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**Research Article**

# Biomimicry of Termite Construction as a Path to Sustainability

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**Abstract**
As global temperatures continue to rise and energy consumption increases, there is an immediate requirement for sustainable solutions to decrease dependence on energy-intensive heating and cooling systems. This research explores passive cooling methods based on the termite mounds, which are recognized for their ability to regulate internal temperatures using natural ventilation and materials. Models resembling termites were built on a small scale using mixtures of soil, along with structural adjustments like ventilation holes, to evaluate how they affect the regulation of temperature and humidity. Information gathered from sensors based on Arduino showed that buildings with structural modifications consistently had lower internal temperatures and humidity levels in comparison to ambient conditions and models without adaptations. The results emphasize the possibility of using biomimicry in building designs as an energy-efficient option compared to traditional HVAC systems. This study suggests that termite-inspired designs can enhance thermal comfort and reduce energy consumption, contributing to climate change mitigation. Future studies should concentrate on adapting these models for real-world use in the construction industry.
**Keywords**: Passive Cooling, Bio-inspired, Termite Nest, Thermo Regulation.

## Introduction

### Background

Human energy consumption has risen steadily with technological advances, contributing to “global warming.” The increased use of fossil fuels has increased greenhouse gas levels, raising the Earth’s surface temperature and posing an “existential threat” to humanity [1].

In response to the increasing global temperature, air-conditioning has become widespread, with heating, ventilation, and air-conditioning systems accounting for over half of USA household consumption in 2020 [1, 2]. Addressing the energy demands of heating and cooling is crucial to mitigating climate change and adopting more sustainable solutions [3].

Notably, animals such as termites offer insights into reducing excessive energy consumption in heating and cooling systems. Termite mounds allow them to survive extreme heat through gas exchange, which removes excess $CO_2$ and ventilation, which dissipates metabolic heat [4]. These mounds create a suitable environment for termites without relying on external energy sources.

### Academic Context (“Dead Body”)

As buildings have significantly contributed to increased electricity consumption in recent years, researchers have explored alternative cooling techniques to reduce reliance on active cooling systems [5]. This shift has driven interest in passive cooling strategies that leverage natural processes to regulate indoor temperatures, reducing dependence on energy-intensive mechanical systems. Techniques, such as facade shading, solar cooling through thermal energy conversion, and natural ventilation have shown potential in reducing energy demand while maintaining suitable temperatures [6].

Research has also explored biomimicry in the search for passive cooling methods. Biomimicry draws inspiration from nature’s cooling strategies, which have been refined through evolution [7]. This approach has influenced new facade and building orientation designs [8]. Termite mounds, known for maintaining stable internal temperatures despite external fluctuations, have a potential for passive cooling. The structural features of termite mounds, such as networks of tunnels and chimneys, facilitate air circulation, maintaining the internal climate. Figure 1 shows this structure and its role in maintaining an optimal environment within the mounds.

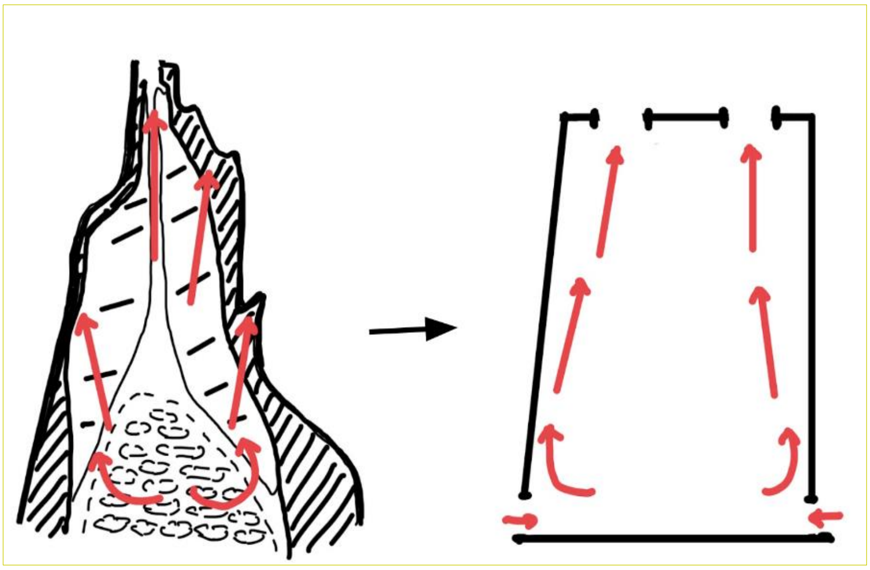

**Figure 1.** Natural ventilation in termite mounds (left) and its adaptation in this study (right). Both illustrations mark the air circulation path by red arrows. The illustration on the left demonstrates the air circulation path in a real-life termite mound (adapted from Jost [9]). The illustration on the right demonstrates the air circulation path in a simplified termite mound design.

