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Thermal Mass Efficiency of Kushite Mud-Brick Architecture: A Simulation-Based Assessment of Passive Thermal Performance in Hot-Arid Climates

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Abstract

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Growing interest in sustainable construction has renewed attention to vernacular building systems as climate-responsive alternatives for hot-arid regions. This study investigates the thermal mass efficiency of Kushite mud-brick architecture using the Western Deffufa of Kerma, Sudan, as a representative case study. Despite the historical significance of this monument, quantitative evaluations of the thermal performance of Kushite architecture remain limited, constituting an important gap in the existing literature.

Thermal simulations were conducted using the DesignBuilder/EnergyPlus platform to evaluate five wall configurations: mud-brick walls with thicknesses of 30, 60, 100, and 150 cm, in addition to a 30 cm reinforced concrete wall representing the contemporary baseline. Simulations were performed for peak summer (27 July–2 August) and peak winter (6–12 January) conditions using Typical Meteorological Year (TMY) climatic data and were assessed according to ASHRAE Standard 55.

The results indicate a progressive improvement in thermal performance with increasing wall thickness. The 150 cm Kushite wall achieved a maximum indoor temperature of 32°C under an outdoor peak temperature of 43°C, corresponding to an attenuation of 11°C and a substantially greater thermal buffering capacity than the concrete baseline. Wall heat gains reached values as low as -21 W/m^2 , indicating a pronounced thermal storage effect. During winter, the same configuration maintained indoor temperatures approximately 2°C higher than those of the concrete reference case.

These findings demonstrate that the Western Deffufa embodies an advanced passive climate-control strategy. Furthermore, the study introduces the “Deffufa Effect”, defined as the thermal inversion phenomenon observed at wall thicknesses between 100 and 150 cm, and proposes it as a measurable passive cooling threshold with potential implications for low-carbon and culturally appropriate building design in hot-arid environments.

Keywords: Kushite architecture; thermal mass; mud-brick; Western Deffufa; DesignBuilder; passive thermal comfort; hot-arid climate; time lag; decrement factor.

1. Introduction

The building sector currently faces increasing pressure to reduce energy consumption while meeting global sustainability targets. Buildings account for approximately 30–40% of worldwide energy use, largely due to the extensive reliance on mechanical cooling and ventilation systems required to maintain indoor thermal comfort (Abu Dabous & Hosny, 2025). In hot-arid regions such as Sudan, extreme solar radiation and high ambient temperatures intensify cooling demands, highlighting the need for climate-responsive design strategies capable of reducing dependence on active energy systems. Consequently, improving the thermal performance of the building envelope has become a fundamental aspect of sustainable architecture (Zarco-Soto et al., 2025).

The building envelope plays a critical role in regulating heat transfer and directly influences indoor environmental quality and energy performance (Amen, 2021; Aziz Amen, 2022; Barbhuiya et al., 2025). Among passive design strategies, thermal mass has long been recognized as an effective mechanism for moderating temperature fluctuations in desert climates. Earth-based materials possess high heat-storage capacity, enabling them to absorb excess heat during daytime hours and release it gradually when outdoor temperatures decrease. This thermal behavior is commonly characterized by two key parameters: time lag and decrement factor (Ergün & Bekleyen, 2025).

Historical precedents provide valuable evidence of the effectiveness of such passive strategies. The Western Deffufa in the ancient city of Kerma, Sudan, represents one of the most remarkable examples of climate-responsive earthen architecture (Abdullahi et al., 2025). As one of the largest mud-brick monuments in the world, its massive walls were constructed with proportions that contributed to indoor thermal stability, as documented by

archaeological investigations conducted by the Swiss mission (Bonnet & Valbelle, 2004). Despite the architectural and historical significance of Kushite monuments, existing studies have largely focused on archaeological interpretation, structural conservation, or the development of modern earthen materials, while quantitative investigations of the thermal performance of Kushite architecture remain scarce (Lakys et al., 2026). This lack of numerical evidence constitutes an important research gap. Accordingly, this study aims to provide a quantitative assessment of the thermal behavior of the Western Deffufa through DesignBuilder/EnergyPlus simulations. By analyzing different mud-brick wall thicknesses and comparing them with a conventional reinforced concrete wall, the study seeks to evaluate the capacity of massive earthen construction to attenuate heat transfer and improve indoor thermal conditions. In doing so, it attempts to bridge the gap between ancient Kushite architectural knowledge and contemporary sustainable building practices in hot-arid climates.

