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Thermal Study of a Prototype Sahelian-Type Emergency Humanitarian Shelter, Semi-Durable, Removable, and Made from Biosourced Materials

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Abstract

In Burkina Faso, insecurity has led to massive displacement of rural populations towards the country's major cities. Humanitarian organizations have worked hard to provide internally displaced people with humanitarian shelters that meet international standards. Despite these enormous efforts, the phenomenon has given rise to a crying need for housing and the proliferation of makeshift emergency shelters, which are confined and precarious, becoming almost like greenhouses in hot weather, as they induce thermal discomfort and overheating. The aim of the study is to propose a prototype for an alternative Sahelian-type emergency shelter that is comfortable, semi-durable, and removable. The aim is to assess the performance and hygrothermal comfort of a standard humanitarian tent made of plastic sheeting (the most widely used in the country) and to compare it with a bioclimatic emergency shelter prototype using local biosourced materials. The study used a dual experimental and numerical approach to measure and simulate the temperature, relative humidity, and hydrothermal comfort of the two shelters. The results showed that the prototype emergency shelter made from local biosourced materials offers better hygrothermal comfort than the humanitarian tent made from plastic sheeting and is more durable and removable. Indeed, in hot weather, it can dampen the thermal wave by an average of 7˚C, induce a thermal phase shift of around 5 hours, and reduce the discomfort rate by 61% compared with the humanitarian tent. Local materials can, therefore, play a strategic role in the construction of emergency shelters in times of crisis or disaster.

Keywords

Emergency Shelter, Humanitarian Tent, Bio-Sourced Materials, Thermal Comfort, Plastic Sheeting

1. Introduction

In 2019, the humanitarian organization Global Shelter Cluster (GSC) provided emergency shelter to 4.9 million people worldwide [1]. By the end of 2023, the United Nations High Commissioner for Refugees (UNHCR) estimated that 63.3 million people were internally displaced by disaster or conflict [2]. In recent years, Burkina Faso, like many other countries, has seen massive displacement of its rural population towards the country's major cities as a result of insecurity. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) had counted some 2.1 million Internally Displaced Persons (IDPs) in Burkina Faso by March 31, 2023 [3] [4].

Humanitarian organizations have made enormous efforts to provide assistance in the form of emergency shelters made of plastic sheeting (family tents, sanitary facilities, etc.) for large numbers of displaced families. There are three main types of emergency shelter made from plastic sheeting: the "Sahel shelter" emergency shelter, the gable-frame humanitarian tent with a double-sloped roof, and the transitional emergency shelter known as the "Refugee Housing Unit" (RHU). However, the very high number of IDPs (most of whom could not be housed) has led to a crying need for housing and the proliferation of makeshift emergency shelters, which are confined and precarious, almost becoming greenhouses in hot weather. This leads to thermal discomfort and overheating in the hot season. As the country has an abundance of local building materials, our study focused on their use in the construction of more appropriate transitional or semi-durable emergency shelters. In fact, the Cluster Abris—Burkina Faso, in its document entitled Shelter cluster strategy, Burkina Faso, recommends promoting the use of local materials resistant to climatic hazards [5] for the construction of more durable shelters for displaced people from areas where security conditions could potentially last over time [6].

In our previous studies, we developed an eco-insulator and interlocking bricks made of compressed earth blocks stabilized with rice husk ash [7]. The eco-insulator (thermal corrector) has a density of 917 ± 46 $kg \cdot m^{-3}$, a thermal conductivity of 0.135 ± 0.010 $W \cdot m^{-1} \cdot K^{-1}$ and a point bending strength of 2.2 ± 0.1 MPa. BTC has a thermal conductivity of 0.703 ± 0.003 $W \cdot m^{-1} \cdot K^{-1}$ and a compressive strength of 6.8 ± 1.2 MPa for a density of 1929 ± 32 $kg \cdot m^{-3}$. The present study takes advantage of these achievements to propose a prototype of a removable, semi-durable emergency shelter. The aim of this study is, therefore, to evaluate and compare the hygrothermal performance and comfort of a standard humanitarian tent made of plastic sheeting and a removable emergency shelter prototype (bioclimatic type) using local bio-sourced materials. The study used both an experimental and a numerical approach to measure and simulate the indoor air temperature and relative humidity of the two types of shelter, as well as their hygrothermal comfort.

