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Experimental Study of the Thermal Behavior of a Bioclimatic Building Prototype in a Sahelian Zone

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Abstract

Buildings constructed with modern materials (cement blocks, sheet metal, reinforced concrete, etc.) in the Sahelian zone often generate excessive electricity consumption and consequently very high electricity bills. This study is a contribution to the development of new building types based on the principle of bioclimatic construction. The aim is to find materials suited to the Sahelian climate and improve thermal comfort. To this end, an experimental study of the hygrothermal behavior of a bioclimatic building prototype with a domed roof is being carried out. Site meteorological data, air temperature and relative humidity of the building's internal environment were measured for three climatic seasons in Burkina Faso. The data acquisition system consists of thermocouples, solarimeters and humidity meters, and the data are processed using Excel and Origin Pro software. The results show that, despite the high temperature values (between 36˚C and 39˚C) of the internal environment measured in the hot season, good thermal performance is achieved, in particular an average phase shift of 7.17 h and an average damping of 10.81˚C. The dome-roofed building could therefore contribute to limiting heat transmission to the building interior, improving thermal comfort all year round. Analysis of humidity profiles shows that indoor humidity varies between 66% and 80% for the September period, and between 44% and 69% for the January period. The high values of internal ambient humidity could be reduced by very good ventilation of the building. This study shows that the proposed bioclimatic building prototype with domed roof could be integrated into the Sahelian habitat.

Keywords

Thermal Comfort, Hygrothermal Behavior, Bioclimatic Building, Thermal Inertia, Domed Roof

1. Introduction

Burkina Faso is a Sahelian country characterized by high temperatures (up to 45˚C), with building models based on Western models requiring cooling systems that consume large amounts of energy. Energy consumption in terms of electricity for air conditioning alone accounts for 30% to 70% of the population's total consumption [1]. The main reason for this rise in energy consumption is the quest for comfort, a priori thermal comfort in indoor living. Taking thermal comfort into account in building design is important not only for the quality of indoor environments, but also for the amount of energy to be supplied for room equipment [2]. One of the conditions for achieving thermal comfort in the home is the use of bio-sourced materials combined with good bioclimatic construction. It is therefore imperative to find construction techniques adapted to the Sahelian context, making the most of available local resources. The right combination of biobased materials, envelope shape and roof form could help improve indoor thermal comfort. According to a study by Kémajou *et al.*, thermal comfort can be achieved through a judicious choice of building materials [3]. Earthen materials are an alternative to modern materials, as shown by several studies in the Sahelian zone. [4]-[7] have shown in their work that buildings constructed with local materials (adobe, compressed earth blocks, cut laterite blocks) have better thermal performance than those built with materials such as cement blocks. The roof is responsible for 50% of cooling requirements in hot-climate countries. Consideration needs to be given to reducing roof-generated cooling requirements and improving indoor comfort in hot-climate countries. Bioclimatic buildings with domed roofs are often built in the Middle East and in some North African countries for their ability to limit heat propagation. Buildings with domed roofs are rarely found, if at all, in the Sahelian zone. These types of buildings have been the subject of several studies designed to highlight their thermal and solar performance. In their study, Victor Gomez-Munoz *et al.* [8] assessed the thermal performance and instantaneous self-shading effect of a hemispherical vault roof. The results obtained were compared with the solar flux received by the flat roof of a modern low-cost home in Mexico. They found that the hemispherical vault received around 35% less energy than flat roofs, in addition to having other advantages, such as greater ceiling height and ventilation possibilities. The Sahelian zone is located in a very sunny area, and the self-shading properties of domed roofs could help reduce the amount of heat absorbed by them. As Ahmadreza K.

Faghib *et al.* [9] have shown, the maximum temperature of the internal air can then be reduced. They studied the thermal performance of domed roofs to determine how they can help to reduce maximum internal air temperatures during the hot seasons. The results of the study show that the performance of buildings with domed roofs is better than that of buildings with flat roofs. In this work, we experimentally investigate the hygrothermal performance of a bioclimatic building with a domed roof and constructed with Kenaf fiber-added earth bricks. To this end, in situ measurements of meteorological data at the building site, the measurement of the building's internal air temperature and the relative humidity of the internal air over three climatic seasons in the Sahelian zone were carried out. This study will provide an insight into the thermal and hydric behavior of buildings with domed roofs in hot-climate countries, compared with conventional buildings, and identify mechanisms for improvement if necessary through a numerical study.