Research has also shown that the material composition of termite mounds also plays a role in addition to their structure. Termite mounds are built from a composite of soil, saliva, and organic matter, forming a durable and insulating structure that helps regulate temperature [9].

Previous research has overlooked a key aspect of termite nests: the combined impact of their material properties and structural features, particularly their air ducts, when applied to smaller-scale models for building designs. Therefore, the present study represents a significant shift, moving beyond isolated strategies to a holistic approach that integrates both the material and structural elements of termite mounds to develop more effective and sustainable building solutions.

**Aim of Study**

This study eliminates the need for external energy consumption for cooling and heating by examining the impact of termite-inspired materials and structural adaptations on temperature and humidity control in small-scale models. Four structures were created: one with basic clay material and three with a termite mound-inspired soil mixture.

Structural adaptations, including variations in ventilation, were also examined. Temperature and humidity were logged using Arduino-based devices, with sensors placed inside and outside the structures during sunlight exposure.

**Methodology**

**Structure**

Three main structures were created for this experiment. The soil composition of the termite mound, as shown in Table 1 and adapted from Lima et al. [10], was replicated by mixing fine and coarse sand with silt and clay. Subsequently, a 15 × 20 × 20 cm frame was constructed using wooden sticks and wood glue, and the soil mixture was applied to the frame in a 1 cm thick layer to form the structure. The top was left open to test different ceiling designs, and the structure was dried in sunlight for 48 h. This was performed for all three structures.

Additionally, three ceilings were prepared as 20 × 20 cm rectangles with a 0.5 cm thickness. One ceiling had no holes, while the other two had four holes with 1-cm and 2-cm radii, respectively, in the center. Figure 2 shows the images of the made structures.

**Table 1.** Composition of material modification of structure. The material composition was adapted from the termite mound composition from Lima et al. [10].

| Total sand | Fine sand | Coarse sand | Silt | Clay |
|---|---|---|---|---|
| 760.2 g | 226.1 g | 534.1 g | 518.3 g | 1000 g |

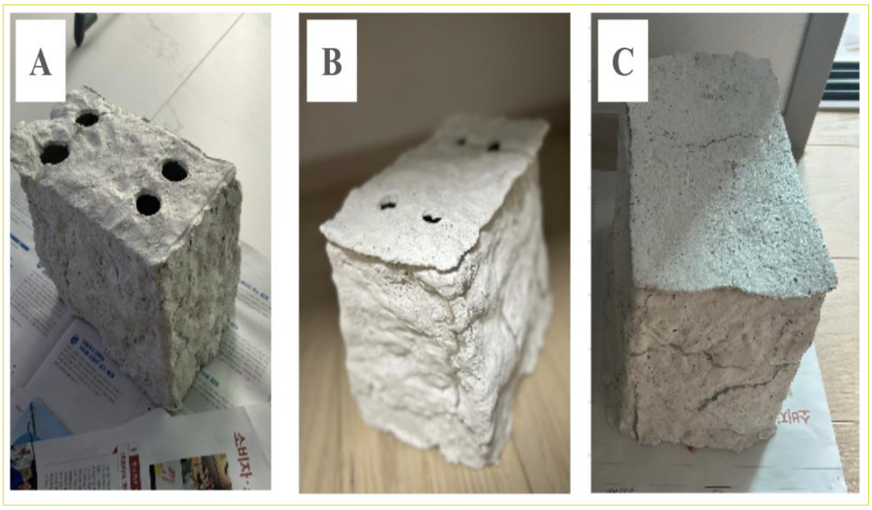


**Figure 2.** Created structures inspired by termite mound features. (A) Both structurally and materially modified with a large-radius air hole. (B) Both structurally and materially modified with a small radius air hole. (C) Only materially modified without any air holes.