1.1 Research Questions

This study addresses the following three research questions:

RQ1: What are the time lag and decrement factor values for mud-brick walls of varying thicknesses (30, 60, 100, and 150 cm) under hot arid climatic conditions?

RQ2: How does increasing wall thickness influence indoor temperature moderation in monumental earthen architecture?

RQ3: How does the thermal mass performance of mud-brick construction compare to conventional concrete walls of equivalent thickness?

This paper is structured as follows: Section 2 presents the case study and simulation methodology. Section 3 reports the results of the thermal analysis. Section 4 discusses the findings in relation to passive design principles. Section 5 draws conclusions and highlights implications for sustainable architecture in hot climates.

2. Materials and Methods

2.1 The Western Deffufa of Kerma

The Western Deffufa in Kerma, northern Sudan, was selected as the principal case study owing to its status as the largest and most significant mud-brick monument in sub-Saharan Africa. Rising to approximately 20 m in height, the structure provides an exceptional example for investigating the thermal behavior of massive earthen architecture. Scientific analyses of the Deffufa's construction materials have confirmed that its mud bricks were manufactured from locally available alluvial soils possessing thermophysical characteristics consistent with traditional Sudanese earthen materials (Gratuze & Honegger, 2022).

The external morphology and internal spatial organization of the monument are illustrated in Figures 1 and 2. Based on the archaeological documentation produced by the Swiss-French-Sudanese Archaeological Mission under the direction of Bonnet (2017), the geometry of the building was reconstructed for digital simulation purposes. Recent archaeological studies have emphasized the complex internal configuration of the Deffufa, which differs markedly from the solid stone structures of contemporary Egyptian architecture. Instead, the monument is characterized by a massive earthen core incorporating internal voids, narrow corridors, and vertical shafts that constitute a distinctive architectural tradition within ancient Kushite culture (Artioli et al., 2019).



Figure 1. View of the Western Deffufa at Kerma, Sudan. Source: Artioli et al. (2019).

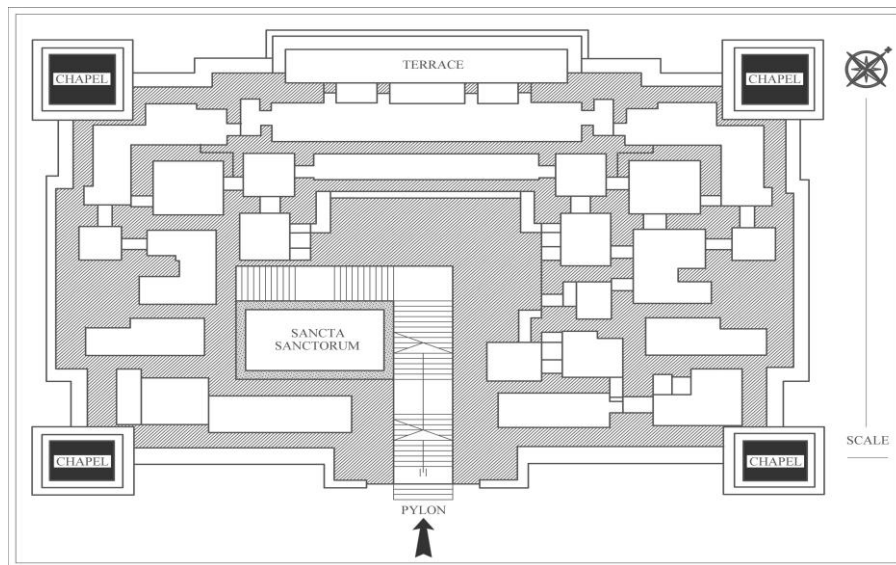


Figure 2. Architectural floor plan of the Western Deffufa, redrawn from archaeological documentation by Bonnet (2004).

In the present study, these internal voids were considered as thermal buffer zones that contribute to air movement and reduce heat transfer through the massive envelope. Such spatial characteristics reflect an advanced understanding of passive climate control principles and demonstrate the environmental intelligence embedded in Kushite architectural traditions.

2.2 Material Properties and Wall Thickness Scenarios

To quantify the influence of thermal mass on indoor thermal comfort, two construction systems were evaluated. The first represents contemporary building practice in Sudan and consists of a reinforced concrete wall with a thickness of 30 cm, which served as the reference case. The second represents the Kushite earthen construction system and comprises mud-brick walls with thicknesses of 30, 60, 100, and 150 cm.