2. Materials and Method

2.1. Presentation of the Bioclimatic Building Prototype

The bioclimatic building is located at the Research Institute for Applied and Technological Sciences (IRSAT) in Ouagadougou, more precisely in the "Kossodo" industrial zone, a section of the National Center for Scientific and Technological Research (CNRST). It is built according to the Nubian vault construction technique, using modern buildings techniques and modern materials such as cement, plastic sheeting, paint, etc. The aim is to ensure the durability of the building's structure. The walls have an octagonal shape and are built with large composite earth bricks (clay + kenaf fiber [4]) of the following dimensions 40 cm * 13 cm * 13 cm. The domed roof is made of adobe bricks (composed of clay and kenaf fibers) measuring 23 cm × 13 cm × 5 cm. The thermophysical properties of the earth bricks used in the construction of the bioclimatic building are given in **Table 1**.

Table 1. Data acquisition periods.

	Density (kg/m^3)	Thermal conductivity (W/m·K)	Thermal capacity (J/K·kg)	Thermal resistance (m^2·K/s)	Thermal diffusivity (m^2/s)	Thermal effusivity (J/m^2·K·s$^{1/2}$)
Wall brick	1923.08	0.447	791	2.239	2.94×10^{-7}	820.320
Roof brick	2073.58	0.416	79,111.69	2.425	$3.0.8 \times 10^{-7}$	1004.390

The building has three openings, two windows and a door (**Figure 1**). The interior volume of the building is 20.66 m^3, *i.e.* 6.66 m^3 for the interior space of the dome and 14 m^3 for the interior space of the walls. **Figure 2** shows the floor plan of the building, a plan view of the building with dome and a plan view of the house without dome.

Figure 1. View of the east side, north-east side and north side of the building.

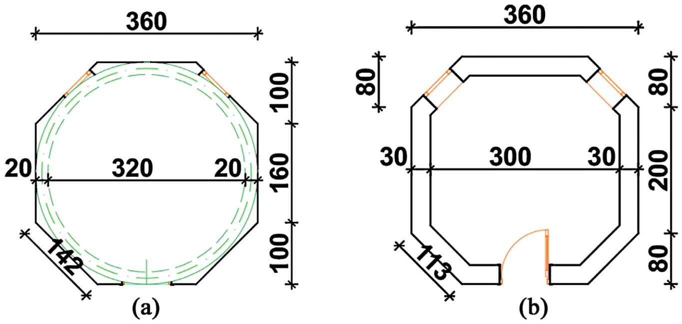

Figure 2. (a) Plan view of house with dome; (b) Plan view of house without dome.

2.2. Instrumentation

Limited resources and the lack of certain measuring devices (air velocity, relative humidity and temperature) meant that we were unable to collect all the data needed to assess thermal comfort. We therefore turned our attention to measuring environmental parameters such as air temperature, relative humidity and solar flux, which can be used to assess the hygrothermal behavior of bioclimatic buildings.

2.2.1. Measurement of Outdoor Ambient and Indoor Ambient Temperatures

The internal and external air temperatures are measured using J-type thermocouples, all connected to a Midi-logger GL220 datalogger. The thermocouple used to measure the internal air temperature is positioned 1.5 m from the low floor, and the thermocouple used to measure the internal air temperature is positioned 2.5 m from the low floor.

2.2.2. Measurement of Relative Humidity in Indoor and Outdoor Ambient Air

Data on the relative humidity of indoor air and outdoor air are collected by two Type MSR 320669 humidity measurement modules. The two moisture meters are stand-alone, independent of each other, and enable air humidity to be recorded. One is placed in the indoor environment to measure indoor humidity, and the other in the outdoor environment to measure outdoor humidity.

2.2.3. Mesure du Rayonnement Solaire du Site

Solar radiation data from the site is measured using a solarimeter (Figure 3). It is placed outside the home, on a flat surface, inclined at an angle of 15˚ and facing south. The solarimeter is connected to the datalogger (Midi-logger GL220), which records the tapping data.

Figure 3. Solarimeter.

Measurements were carried out during the characteristic months of the different climatic seasons in Burkina Faso. Table 2 shows the different measurement periods.

Table 2. Data acquisition periods.