**Temperature Experimental Setup**

An Arduino-based temperature-logging device was created to record interior temperatures in the structures and ambient air temperatures using an Arduino Uno Rev3 microcontroller and an Arduino DS18B20 temperature sensor, with four sensors. A small entry hole was carefully created from the corner of the mound ceiling, after which the structure ceiling was repaired with the matching construction material, either termite-mound-inspired or clay. To ensure consistent sensor placement, their positions were measured and marked with thin iron wire. The data loggers measuring the internal temperature of the structures were placed 6 cm above the ground, avoiding contact with the walls. The ambient air temperature sensor was placed near the structures, approximately 6 cm above ground level.

**Humidity Experimental Setup**

An Arduino DHT22 temperature sensor with four sensors was used. Similar to the temperature-logging device, a small entry hole was created from the corner of the mound ceiling. The entry hole was repaired with matching construction material after the sensors were installed. The positions of the sensors for interior humidity data were marked with thin iron wire. The data loggers measuring the internal temperature of the structures were placed 6 cm above the ground, avoiding contact with the structure wall.

**Experimental Procedures**

The structures and sensors were placed outside in the sunlight to begin testing. The temperature and humidity recordings were then started and logged for 1 h 30 min and 2 h, respectively. This test was repeated for each structure to ensure that the data collected previously were proper.

**Results**

A total of 331 valid records of temperature and humidity were obtained during the experimental period.

**Temperature**

The ambient air temperature averaged 32.21°C. Structures with structural adaptations, including small and large air holes, had interior temperatures lower than the ambient temperature, with mean values of 30.67°C and 31.13°C, respectively. While the temperatures within the two structurally adapted structures consistently remained below the ambient air temperature, the temperature within the structure without the structural adaptations fluctuated around the ambient temperature, with slight variations either above or below it throughout the experimental period. The mean interior temperature in the structure without structural adaptations was 32.26°C. Figure 3 shows a time-series plot demonstrating the temperature variations in both structurally and non-structurally adapted structures regarding the ambient temperature during the experiment.

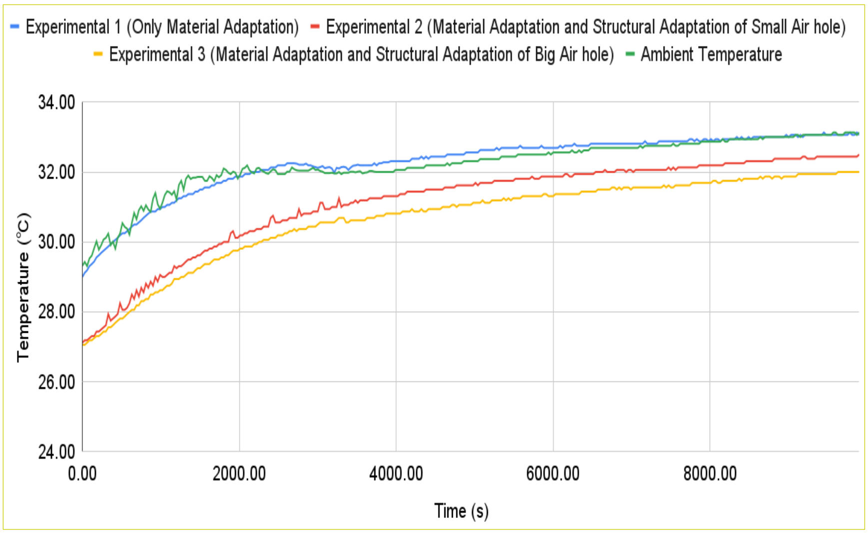


**Figure 3.** Time-series plot of internal temperature in structures with and without structural adaptations. The plot shows the thermal performance of each structure across different phases of the experiment. The plot also illustrates the ambient air temperature to provide a benchmark for the interior temperatures.

The temperature difference between the interior of the structures and the ambient air was assessed to determine the impact of the structural adaptations. This was conducted across three distinct time frames: the entire duration of the experiment, the first half characterized by the warming-up phase, and the second phase characterized by the stabilizing phase. Two phases, the warming-up phase and the stabilizing phase, were divided to ensure that significant standard deviation change throughout the experiment would not be neglected.