These wall thicknesses reflect the transition from ordinary domestic buildings to monumental architectural forms characteristic of ancient Kerma. The thermophysical properties assigned to the mud-brick material were based on values reported for traditional earthen materials, including a density of 1800 kg/m³, a specific heat capacity of 1000 J/kg·K, and a thermal conductivity of 0.65 W/m·K (Heracleous et al., 2025; Heracleous et al., 2023; Belarbi et al., 2025; Khoukhi, 2018; Brambilla & Jusselme, 2017).

The five wall configurations considered in this study are illustrated schematically in Figure 3, highlighting the proportional differences between the concrete reference case and the four mud-brick alternatives (Alayed et al., 2022; Taylor et al., 2008; Fernandes et al., 2019).

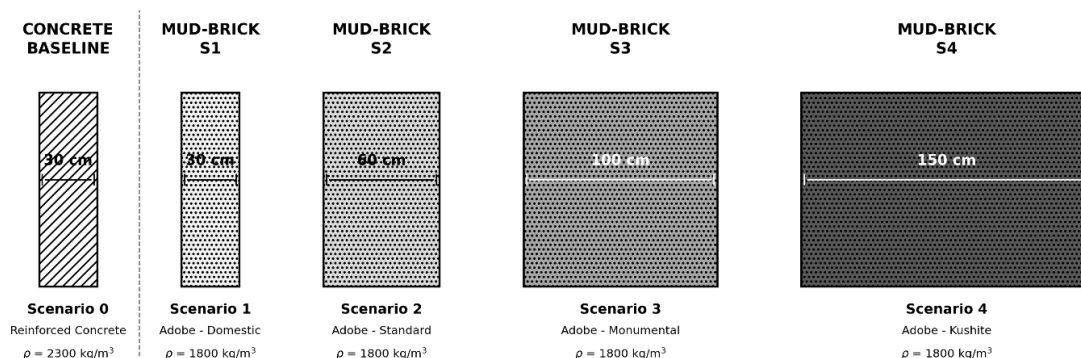


Figure 3. Schematic representation of the five wall thickness scenarios considered in the simulation.

2.3 Simulation Framework (DesignBuilder/EnergyPlus)

Thermal performance was evaluated using DesignBuilder (v2025.1) coupled with the EnergyPlus simulation engine, a validated approach widely employed for assessing the thermal behavior of traditional building envelopes (Chkeir et al., 2024). The simulation framework was developed to quantify the influence of wall thickness on indoor thermal performance under hot-arid climatic conditions.

Typical Meteorological Year (TMY) climatic data for Dongola, Sudan, were employed to represent local environmental conditions. Two representative periods were selected to capture seasonal extremes: the peak

summer week (27 July–2 August) and the peak winter week (6–12 January).

To evaluate the thermal response of each wall configuration, hourly simulation outputs were extracted instead of daily averages. This approach enabled the calculation of two key thermal performance indicators, namely time lag (ϕ) and decrement factor (f), following the analytical framework proposed by Lakys et al. (2026).

Natural ventilation was activated using the “Calculated Natural Ventilation” option in DesignBuilder to simulate airflow through the internal voids of the Western Deffufa and to investigate the interaction between thermal mass and thermal buoyancy. The principal simulation parameters adopted in the present study are summarized in Table 1.

Table 1: The Key Simulation Framework Parameters.

Parameter	Setting
Software	DesignBuilder v2025.1 / EnergyPlus
Climate Data	Typical Meteorological Year (TMY) Dongola, Sudan
Analysis Period	Peak Summer: 27 July –2 August
Time Step	Sub-hourly
Ventilation Mode	Calculated Natural Ventilation
Heat Balance Algorithm	Conduction Finite Difference
Evaluation Standard	ASHRAE 55

The simulation settings were selected to ensure consistency in the comparison among all wall configurations and to provide reliable estimates of passive thermal performance under representative hot-arid climatic conditions.

2.4 Evaluation Metrics

Thermal performance was evaluated according to ASHRAE Standard 55 by comparing the thermal behavior of the four mud-brick wall configurations with the reinforced concrete reference case. Particular emphasis was placed on the ability of massive earthen walls to delay heat transfer and enhance indoor thermal stability, thereby reducing the dependence on mechanical cooling.

Two key indicators were used to quantify thermal mass performance: time lag (ϕ) and decrement factor (f). Time lag represents the temporal delay between the peak outdoor temperature and the corresponding peak indoor surface temperature and is expressed in hours (Heracleous et al., 2025). The decrement factor represents the ratio between the indoor temperature amplitude and the outdoor temperature amplitude and is expressed as:

$$f = \Delta T_{\text{indoor}} / \Delta T_{\text{outdoor}}$$

where ΔT_{indoor} denotes the difference between the maximum and minimum indoor air temperatures, while $\Delta T_{\text{outdoor}}$ represents the corresponding outdoor temperature range during the same 24-hour period. A higher time lag and a lower decrement factor indicate superior thermal mass performance, reflecting the ability of the building envelope to attenuate and delay heat transfer (Alayed et al., 2022; Reilly & Kinnane, 2017).