2. Materials and Methods

2.1. Emergency Humanitarian Shelter Models

The emergency shelters commonly used in humanitarian relief operations are mostly made of plastic sheeting, more specifically polyethylene. Polyester, polyvinyl chloride (PVC), and polycotton (60% polyester + 40% cotton) are also available. These tarpaulins are strong, flexible, water-resistant, and even waterproof. A standard sheet of plastic sheeting consists of a woven or braided black high-density polyethylene core and a layer of low-density polyethylene laminate on each side [8], with a minimum weight of 200 g/m^2. Chemical additives such as calcium carbonate are incorporated into the core and outer layers to give the tarpaulin color, soften it, modify its opacity, and enhance its resistance to UV rays [9]. Plastic sheeting can have a significant negative impact on the environment in the absence of local collection and recycling infrastructures. **Figure 1** shows photographs of two types of emergency humanitarian shelter commonly used in Burkina Faso.

Figure 1. Standard emergency shelters: (a) Sahelian tent type [10], (b) Gabled frame type.

- The Sahelian tent emergency shelter is an improvement on the traditional tents used in the Sahel by nomadic or semi-nomadic populations. It consists of a framework of metal or wooden poles, see **Figure 1(a)** and a eucalyptus wood frame. The structure is covered with plant mats (mainly straw) and plastic sheeting. It has an approximate lifespan of one year, with living space ranging from 14 to 24.5 m^2, and can accommodate 4 to 7 people [11].
- The gabled frame tent with a double-pitched roof has a herringbone structure, **Figure 1(b)**, covered with straw mats for thermal insulation and tarpaulin for waterproofing and weather resistance. This type of tent is best suited to sedentary populations. The standard size is 17.5 m^2 and can accommodate 5 people (at a rate of 3.5 m^2 per person, according to humanitarian standards). Our study focuses on this model of emergency shelter made from plastic sheeting.
- The Refugee Housing Unit is a prefabricated tent, more resistant to wear and tear and semi-durable; its average lifespan is 3 years, and its interior has a surface area of 17.5 m^2 (for 5 people). The structure is made of galvanized steel, with panels for thermal insulation. The envelopes of emergency shelters have a low thermal mass, which, combined with the low strength of the tarpaulins, limits the possibility of thermal insulation [1] [12]. This suggests that their interior comfort remains problematic in hot climates.

2.2. Description of the Bioclimatic Emergency Shelter Prototype

The prototype emergency shelter (**Figure 2**) is 5.0 m long, 3.5 m wide, and 2.4 m high. It covers a total floor area of 17.5 m^2, can shelter 5 people, occupies a volume of around 42 m^3 and is in direct contact with the ground. The walls are made of compressed earth blocks (C.E.B.) stabilized with rice husk ash and supported by an embedded iron framework that holds the structure firmly in place. The blocks are self-locking, making the shelter removable. The shelter can, therefore, be dismantled and reassembled elsewhere, or, for example, when the people concerned return to their home localities. The roof is made of sheet metal but insulated from the inside by a false ceiling made from an eco-material of rice husks and kapok wool.

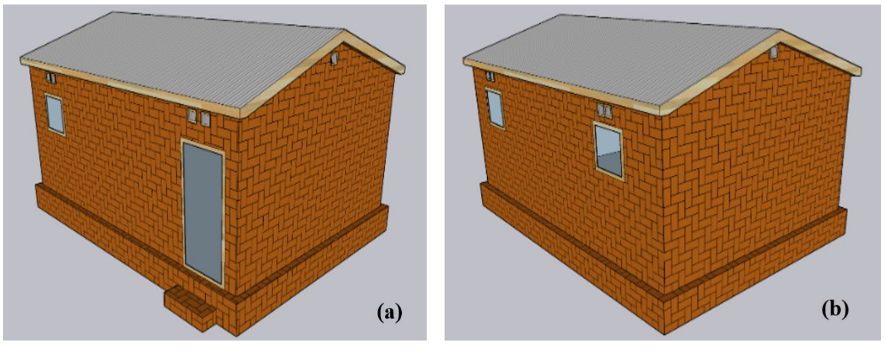

Figure 2. Prototype emergency shelter made from bio-based materials: (a) front facade and (b) rear facade.

Some values for the thermo-physical properties of the materials (corrugated sheet metal, iron louvers, tarpaulin and straw mats) making up the shelter envelope were determined by characterization tests, while others were taken from the literature [13]-[18]. They are given in **Table 1** below:

Table 1. Thermo-physical properties of various materials.