Years	2023	2024	
Months	September	January	April-May
Periods	From 18/09/2023 to 30/09/2023	From 01/01/2024 to 12/01/2024	From 23/04/2024 to 6/05/2024

At the end of each measurement period, data is retrieved in CSV format on USB sticks, pre-processed in Excel and finally processed with Origin Pro software.

3. Results and Discussion

3.1. Total Solar Radiation

Solar radiation data for the period from 09/18/2023 to 09/26/2023 and for the period from 04/23/2024 to 05/06/2024 are shown in Figure 4.

The maximum values of global solar radiation measured differ from one day to the next for both measurement periods. The irradiance for the measurement period from 09/18/2023 to 09/26/2023 (Figure 4(a)) is very unstable compared with the irradiance for the measurement period from 04/23/2024 to 05/06/2024. Indeed, during September (the month marking the end of the rainy season), the period in which we carried out the first phase of measurements, some days were rainy, resulting in the presence of cloud cover. This cloud cover is certainly responsible for the instability of the observed radiation. Maximum values during this period regularly exceeded 1000 W/m². This can be explained by the fact that the sky is completely clear just after a rain, very often offering clear skies and conditions for measuring high values of global solar radiation. Over the period from 04/23/2024 to 05/06/2024 (Figure 4(b)), maximum solar radiation values ranged from 800 W/m² to 1000 W/m². These maximum values are typical of maximum radiation values in the warm season.

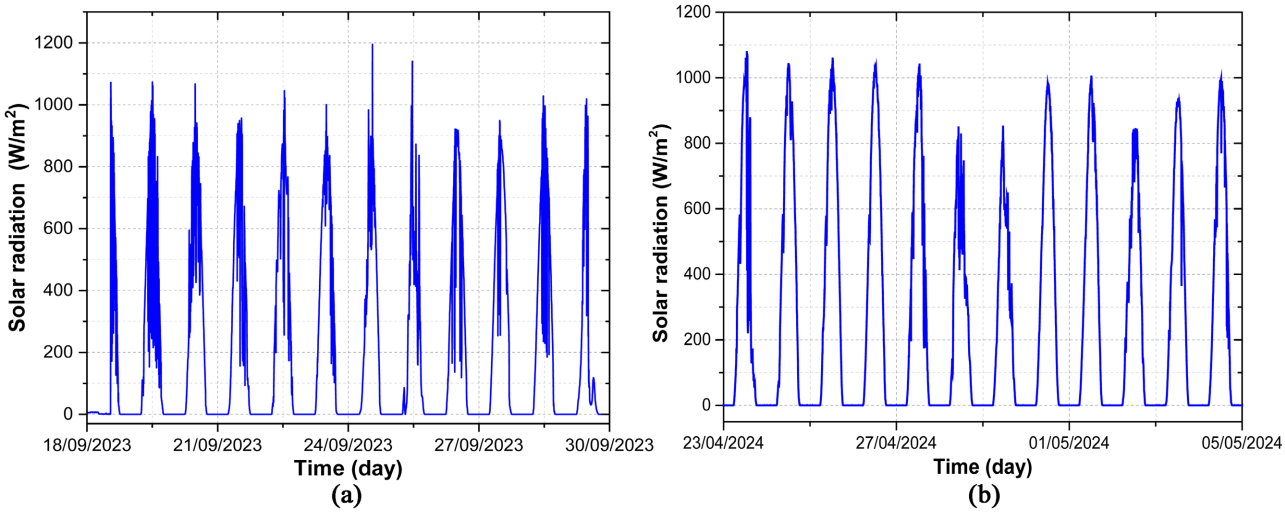

Figure 4. (a) Total solar radiation of the site from 18/09/2023 to 30/09/2023; (b) Total solar radiation of the site from 23/04/2024 to 06/05/2024.

3.2. Temperature Profile for Internal and External Ambient

3.2.1. Period from 18/09/2023 to 26/09/2023

Figure 5 shows the evolution of the temperatures of the inside air of the habitat, the inside air of the cupola and the outside air for the period from 09/18/2023 to 09/26/2023.