The mean temperature difference between the structure with small structural adaptation and the ambient air was observed to be -1.48°C during the first phase of the experimental period and -0.67°C in the second half, resulting in an overall mean difference of -1.07°C across the entire experimental period. The structure with large structural adaptation showed an even greater difference, with a mean of -1.90°C in the first phase and -1.17°C in the second phase combining to an overall mean difference of -1.53°C. Additionally, the standard deviation of the structure with small structural adaptation decreased from 0.66°C during the 1st phase to 0.03°C during the second phase. Similarly, the standard deviation of the structure with large structural adaptation decreased from 0.57 °C to 0.04°C between the first phase and the second phase of the experiment.

Similar to the trends in the time-series graph, the temperature differences between the structurally adapted models and the ambient air were consistently greater than those observed from the structure without any structural adaptations (Table 2). The mean temperature difference for the structure without structural adaptation was 0.00°C in the first phase and slightly increased to 0.10°C in the second phase, averaging to a minor difference of 0.05°C over the full experimental period.

**Table 2.** Temperature difference between internal temperature of structures and the ambient air. The table examines 3 separate time frames: the full experimental duration, first phase of the experiment, and the second phase of the experiment. This figure examines the mean value and the standard deviation of temperature at each time frame.

| | **Temperature data** | | | | | |
|---|---|---|---|---|---|---|
| | **Full test** | | **1st half test (Warming up period)** | | **2nd test (Stabilized period)** | |
| | $\bar{x}$ | $\sigma x$ | $\bar{x}$ | $\sigma x$ | $\bar{x}$ | $\sigma x$ |
| Temp*None*-Temp*Control* | 0.05 | 0.19 | 0.00 | 0.24 | 0.10 | 0.09 |
| Temp*Small*-Temp*Control* | -1.07 | 0.62 | -1.48 | 0.66 | -0.67 | 0.03 |
| Temp*Big*-Temp*Control* | -1.53 | 0.54 | -1.90 | 0.57 | -1.17 | 0.04 |

During the first phase, the median temperature difference for the structure without structural adaptation was 0.08°C. In contrast, the structure with small and big structural adaptation measured a negative median temperature difference with -1.39°C and -1.89°C, respectively. During the second phase, the median temperature differences were higher than in the first phase. The structure without structural adaptation measured a median temperature difference of 0.12°C. The structure with small structural adaptation was -0.68°C, and the structure with large structural adaptation was -1.18 °C (Figure 4).

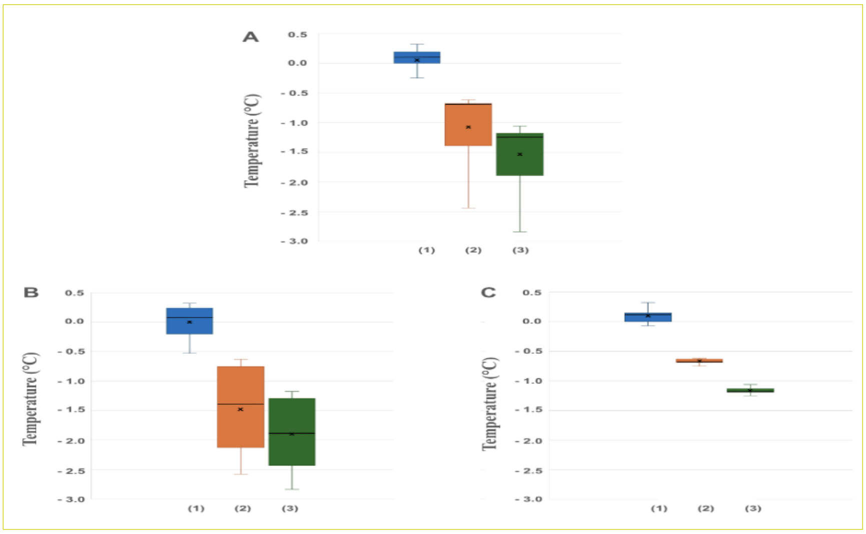


**Figure 4.** Temperature difference between internal temperature of structures and the ambient air. A. Box plot examining the temperature difference between the internal temperature of structures and the ambient air over the full experimental period. B. Box plot examining the temperature difference between the internal temperature of structures and the ambient air over the first phase of the experiment. C. Box plot examining the temperature difference between the internal temperature of structures and the ambient air over the first phase of the experiment. In all three box plots, (1) represents temperature difference between structures without structural adaptation; (2) represents temperature difference between structures with small structural adaptation; and (3) represents temperature difference between structures with large structural adaptation.