In addition to these indicators, indoor temperature range and comfort hours within the ASHRAE 55 comfort limits were used to compare the thermal performance of all wall configurations. The evaluation criteria adopted in this study are summarized in Table 2.

Table 2: The evaluation criteria applied to compare all five scenarios are summarized.

Metric	Definition (Delay between peak)	Target
Time Lag (ϕ)	outdoor and indoor temperature	Higher = Better
Decrement Factor (f)	Ratio of indoor to outdoor temperature amplitude	Lower = Better
Indoor Temperature Range	Max–Min indoor air temperature over 24hrs	Narrower = Better

Comfort Hours	Hours within ASHRAE 55 comfort zone per day	Higher = Better
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3. Results

3.1 Summer Thermal Performance (27 July–2 August)

The simulation results obtained for the peak summer period demonstrate a progressive improvement in indoor thermal performance with increasing wall thickness. During this period, the outdoor dry-bulb temperature varied between 28°C and 43°C, corresponding to an outdoor temperature amplitude of approximately 15°C. The hourly thermal profiles for the five wall configurations are presented in Figures 4–8.

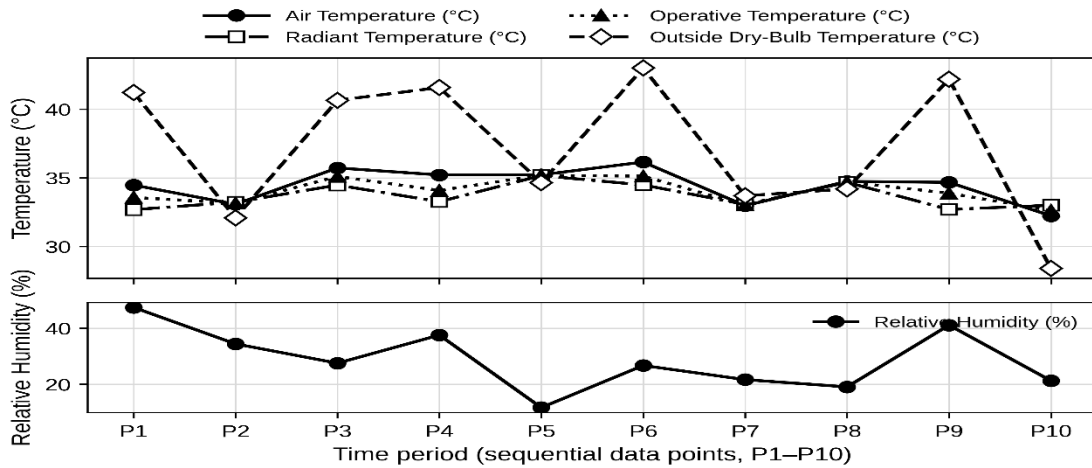


Figure 4. Hourly temperature and relative humidity profiles for the 30 cm concrete wall scenario during the summer period.