We can see from Figure 5 that the external air temperature varies between 19.1˚C and 42.5˚C, with an average of 29.32˚C. Maximum values are reached between 12 h 0 min and 14 h 40 min. Internal air temperatures range from 27.6˚C to 32.2˚C, while those in the dome vary from 27.8˚C to 32.9˚C. The maximum temperatures of the building's internal environments are reached between 21 h 40 min and 22 h 18 min respectively. Differences between the peak temperatures of the external and internal environments vary between 7˚C and 10˚C, and thermal phase shifts vary between 7 h and 9 h. The temperature of the external environment fluctuates considerably. This is due to the instability of climatic parameters (solar radiation, rain, etc.). The temperature of the air inside the building (that of the habitat and that of the dome) is very stable compared to the temperature of the outside air. The temperature inside the dome is slightly higher than in the living area. This is due to thermal draught, which causes warm, low-density air to be drawn into the dome and extracted through the chimney.

Table 3 summarizes the characteristic points of this measurement period.

These results show that, during the rainy season, the building considerably reduces heat transmission through the building walls.

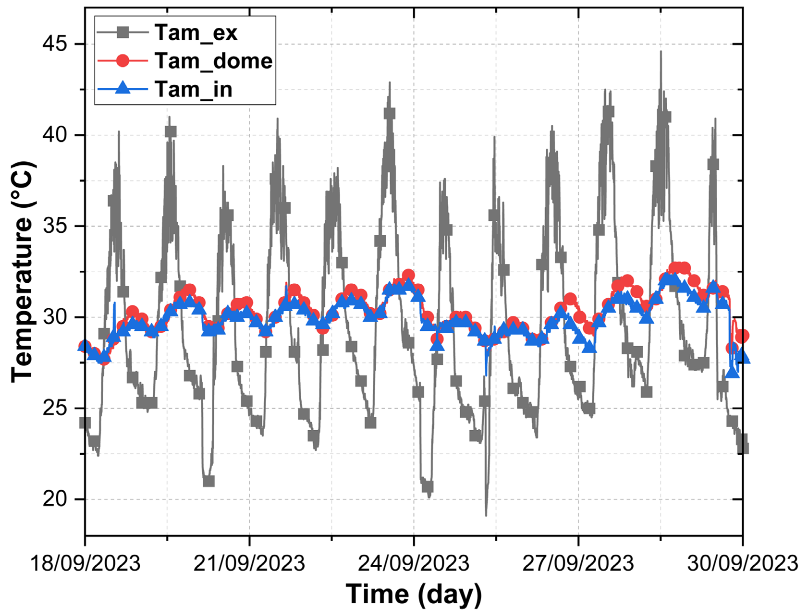

Figure 5. Temperature profile for internal and external environment from 09/18/2023 to 09/26/2023.

Table 3. Maximum, minimum and average temperature values for external, internal habitat and dome environments.

	Temp. Min (˚C)	Temp. Avg. (˚C)	Temp. Max (˚C)
External ambient	19.1	29.32	42.5
Internal ambient of the habitat	27.6	29.79	32.3
Internal ambient of the dome	27.8	30.15	32.9

3.2.2. Period from 05/01/24 to 08/01/24

Figure 6 shows the temperature variation of the external environment, the internal environment of the habitat and the internal environment of the dome, for the period 05/01/2024 to 08/01/2024. External temperature values range from 16˚C to 42.8˚C, with an average of 27.52˚C, and are reached between 12 h 35 min and 13 h. Internal temperature values vary between 26˚C and 29˚C, and internal air temperature values in the dome vary between 27˚C and 30˚C, and are reached between 12 h 40 min and 13 h 18 min. The difference between the peak external air temperature and the peak internal air temperature is around 10˚C. The phase shifts between the peaks of external and internal air temperatures vary between 8 h and 10 h. We note that the temperatures of the dome's external and internal environments reach their maximum values at the same times. This could be explained by the fact that wind speeds at this time of year are high, reaching 3.7 m/s on average, causing convective movements through the chimney opening at the top of the dome. The outside wind then penetrates through the chimney into the dome, impacting the temperature of its internal environment.