**Humidity**

The data on humidity revealed that the ambient air had lower humidity levels compared to all the tested structures. However, the structure with small structural adaptation exhibits fluctuations, with occasional lower and higher humidity levels compared to the ambient air. The structure without any structural adaptation recorded the highest humidity level, reaching an average of 61% relative humidity. In contrast, structures with small and large structural adaptation demonstrated lower humidity levels, with the structure having small adaptation reaching 56% relative humidity and that having large adaptation reaching 57% relative humidity (Figure 5).

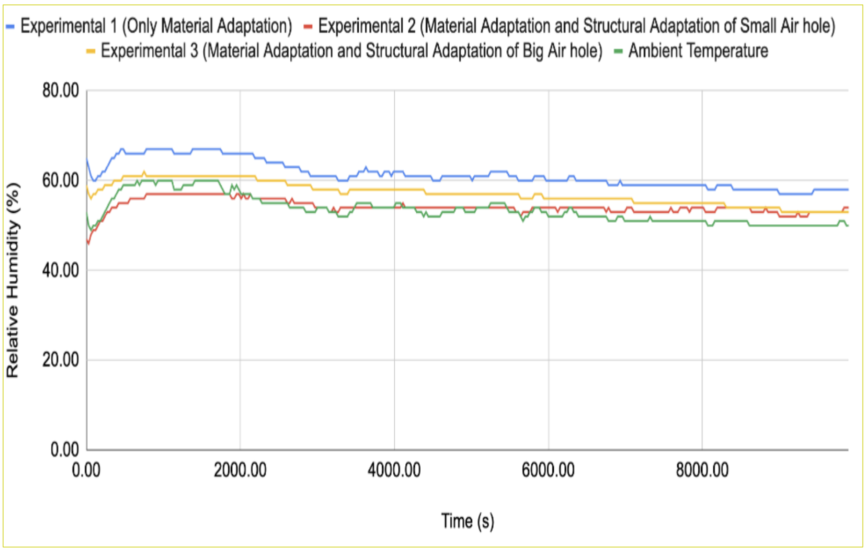


**Figure 5.** Time-series plot of relative humidity in structures with and without structural adaptations throughout the experimental period. The plot shows relative humidity for each structure across different phases of the experiment. The plot also illustrates the ambient air relative humidity level to provide a benchmark for the interior relative humidity.

The humidity difference between the structures and the ambient air was analyzed similarly to the temperature difference to determine the impact of the structural adaptations. The humidity difference between the model with small structural adaptation and ambient air averaged 0.65% relative humidity for the entire experiment. Specifically, the mean difference was -0.65% relative humidity during the first half of the experiment and increased to 1.94% in the second half.

For the model with large structural adaptations, the humidity difference to the ambient air averaged -3.62% relative humidity across the experiment, with a mean difference of -3.65% relative humidity in the first half and -3.59% relative humidity in the second half of the experiment.

In contrast, the model without structural adaptation showed a greater difference in humidity compared to the ambient air, with a mean difference of 7.83% relative humidity. The first half of the experiment showed a mean difference of 7.98% relative humidity, while the second half recorded a mean difference of -3.59% relative humidity. In an overall trend, structurally adapted models maintained a lower humidity level compared to the structurally unadapted model (Table 3).

**Table 3.** Relative humidity difference between internal temperature of structures and the ambient air. The table examines three separate time frames: the full experimental duration, first phase of the experiment, and the second phase of the experiment. The table examines the mean value and the standard deviation of relative humidity at each time frame.

| | Humidity data | | | | | |
|---|---|---|---|---|---|---|
| | Full test | | 1st half test (Warming up period) | | 2nd test (Stabilized period) | |
| | x̄ | σx | x̄ | σx | x̄ | σx |
| Humid*None*-Humid*Control* | 7.83 | 0.87 | 7.98 | 1.11 | -3.59 | 0.73 |
| Humid*Small*-Humid*Control* | 0.65 | 1.98 | -0.65 | 1.78 | 1.94 | 1.16 |
| Humid*Big*-Humid*Control* | -3.62 | 1.23 | -3.65 | 1.61 | -3.59 | 0.73 |

The box plot in Figure 6 reaffirms the trend of the two structures, in which structural adaptation had a greater humidity difference between the inner humidity of the structure and ambient air. It also shows the tendency of the first phase of the experiment, the phase of heating up, to have a lower humidity level than the second phase of the experiment, the phase of stabilizing.

