. The doors and windows were at temperatures about 45 °C. In Figure 5, the internal temperature reached was about 25 °C.

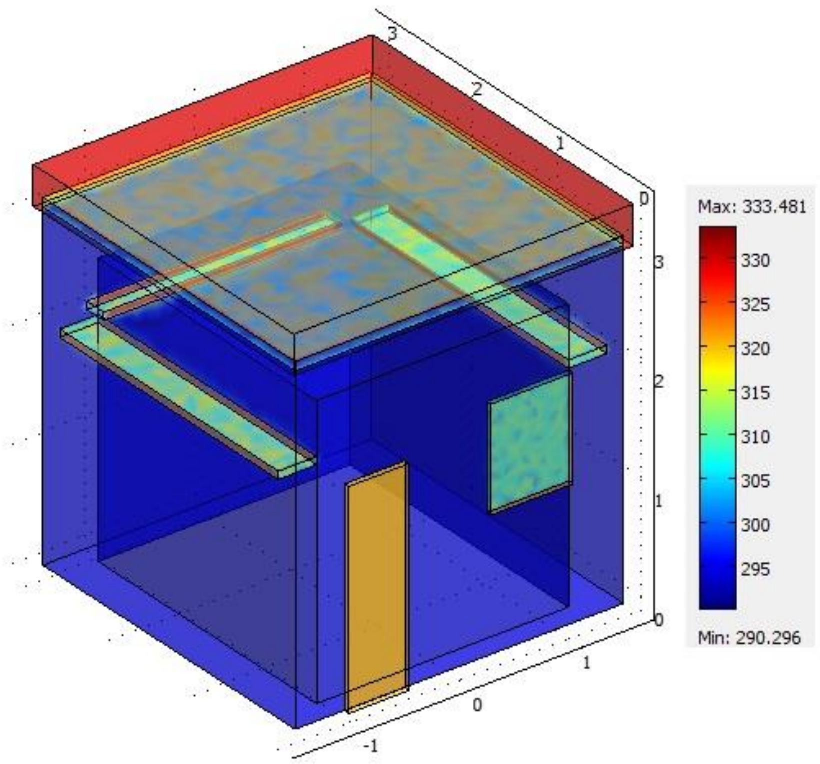


Figure 5. Thermal simulation of the internal behavior of the PET prototype, using the external temperature data from the real prototype.

Figure 5 shows a maximum temperature of 44.65 °C in the upper part of the house, and a minimum temperature of 36 °C, showing a stable behavior and a small variation in temperature. At the base of the building, different temperatures were observed, according to the initial conditions and the contacts with the structure.

3.5. External measurement of the prototype

Thermographic images of the constructed prototype having "PET walls" were taken (CIDETEQ, Qro., México), and a stable external behavior was observed in the different areas. In Figure 6b, a thermographic image of the prototype room façade is shown. The colder parts, shown in dark colors, are the window and the glasses that are part of the door, to prevent the direct entrance of solar radiation, maintaining a temperature of about 45 °C in the external walls.

Figure 6a shows a thermographic image taken from the rear section of the prototype and the average temperature was also observed at 45 °C. This temperature was very similar to that of the façade that received a higher amount of solar radiation. The red and white spots indicate higher temperatures. This is due to variations in the structure originated in the construction stage, where probably the proportions of the material of the coating mixture are different in the white side area. Thermographs were taken in July, which usually is a warm month in the area. The external environmental temperature was 27.8 °C at the time of taking the thermographs. This indicates the accumulation of temperature in external walls. In Figure 6a, the thermography shows part of the roof and part of the external area of the wall from behind the building. It is possible to see a line in the lower part of this thermography that is associated with a line of recycled glass bottles used in three sides as skylights of the room to provide daylight and passive ventilation.