Emergency shelter	Materials	Thermophysical properties			
		Thickness (m)	Density ($kg \cdot m^{-3}$)	Heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Shelter prototype	Walls (Stabilized BTC)	0.22	1900	800	0.80
	Roof (Corrugated iron)	0.00035	7800	480	50.00
	Insulation (Eco-material)	0.02	936	772	0.14
	Floor (Cement screed)	0.08	2450	920	2.00
	Openings (Iron louvers)	0.001	7824	1090	45.28
Tarpaulin tent	Tarpaulin (Polyethylene)	0.008	920	2200	0.33
	Insulation (Straw mats)	0.0007	45	1330	0.07
	Floor (Earthen floor)	0.08	2450	920	2.00
	Openings (Corrugated iron)	0.0035	7800	480	50.00

2.3. Measuring Instruments

Measurements were taken of: air temperature and relative humidity (inside and outside) in both types of shelter, solar radiation, mean radiant temperature of interior walls and thermal comfort indices. Various measuring instruments were used: ambient temperature and humidity sensors, model "MSR 145 S". The parameters of hygrothermal comfort and heat index were evaluated using an "87786 WBGT Logger" equipped with a black globe thermometer to measure average radiation temperature, an anemometer to measure air speed in accordance with standard EN 13779, a thermometer to measure air temperature and a hygrometer to measure relative humidity.

For measurement, the WBGT-meter is positioned (for a seated individual) at head, trunk and leg height, or 1.5 m above the floor. Internal and external building wall, roof and floor temperatures were measured using Graphtec Midi Logger GRAPHTEC GL240 data loggers fitted with J-type thermocouples. The temperature range measured by the thermocouples varies from −100˚C to +100˚C, with an accuracy of ± 0.5˚C. Solarimeters were used to measure the overall flux density of solar radiation entering the shelter.

2.4. Method for Assessing Hygrothermal Comfort in Emergency Shelters

To define the adaptive comfort range for natural ventilation, we drew on existing studies [19]-[23], standards (NF EN 15251, RE2020) [24], our in-situ surveys, feedback on the subjectivity of occupants' perception of thermal comfort and acclimatization to the hot, dry tropical climate. For our study, we decided that a comfort temperature (an operative indoor temperature) of between 20˚C and 32˚C (20˚C ≤ Top < 32˚C) is realistic for the satisfaction of 80% of occupants. The pairs of points (outdoor temperature, indoor operating temperature) are plotted on a diagram. On the basis of this range, and for periods when the shelter is occupied, the number of hours during which the shelter's inside temperature is outside the said range is counted, and defines the time during which comfort is not achieved (discomfort time). Then, the sum of the temperature differences (hour by hour) between the indoor air temperature and the maximum comfort temperature was calculated to take into account the discomfort degree-hours (DH), expressed in ˚C·h, it is an index of thermal discomfort intensity [18] [19].

2.5. Modelling and Simulation of Shelter Thermal Behavior

The heat and moisture transfer equations between the shelter and its environment, including the occupants, are established by assimilating the interior air volume and wall surfaces (interior and exterior) to temperature nodes. For modeling and simulation, the simplifying assumptions are:

1) the thermophysical properties of building materials are assumed to be constant;

2) housing wall temperatures are assumed to be uniform;

3) the surfaces (internal and external) of the habitat are assimilated to gray bodies;

4) the celestial vault behaves like a black body;

5) interior air is assumed to be homogeneous and of uniform temperature.

- Heat balance of an exterior wall node

$$\begin{aligned}\rho_{se}\cdot e_{se}\cdot c_{se}\frac{\mathrm{d}T_{se}}{\mathrm{d}t}=h_{ce}\left(T_{ae}-T_{se}\right)+h_{rc}\left(T_c-T_{se}\right)+h_{rs}\left(T_s-T_{se}\right)\\+U_{se}\left(T_{si}-T_{se}\right)+\alpha_{se}G\end{aligned} \tag{1}$$

The coefficients were calculated using the correlations of W.H Mc Adams-[25].

$$h_{ce}=5.7+3.8\,v \tag{2}$$

$$h_{rc}=\sigma\varepsilon_{se}\left(T_c^2+T_{se}^2\right)\left(T_c+T_{se}\right)\left(\frac{1+\cos\beta}{2}\right) \tag{3}$$

$$h_{rs}=\sigma\varepsilon_{se}\left(T_s^2+T_{se}^2\right)\left(T_s+T_{se}\right)\left(\frac{1-\cos\beta}{2}\right) \tag{4}$$

$$T_c=0.0552T_{ae}^{1,5} \tag{5}$$

$$T_s=T_{ae}+2 \tag{6}$$

- Heat balance of an interior wall node

$$\rho_{si} \cdot e_{si} \cdot c_{si} \frac{\mathrm{d}T_{si}}{\mathrm{d}t} = U_{si}\left(T_{se} - T_{si}\right) + h_{ci}\left(T_{ai} - T_{si}\right) + h_{rm}\left(T_{rm} - T_{si}\right) \tag{7}$$

$$h_{ci} = a\left|T_{si} - T_{ai}\right|^{n} + b \tag{8}$$

$$h_{rm} = \sigma\varepsilon_{si}\left(T_{rm}^2 + T_{si}^2\right)\left(T_{rm} + T_{si}\right) \tag{9}$$

$$T_{rm} = \frac{\sum_{p=1}^{N_{pi}}\left(S_{si,p} \times T_{Si}\right)}{\sum_{p=1}^{N_{pi}} S_{si,p}} \tag{10}$$