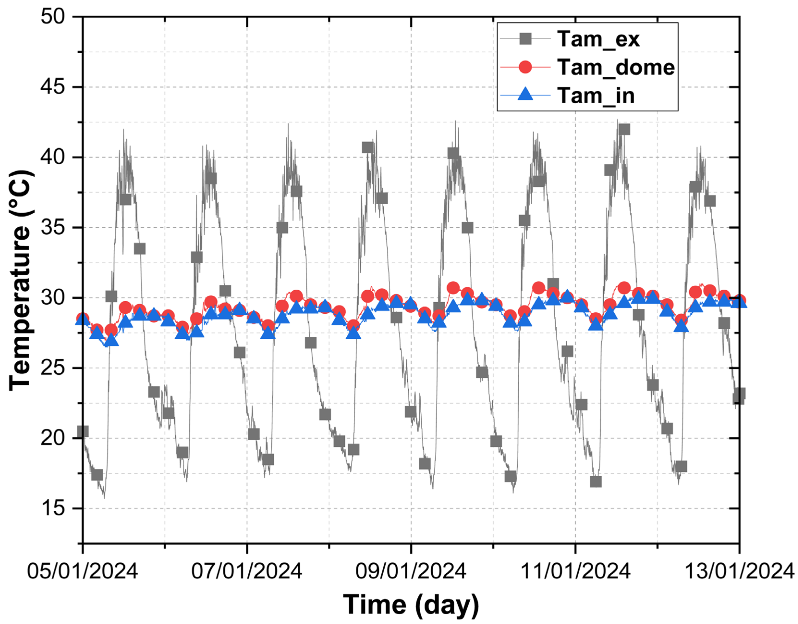

Figure 6. Internal and external ambient temperature profile for the period 05/01/2024 to 08/01/2024.

Characteristic ambient temperatures are summarized in **Table 4**.

Table 4. Maximum, minimum and average temperature values for external, internal habitat and dome environments.

	Temp. Min (˚C)	Temp. Avg. (˚C)	Temp. Max (˚C)
External ambient	16	27.57	42.8
Internal ambient of the habitat	26	28.77	29
Internal ambient of the dome	29.3	29.29	30.31

As with the rainy season, we can see that temperatures in the dome are slightly higher than those inside the house. This could be explained by thermal draught and air infiltration through the roof.

3.2.3. Period from 23/04/24 to 06/05/24

Figure 7 shows the temperature trends of the inside air of the habitat, the inside air of the dome and the outside air for the period from 04/23/2024 to 05/06/2024. External air temperatures range from 30.3˚C to 48.7˚C, with an average value of 35.72˚C. Building internal air temperatures range from 36.4˚C to 39.5˚C, with an average value of around 37˚C.

The maximums values for internal air temperatures are 39.2˚C for the habitat and 39.50˚C for the dome, and these maximum values are reached between 20 h 30 min and 22 h 30 min. There is a phase shift of around 5 h.

Observation of the curves shows that the temperatures of the internal environments (that of the habitat and that of the dome) show a similar trend. The temperature of the dome's internal atmosphere is slightly higher than that of the habitat's internal atmosphere. The temperatures of the building's internal air (that of the habitat and that of the dome) are very stable in relation to the temperature of the external air. This stability can be explained by the thermophysical properties of the two types of earth bricks, and by the thickness of these bricks, which prevent the transmission of high heat to the building interior, and consequently, fluctuations in internal ambient temperatures. From Figure 7, we can see the maximum, average and minimum temperature values for the different environments. These values are shown in Table 5.

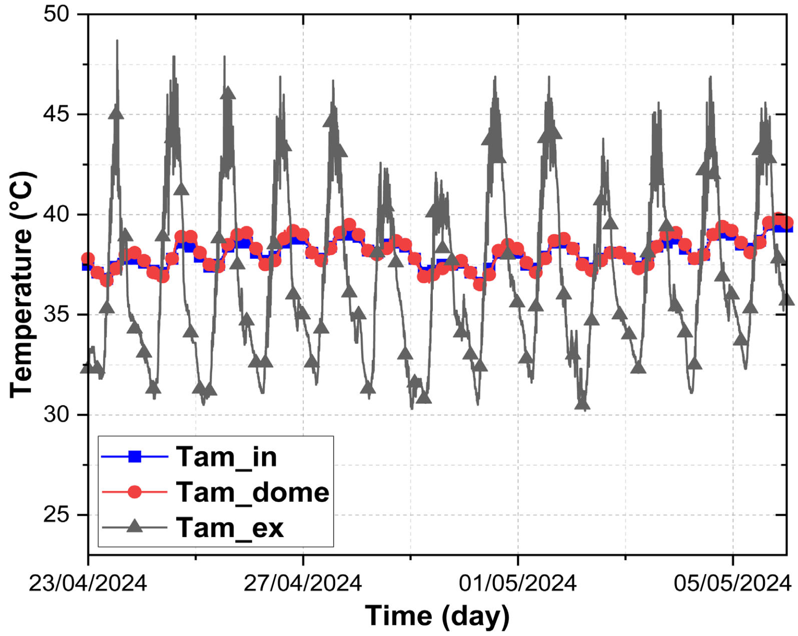

Figure 7. Temperature profile for internal and external environment from 04/23/2024 to 05/09/2024.