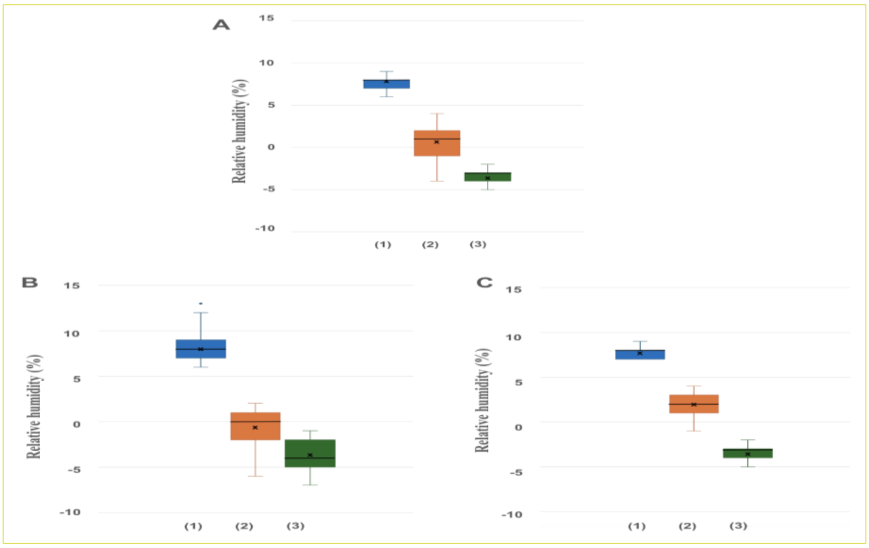


**Figure 6.** Humidity differences between relative humidity of structures and the ambient air. A. Box plot examining the relative humidity difference between the internal relative humidity of structures and the ambient air over the full experimental period. B. Box plot examining the relative humidity difference between the internal relative humidity of structures and the ambient air over the first phase of the experiment. C. Box plot examining the relative humidity difference between the internal relative humidity of structures and the ambient air over the first phase of the experiment. In all three box plots, (1) represents the relative humidity difference between structures without structural adaptation; (2) represents the relative humidity difference between structures with small structural adaptation; and (3) represents the relative humidity difference between structures with large structural adaptation.

**Heat Index**

The heat index was also analyzed as a separate variable using both temperature and humidity to represent the perceived temperature by humans. The heat index was calculated using Eq. (1) provided by the United States National Oceanic and Atmospheric Administration (NOAA) [11].

$$HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH \quad (1)$$

The heat index data revealed trends similar to those observed in the temperature measurements of the structures. Specifically, the two structures with structural modifications inspired by termite amounts consistently exhibited lower heat index values compared to the structure without any modifications and the ambient air temperature. However, the heat index data indicated a relatively smaller difference in the impact of the size of structural modification, specifically the air holes. The trend showed that the size of the air holes played a less significant role in influencing this reduction (Figure 7).

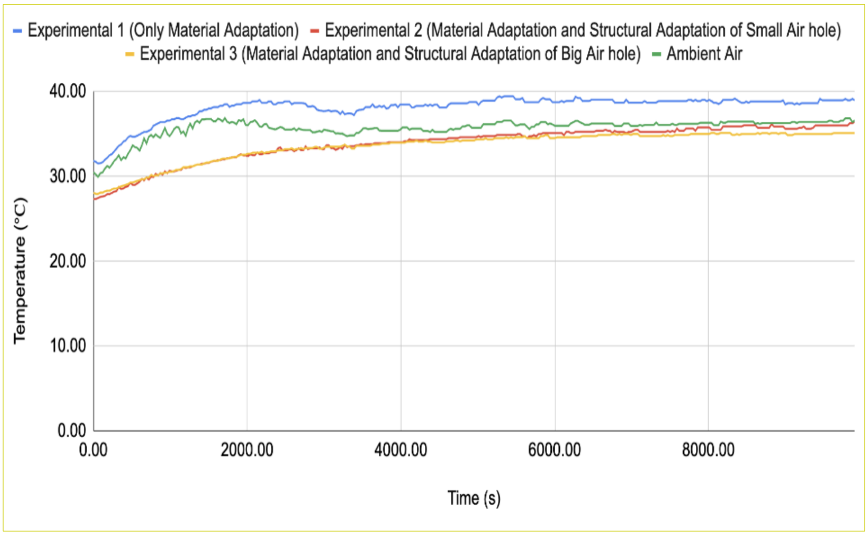


**Figure 7.** Time-series plot of heat index in structures with and without structural adaptations throughout the experimental period. The plot shows heat index for each structure across different phases of the experiment. The plot also illustrates the heat index as a reference point.