- Indoor air node heat balance

$$\rho_{ai} V_{ai} c_{ai} \frac{\mathrm{d}T_{ai}}{\mathrm{d}t} = \sum_{p=1}^{N_{pi}} h_{ci,p} S_{si,p}\left(T_{ai} - T_{si,p}\right) + \rho_{ai} c_{ai} \dot{Q}_v\left(T_{ae} - T_{ai}\right) + \Phi_{\mathrm{int}} \tag{11}$$

- Method for solving the system of equations

The overall heat transfer balance in the shelter is the coupled system of equations (1), (7), (10) and (11), comprising all the balances for the walls, the interior air volume and the floor. The system of differential equations is then discretized at time step $\Delta t = 1$ h using the finite-difference method according to the implicit scheme, and then translated into matrix form according to Equation (12).

$$\left(\frac{C}{\Delta t} - A\right) * T\left(t + \Delta t\right) = \frac{C}{\Delta t} * T\left(t\right) + B * U\left(t + \Delta t\right) \tag{12}$$

The resulting discretized system is solved by an iterative Gauss-Seidel method, assuming that at the initial time t0 of the simulation, all temperatures are equal to room temperature. At each time step Δt, heat transfer coefficients are calculated at time $t + \Delta t$. The temperature values are then calculated and compared with the previous values. If the residual (absolute error) between these values is greater than the chosen tolerance ($\varepsilon_T = 0.1$˚C), the calculated values replace the previous ones, and so on until the temperatures converge.

3. Results

3.1. Climatic Conditions in the Study Zone

The study area is the town of Kongoussi, around 110 km north of Ouagadougou, the capital of Burkina Faso. Its geographical coordinates are: latitude 13.32˚ North, longitude 1.53˚ West, and altitude 330 m. The climate is tropical, hot, and dry, with a very hot period lasting around three months (March, April, May). Average daily maximum temperatures exceed 38˚C (min 30˚C and max 42˚C) for a typical 10-year period (2014-2023). Figure 3 shows the evolution of minimum (TaeMin), maximum (TaeMax), and average (TaeMoy) outdoor ambient temperature values for the typical year. April is the hottest month of the year, with average daily maximum temperatures in excess of 40˚C and minimum temperatures of 28˚C. The cool season lasts around two months (December, January), with average daily maximum temperatures below 33˚C. January is the coldest month of the year, with average minimum temperatures of 18˚C and maximums of 32˚C.

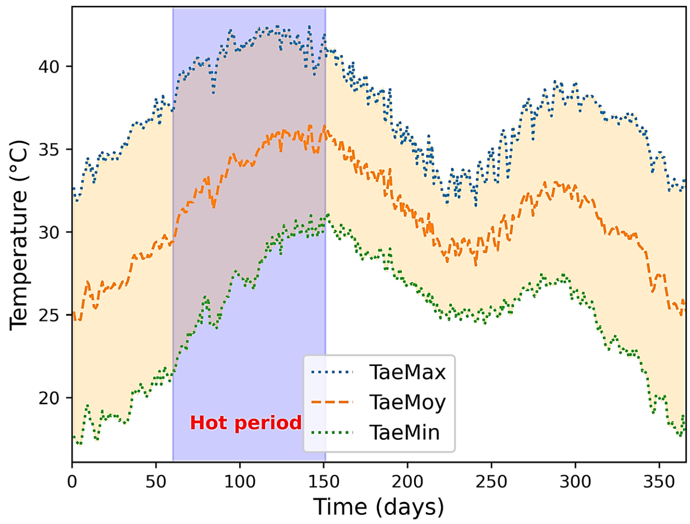

Figure 3. Average daily ambient temperature for a typical year.

3.2. Thermal Performance of Emergency Shelters

1) Experimental measurements on the humanitarian plastic sheeting tent (TBP)

The measurement campaign lasted 22 days (from October 27 to November 17, 2024). **Figure 4** compares the simulated and measured temperatures of the air inside the plastic sheeting tent (TBP) for a seven-day measurement period. The minimum temperature is 18.2˚C (simulated value 21.6˚C), the maximum temperature is 45.4˚C (simulated value 42.7˚C), and the mean temperature is 29.6˚C (simulated value 30.9˚C). The mean absolute error (MAE) is 3.9˚C, the root mean square error (RMSE) is 4.2˚C, the mean relative error does not exceed 14.3%, and the coefficient of determination is 0.89. The linear regression line is shown in **Figure 5**.