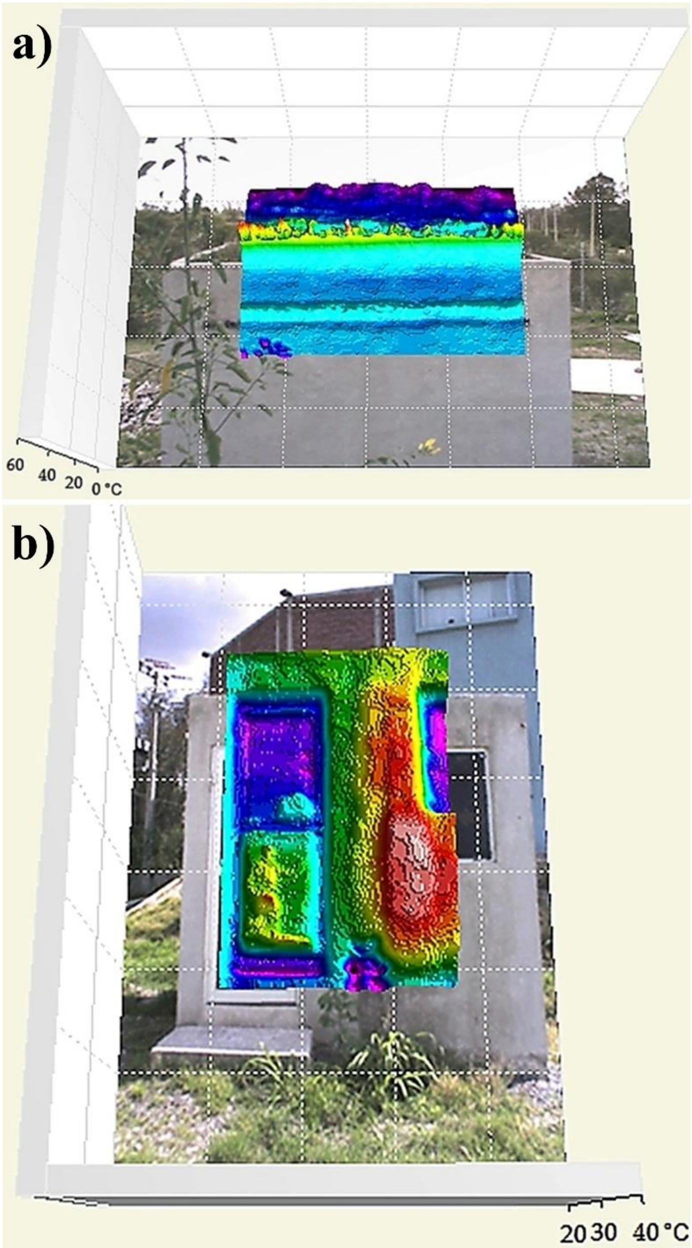


Figure 6. Thermographic image, a) rear view and b) façade view.

The similarity in temperature of the roof with that of the floor surrounding the structure is outstanding. This was caused by the use of site soil. The endemic plants, being seasonal, were not present at the moment of taking the image, neither in the ceiling nor on the floor. One of the goals of green roofs is to mimic the surroundings, which was achieved by seeing a superior perspective of the prototype room. Another objective of green roofs is to attenuate the heat island effect in urban areas, which is achieved by having plants. In the case of the prototype, this last one is fulfilled in summer and autumn, when there is foliage on the top area.

3.6. Internal monitoring of the prototype

The humidity and thermal sensors were placed in two internal parts of the prototype, one of them close to one side of the window and the other in the lower part of the prototype, with the precaution that they should not at any moment, receive direct solar radiation. A pair of sensors were placed as references under the shed and with ventilation in nearby places. Once installed, the monitoring of temperature and humidity was carried out for about one month between February and March. At this time, the ventilation of the prototype remained open. It is worth mentioning that these are winter months with low temperatures.

Figure 7 shows the different temperatures and humidities obtained during the evaluation period. Zigzag lines indicate high and low points, representing one-day cycles between each peak, while more uniform lines represent the daily average of both temperature and humidity. As a control, a reference site was selected, which was an open area with a roof but without walls having ventilation but the sensors were protected from rain and direct sunlight. Figure 7a shows the temperature and humidity of the reference site while Figure 7b shows those of the PET housing prototype. These graphs indicate that temperature and humidity varied widely. The average daily variation was about 10.3 °C and 30.4 %RH, respectively.

In Figure 7a, a more controlled temperature and humidities were observed, which leads to considering an adequate performance of the prototype in the two measured parameters. The average daily temperature and humidity variations were 1.98 °C and 13.8 %RH, in the case of the PET prototype.

Figure 7c shows the average temperature and humidities without the daily data of both, the evaluated prototype and the reference site. In these graphs, it is observed that the average temperature of the prototype follows the same trend as the temperature of the site, only with smaller magnitudes. Similarities were found in the lines of humidity, but on the contrary, both the temperature and the internal humidity are greater than the external ones. Regarding the general behavior of temperature and humidity, a high contrast between these two measurements was observed, as the humidity decreases, the temperature tends to increase and vice versa.