Table 5. Maximum, minimum and average temperature values for external, internal habitat and dome environments.

	Temp. Min (˚C)	Temp. Avg. (˚C)	Temp. Max (˚C)
External ambient	30.3	35.72	48.7
Internal ambient of the habitat	36.2	36.8	39.2
Internal ambient of the dome	36.4	37	39.5

We note that the damping between the external air temperature and the internal air temperature of the building during the warm period of the year is more than 8˚C.

3.2.4. Average Amortization and Average Thermal Phase Shift of the Internal Air Temperature in Relation to the External Ambient Air Temperature

The average differences between the peak temperatures and the average thermal phase shifts for the three measurement periods are summarized in Table 6:

Table 6. Maximum, minimum and average temperature values for external, internal habitat and dome environments.

	Average amortization	Average phase shift
From 18/09/2023 to 30/09/204	10˚C	7.4 h
From 05/01/2024 to 13/01/2024	11.95˚C	9.12 h
From 23/04/2024 to 24/05/2024	10.5˚C	5 h

Analysis of the table shows that during all measurement periods, the average amortization is above 10˚C and the average thermal phase shift is above 5h. To fully appreciate the results obtained, we compare our results with those obtained in the work of Etienne MALBILA *et al.* [10], who, in their work, evaluated the average phase shift and average amortization of a cement block building located in the same climatic zone. **Table 7** compares our work with that of [10].

Table 7. Comparison of our results with those obtained by [10].

	Average amortization (˚C)	Average thermal phase shift (h)
Work [10]	3.625	1
Ours results	10.81	7.17

These results show that the thermal performance of our buildings, when compared with buildings constructed using modern materials, is satisfactory. These results are linked to the thermophysical properties of adobe bricks mixed with kenaf fibers (see **Table 1**), which give the building the ability to delay and attenuate the transmission of heat to the interior of the dwelling. These performances can also be explained by the dimensions of the building's walls [11]. The shape and thickness of the roof also contribute to these results, and will be the subject of further study.

3.3. External and Internal Relative Humidity Profile

3.3.1. Period from 18/09/2023 to 26/09/2023

Figure 8 shows the external and internal air humidities measured over the period from 09/18/2023 to 09/26/2023. External humidity ranged from 20% to 76%, and internal humidity from 66% to 80%. Internal humidity was stable and very high during the measurement period. For reasons of time, measurements began one week after completion of the roof waterproofing work. Before the waterproofing system was installed, the roof was exposed to rain several times. The briquettes (clay + fibers) had therefore absorbed a large quantity of water. This water would have been transferred to the interior of the building, increasing the humidity inside. So, in addition to the moisture transferred through the walls, another source of moisture is responsible for the high humidity levels in the home. Earthen buildings are highly vulnerable to the elements, especially the roof. So it's vital to get the roof watertight before the rainy season. It's also worth noting that during the measurement period, doors and windows remained closed, which prevented the excess moisture accumulated in the home from evacuating. This also points to the absence of a good natural ventilation system, which could have helped reduce the humidity stored in the home.