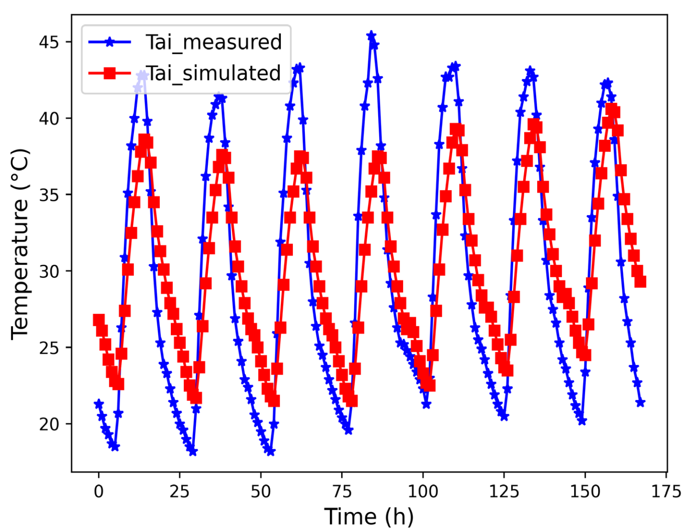

Figure 4. Measured and simulated indoor air temperature trends in the TBP tent.

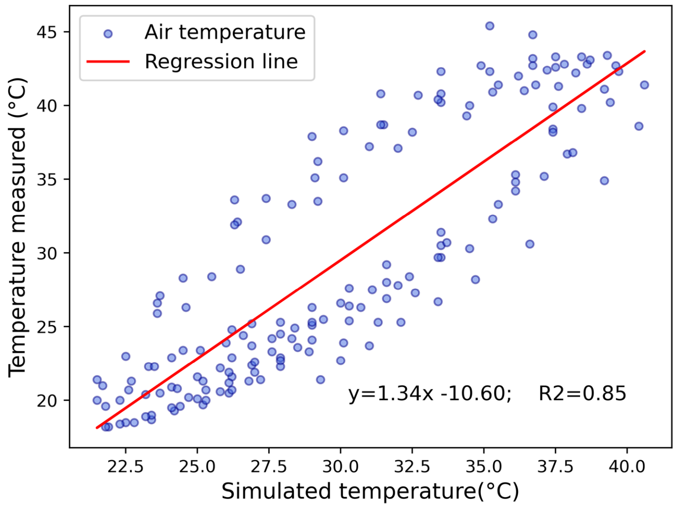

Figure 5. Linear correlation between measured and simulated TBP tent interior air temperatures.

2) Shelter thermal damping and damping factor

Figure 6 shows, for the typical year, the evolution of emergency shelter temperatures as a function of time and the damping of the heat wave induced by the two shelters' envelopes. We found that the inside air temperature of the plastic sheeting tent (TBP) was generally higher than that of the outside air during the day (6 a.m. to 6 p.m.). On the other hand, the prototype made from bio-sourced materials (PMB) induces a damping of up to 8.4˚C compared with the outside temperature; the annual average is 5.8˚C.