**Discussion**

**Analysis**

While numerous studies have explored the structural features of termite mounds and their ability to regulate temperature and humidity, research on the impact of termite-inspired structural features in human construction is lacking. Specifically, studies that explore the influence of these bio-inspired structural adaptations on temperature and humidity, which are crucial to the perceived air quality and environment for inhabitants, are scant [12].

The results of the study showed a significant impact of structural adaptations on temperature and humidity regulation within built environments. The findings were consistent with Korb's research that the internal temperature of termite mounds is lower than the ambient air temperature [13].

Contrary to the common belief that increased exposure to outside temperatures will cause the interior temperature to match the ambient air temperature, the findings suggest that small and large structural adaptations consistently maintain lower interior temperatures compared to the ambient air. Despite warmer external air flowing into the structures, the designs with structural adaptations effectively regulate the internal temperature. In contrast, the structure without any adaptations measures mean temperatures higher than those of the ambient air. This result highlights that structural adaptations effectively maintain a cooler interior environment, indicating that the natural air ventilation and circulation facilitated by the air holes in termite mounds can be applied to human construction.

Comparing temperature differences in structures, structures with structural adaptations measured lower than that without continuing into the stabilizing phase, although with reduced median differences between the structures, indicating a constant and stable cooling effect that stabilizes over time. The reduced standard deviation in temperature differences during the stabilizing phase demonstrates the increased consistency and reliability of temperature regulation provided by the structural adaptation.

Humidity levels within the structures also differed; structures with structural adaptations maintained lower relative humidity compared to that without structural adaptation. The small adaptations were less effective in maintaining low humidity levels compared to the large adaptations but still maintained relative humidity levels better than the structure without structural adaptations. These results highlight that the structural adaptations not only help in temperature regulation but also contribute to maintaining a more comfortable humidity level. The ability of the structures with structural adaptation to maintain lower humidity levels can be attributed to improved air exchange rates, which reduce the moisture accumulation within the structure [14].

The heat index analysis further supports the effectiveness of structural adaptations in enhancing thermal comfort. Structures with structural adaptations consistently exhibited lower heat index values, reflecting a lower perceived temperature for inhabitants. The size of the air holes had a less pronounced effect on the heat index compared to the temperature and humidity results, suggesting that while the structural adaptations are effective, other factors such as external shading and wind velocity in the structure might also play significant roles in thermal comfort.

**Consideration and Limitations**

The initial trial and data were rejected owing to a sensor error of DHT22; this was resolved by replacing the sensor with the DS18B20 sensor. Although this resolved the temperature data accuracy, the humidity results showed slight artificial discrepancies, such as step jumps, likely due to sensor limitations. However, the humidity data were maintained at the accuracy of ± 2% relative humidity.

**Implications and Future Research**

The consistent lower interior temperature than the temperature of ambient air in the structure with structural adaptation is important for enhancing indoor thermal comfort without requiring external energy usage. This study has implications for energy efficiency. By reducing the need for active cooling systems to achieve and maintain comfortable indoor temperatures, these structural adaptations inspired by termite mounds can lower energy consumption. This reduction in energy demand leads to cost savings and contributes to reducing greenhouse gas emissions associated with electricity generation, thus supporting global efforts to mitigate climate change. In a climate where air-conditioning is heavily relied upon, such passive cooling using a strategy of termite-mound-inspired structural adaptation can reduce the overuse of electrical power.

**Conclusion**

This study highlighted the significant role of structural adaptation in human construction, inspired by termite mounds for maintaining thermal comfort in structures. The study underscored the potential for practical application of these features in real-life human construction, such as residential buildings. This new biomimicry passive cooling system could serve as a passive cooling system that could complement or even replace active systems such as HVAC, contributing to environmental conservation and climate change mitigation. However, although the study aligned with previous findings regarding termite mounds, further research is required on larger-scale models to fully validate the practicality of these structural adaptations in human construction. The limitations of the relatively small models used in the study may have affected the observed temperature differences.

**Declarations**

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**Author Contribution:** The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.
**Conflict of Interest:** The author declares no conflict of interest.
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