3.3.2. Period from 05/01/2024 to 08/01/2024

Figure 9 shows the internal and external humidities for the period 05/01/2024 to

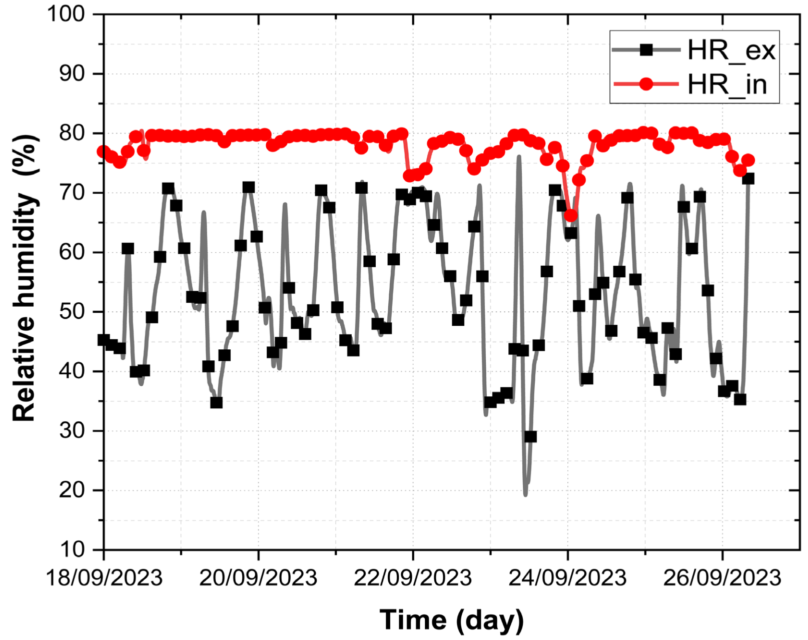

Figure 8. Relative humidity of internal and external environments from 09/18/2023 to 09/26/2023.

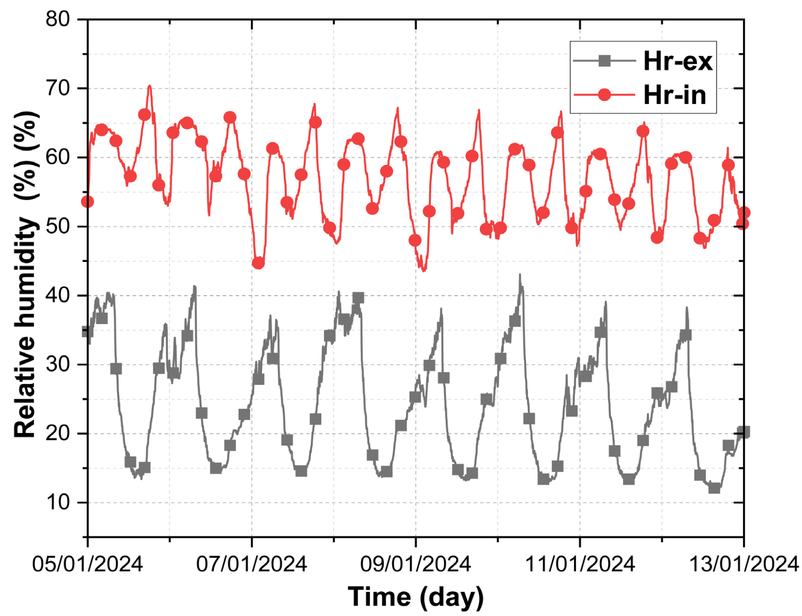

Figure 9. Relative humidity of internal and external environments from 05/01/2024 to 08/01/2024.

08/01/2024. External relative humidity ranged from 14% to 44%, and internal relative humidity from 44% to 69%, with an average of 59%. We can say that, for this period, internal relative humidity values are acceptable in relation to thermal comfort requirements. We note that the values of relative humidity inside the home remain higher than the values of relative humidity in the outside air. This could be explained by the fact that the door and windows were closed during the measurement period, preventing any exchange of air between the inside and outside of the home.

4. Conclusion

The experimental study examined the hygrothermal performance of the test building. Analysis of the results showed that temperatures in the habitat varied between 27.6˚C and 32.2˚C for the September period, between 26˚C and 29˚C for the January period, and between 36.5˚C and 39.2˚C for the April period. Internal temperatures obtained during all measurement periods are outside the comfort zone and more stable than external temperatures, which fluctuate widely. The average amortization and phase shift of the bioclimatic building are 10.81˚C and 7.17 h respectively. These results can be explained by the good thermophysical properties of the Kenaf-fiber-added clay bricks used in the building's construction (roof and wall) and by the thickness of the walls. Analysis of the humidity profiles shows that indoor humidity varies between 66% and 80% for the September period, and between 44% and 69% for the January period. Internal humidity is very high, indicating very poor ventilation in the test building. The amortisation and phase shift obtained show that the bioclimatic building with domed roof can be integrated into the Sahelian habitat and contribute to reducing the thermal gains to be combated and consequently contribute to improving thermal comfort. In future work, we will be looking at different simulation scenarios to improve the hygrothermal performance of the building, particularly with night-time ventilation. A complementary experimental study is required to determine the real impact of natural ventilation and air infiltration through the envelope on internal temperature and humidity.

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Conflicts of Interest

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

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