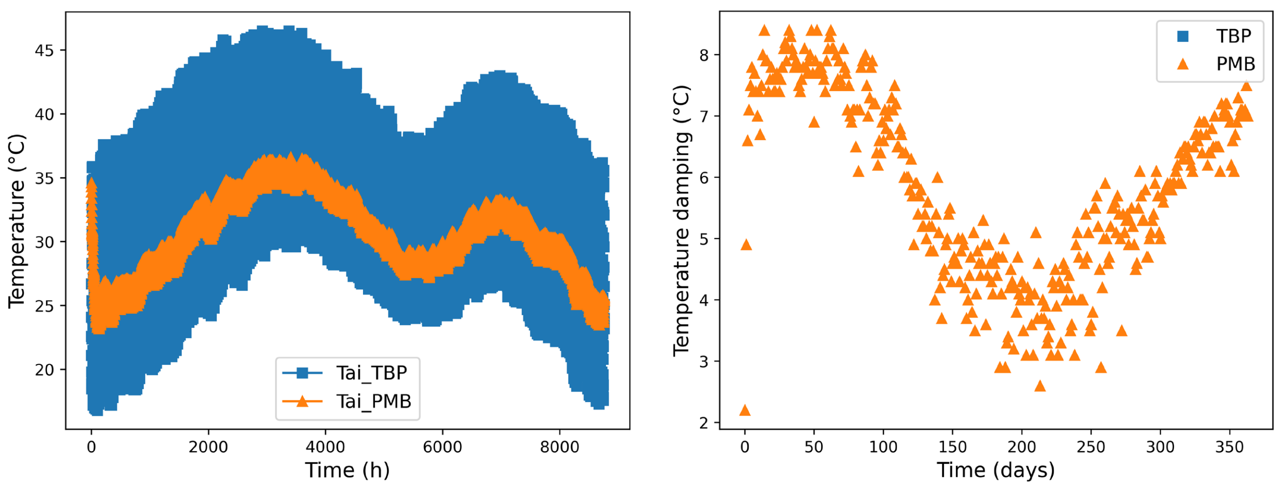

Figure 6. Evolution of shelter thermal damping over the year.

Figure 7 shows the temperature of the two shelters on the hottest day of the typical year. It also shows the damping of the thermal wave induced by the prototype made of bio-sourced materials in relation to the outside air temperature: the damping is 6.0˚C for the PMB.

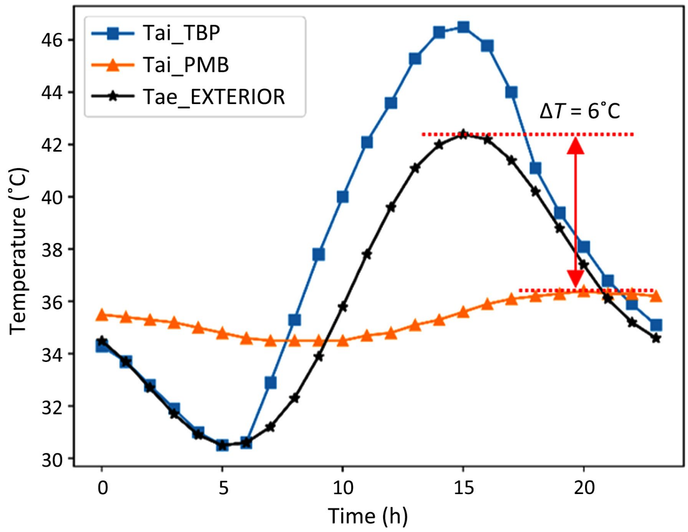

Figure 7. Thermal damping of shelters on the hottest day of the year.

The PMB prototype has a damping factor f ranging from 0.12 to 0.28, with an average damping factor of 0.14. It therefore generates a reduction in thermal amplitude ranging from 71% (f = 0.29) to 88% (f = 0.12), with an average reduction of 86% (f = 0.14).

3) Thermal phase shift of the shelters

Figure 8 shows the frequency, in number of days, of the thermal phase shifts of the two shelters.

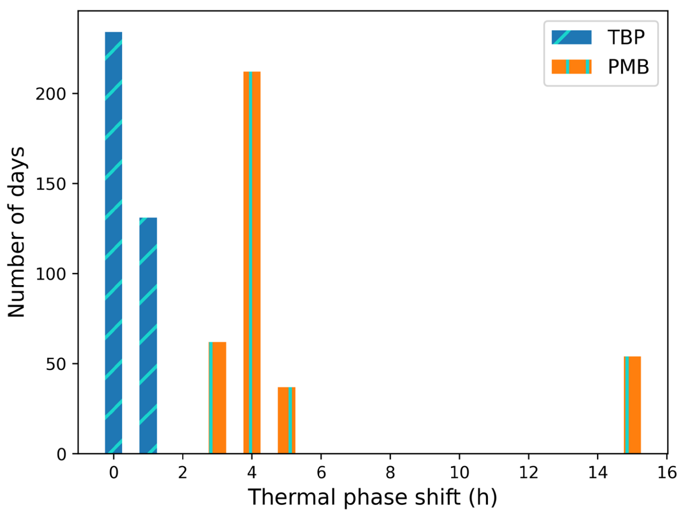

Figure 8. Frequency of thermal phase shifts for the two shelters over the year.

For the plastic sheeting tent (TBP), the maximum thermal phase shift is 1 h (133 days of the year are concerned, i.e. 36%), while the prototype made from biosourced materials induces a thermal phase shift that varies between 3 h and 15 h, with an average of 5.6 h. Of the 365 days of the year, 61 days (17%) have a thermal phase shift of 3 h, 206 days (56%) have a phase shift of 4 h, 44 days (12%) have a phase shift of 4 h and 54 days (15%) have a thermal phase shift of 15 h. **Figure 9** shows the thermal phase shift of the prototype on the hottest day, at 5 h.