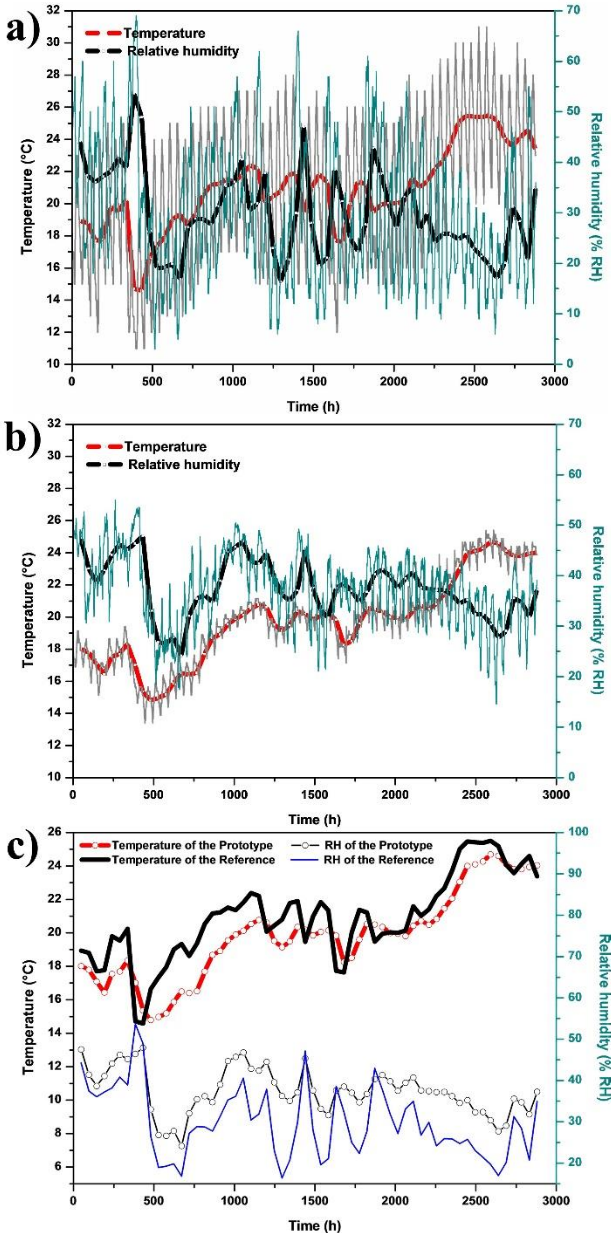


Figure 7. Temperature and humidity as a function of time a) reference site, b) the PET housing prototype, and c) the average values without the daily data.

3.7. The degree of sustainability of the built prototype

The evaluation of the prototype's degree of sustainability was carried out, considering only the construction stage (the prototype was no inhabited), thus, obtaining a total of 105 points out of 155 possible, for the first stage (Table 3). With this, a 67.74% sustainability in a housing according to the methodology developed was achieved, which represents only the construction stage. In Table 3, the numbers in bold/italic are these where the prototype did not fulfill the parameters.

Table 3. Detailed prototype sustainability assessment for the construction phase.

FACTORS	Prototype	Ideal
Respect the surrounding flora and fauna	10	10
The ground meets the construction characteristics	5	5
There is permission for the use of land for housing construction	5	5
Materials adjacent to the site	10	10
Recycling materials	15	15
Rapidly renewable materials	***0***	**15**
Vernacular materials	***5***	**10**
Ceiling height	***0***	**5**
Roof tilt	***0***	**5**
Orientation of housing	***5***	**10**
Ventilation	10	10
Natural lighting	10	10
Vegetation around the house	5	5
Consumable vegetables using composting	***0***	**15**
Minimize the amount of waste	25	25
Total	105	155

4. Conclusions

This work consists in three aspects, a proposal for the quantitative measurement of sustainability for housing, the development of a prototype using PET construction for wall and roof assembly, and evaluating the structure with direct temperature/humidity and simulation.

Different indicators were proposed for sustainability assessment as well as the assignment of quantitative values. In this case, the constructed prototype obtained a score of 67.74% in the proposed scale of sustainability for housing, with consideration for only the construction stage. In other words, it obtained 105 points out of 155 possible.

Regarding the external behavior of the PET bottles prototype, it can be concluded that it had a uniform external behavior, maintaining a temperature of about 45 °C within the walls. However, the maximum internal temperature was 30 °C, which was lower than the reference temperature. This value was not affected by changing the incoming illumination by door or window. It is however, possible to affirm that there were excellent insulation properties (evaluated in the months May - July).

The internal behavior of the prototype built with PET bottles showed a low temperature of about 10 °C. This was because the ventilation was not covered, on purpose to evaluate the lowest temperature value, and the cold air of the outside entered without restriction, causing low internal temperatures (evaluations during the months February - March). With the result provided by the sensors, we can conclude that the prototype built with PET bottles was thermally stable since the average daily temperature of the prototype variate a fifth part compared to the fluctuation of the average temperature recorded in the area.

The internal humidity was maintained between 15% and 55% RH. In the external environment, the range was between 3% and 70% RH. There is a significant difference between the inner and outer environments. The ideal humidity ranges for inhabited housing are in the range between 35% and 65% RH. The prototype reaches very low humidity because the ventilation was kept open and highly related to the external one.

The simulation presented a possible performance and thermal transfer in line with the characteristics of the initial conditions and the border conditions that were used for evaluation. However, there are still factors not included in this simulation, such as solar radiation heating, convection, and conduction, to simulate situations more closely related to the actual behavior that the built prototype could present. The external simulation of the prototype resembles the images obtained in the thermographs.

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