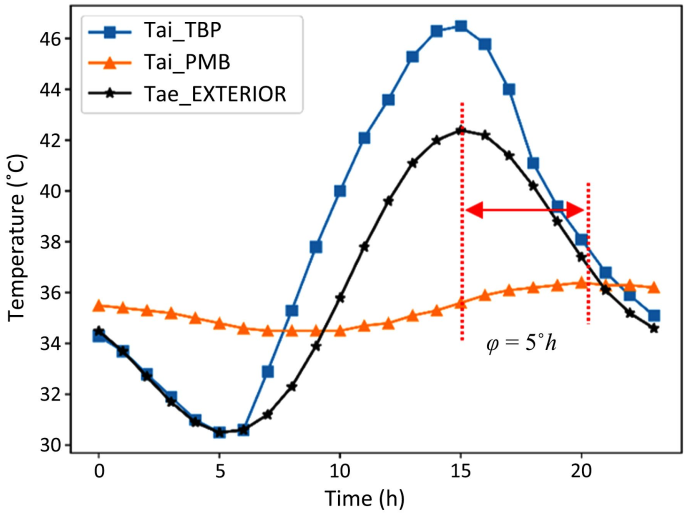

Figure 9. Thermal phase shifts in shelters on the hottest day of the year.

3.3. Thermal Comfort in Shelters

1) Intensity of thermal discomfort in shelters

Figure 10 shows, for the warmest period of the year, the intensity of discomfort in shelters in terms of discomfort degree-hours as defined by RE2020. For the same length of occupancy over the whole year, the thermal discomfort intensity (in discomfort degree-hours) is 33,886˚C·h for the plastic sheeting tent (TBP) and 10,513˚C·h for the prototype made from bio-sourced materials (PMB). The PMB reduces thermal discomfort by 69% (hot period 55%).

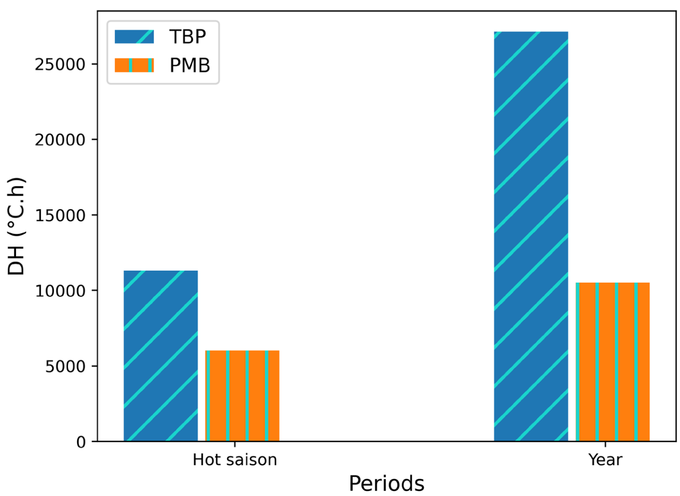

Figure 10. Intensity of hot discomfort in shelters during the hot period and year.

We can see that the plastic sheeting tent presents a more intense thermal discomfort, whatever the month of the year (**Figure 11**). The good comfort of the biobased prototypes is due to the good inertia of the biobased materials (clearly superior to that of the plastic sheeting) and to the insulation of the roof by the biobased thermal corrector (which insulates better than the straw mats of the tent).

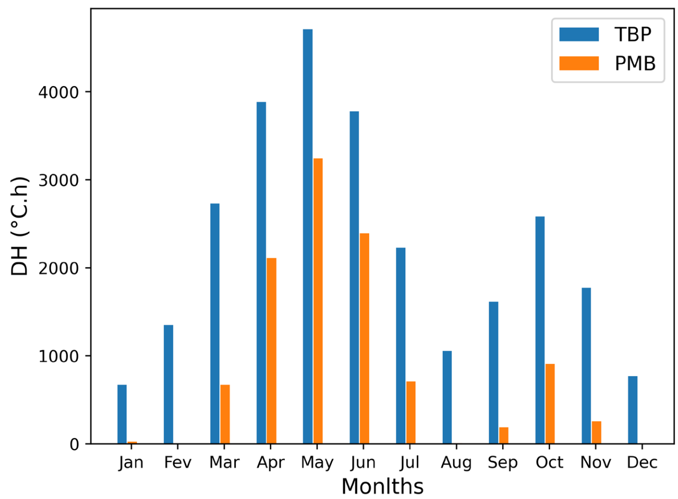

Figure 11. Intensity of hot discomfort in shelters by month.

2) Duration of thermal discomfort in shelters

To determine the duration of hot discomfort in shelters (temperature above 30˚C at night and 32˚C during the day), we counted the number of hours during which the indoor operating temperature exceeded these maximum comfort temperatures. The percentage of uncomfortable hours in relation to the total occupancy time of each shelter (8760 h in the year and 2208 h in the hot season) is given in **Table 2**.

The plastic sheeting tent (TBP) has a relative discomfort time of around 62% of total occupancy time during the year. The prototype (PMB) reduces discomfort to 45% of annual occupancy time. We also note that it is only during the hottest months (March, April, May) that the PTB prototype registers higher discomfort times than the plastic sheeting tent.

Table 2. Duration of hot discomfort as a function of shelter type.

Periods	Discomfort indicators	Standard tent	Prototype shelter
		TBP	PMB
Year	Number of hours of discomfort	5415 h	3919 h
	% of duration of discomfort	62%	45%
Hot period	Number of hours of discomfort	1742 h	1817
	% of duration of discomfort	79%	82%

The percentages of discomfort hours in relation to total occupancy time, day and night, are given in **Table 3**. Over the year, the percentage of discomfort duration is 76% for the TBP and 30% for the PMB (61% comfort improvement) for the PMB. However, at night, the prototype slightly prolongs the duration of hot discomfort while considerably reducing its intensity.

Table 3. Duration of hot discomfort during the day and night.

Periods	Discomfort indicators	Year		Hot period	
		TBP	PMB	TBP	PMB
Jour (5 h - 18 h)	Number of hours of discomfort	3316 h	1310 h	17 h	753 h
	% of duration of discomfort	76%	30%	83%	68%
Nuit (18 h - 5 h)	Number of hours of discomfort	2099 h	2609 h	825 h	1064 h
	% of duration of discomfort	TBP	PMB	TBP	PMB

4. Conclusion

The problem of the unsustainability and poor weather resistance (wind, rain, sun) of emergency shelters, particularly plastic sheeting tents, is an acute one. The aim of this study was to evaluate and compare the hygrothermal performance and comfort of the plastic sheeting emergency tents mainly used in Burkina Faso and a bioclimatic removable emergency shelter prototype. Using an experimental approach and numerical simulation, the study assessed the thermal performance and indoor comfort of the two types of shelter. Compared with a plastic sheeting tent, the prototype emergency shelter made from bio-based materials reduces thermal discomfort by an average of 69%, the amplitude of the thermal wave by 86% (average damping factor 0.14) and induces an average thermal phase shift of 5.6 hours. The comparative study showed that the prototype emergency shelter made from bio-based materials offers added value in terms of durability and interior comfort.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclatures

ρ_{se}: Exterior wall density (kg/m^3)
e_{se}: Exterior wall thickness (m)
c_{se}: Heat capacity of an external surface (J/(kg·K))
α_{se}: Absorptivity coefficient of an exterior wall
h_{ce}: Coefficient of convective exchange with outside air (W/(m^2·K))
h_{rc}: Coefficient of radiative exchange with the sky (W/(m^2·K))
h_{rs}: Coefficient of radiative exchange with the ground (W/(m^2·K))
Use: Heat transfer coefficient within an external wall (W/(m^2·K))
T_{se}: Temperatures of: the exterior wall (˚C)
T_{ae}: Outside air temperature (˚C)
T_c: Sky temperature (˚C)
T_s: Ground temperature (˚C)
T_{si}: Interior wall temperature (˚C)
G: Global solar radiation (W/m^2)
v: Wind speed (m/s)
σ: Boltzmann constant
ε_c: Emissivity of the sky
ε_s: Ground emissivity
ε_{se}: Emissivity of external wall
ρ_{si}: Density of an interior wall (kg/m^3)
e_{si}: Wall thickness (m)
c_{si}: Heat capacity of an interior surface (J/(kg·K))
U_{si}: Exchange coefficient: conductive within an interior wall (W/(m^2·K))
h_{ci}: Convective coefficient with indoor air (W/(m^2·K))
hrm: Average radiation coefficient of all interior walls (W/(m^2·K))
T_{si}: Interior wall temperature (˚C)
T_{ai}: Interior air temperature (˚C)
T_{rm}: Average radiation temperature of all interior walls (˚C)
$S_{si,p}$: Surface area of an interior wall p (m^2)
ρai: Density of indoor air (kg/m^3)
V_{ai}: Volume of indoor air (m^3)
c_{ai}: Heat capacity of indoor air (J/(kg·K))
Q_v: Indoor air renewal rate (m^3/h)
Φ_{int}: Interior heat flux (W/m^2)
$h_{ci,p}$: Convective exchange coefficient of the interior wall p (W/(m^2·K))
f: damping factor
φ: thermal dephasing

Indices

se: exterior surface
si: interior surface

ai: indoor air
ae: outside air
int: interior