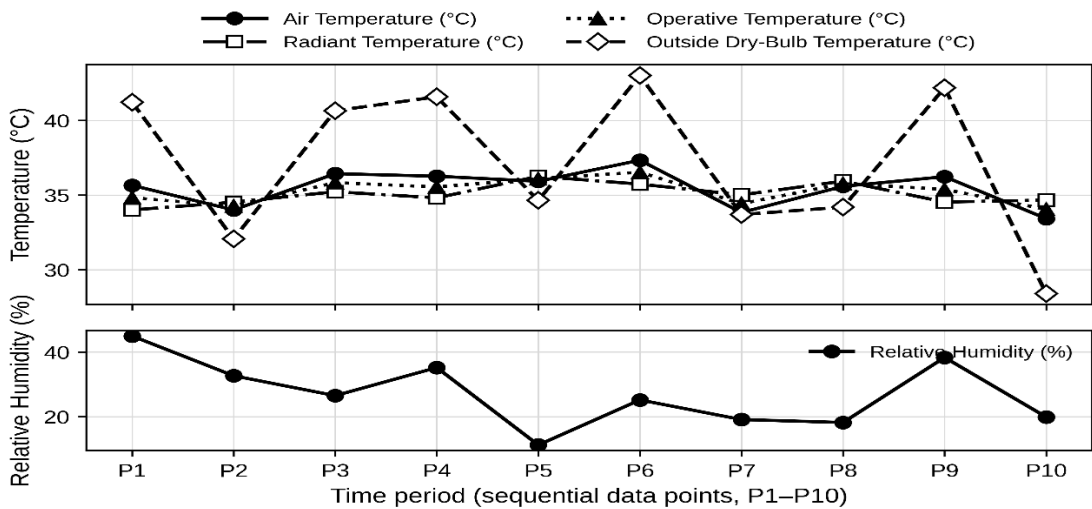


Figure 5. Hourly temperature and relative humidity profiles for the 30 cm mud-brick wall scenario during the summer period.

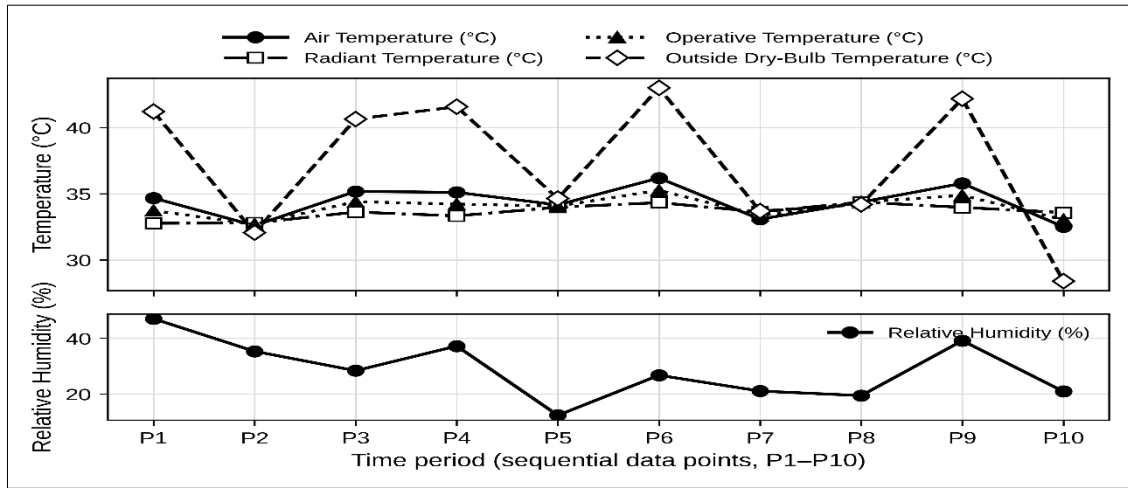


Figure 6. Hourly temperature and relative humidity profiles for the 60 cm mud-brick wall scenario during the summer period.

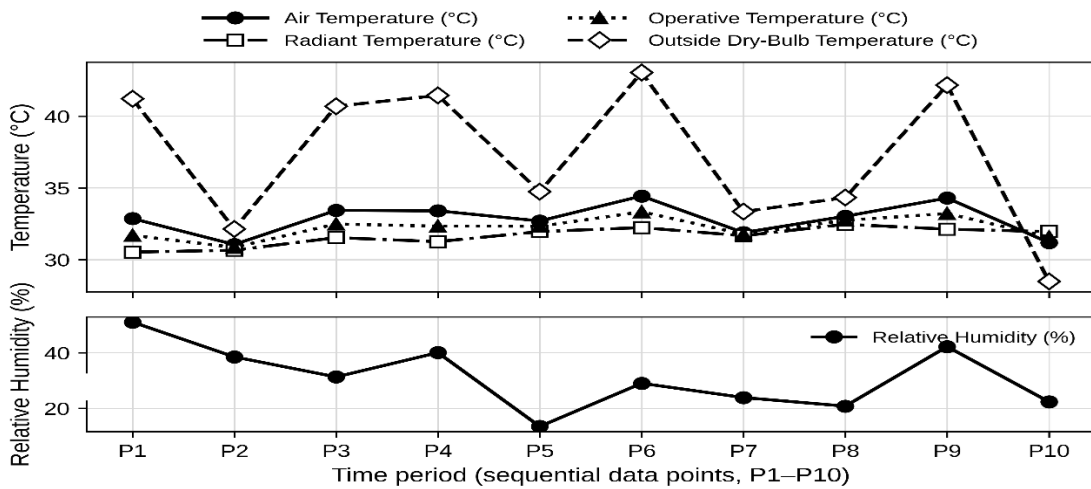


Figure 7. Hourly temperature and relative humidity profiles for the 100 cm mud-brick wall scenario during the summer period.

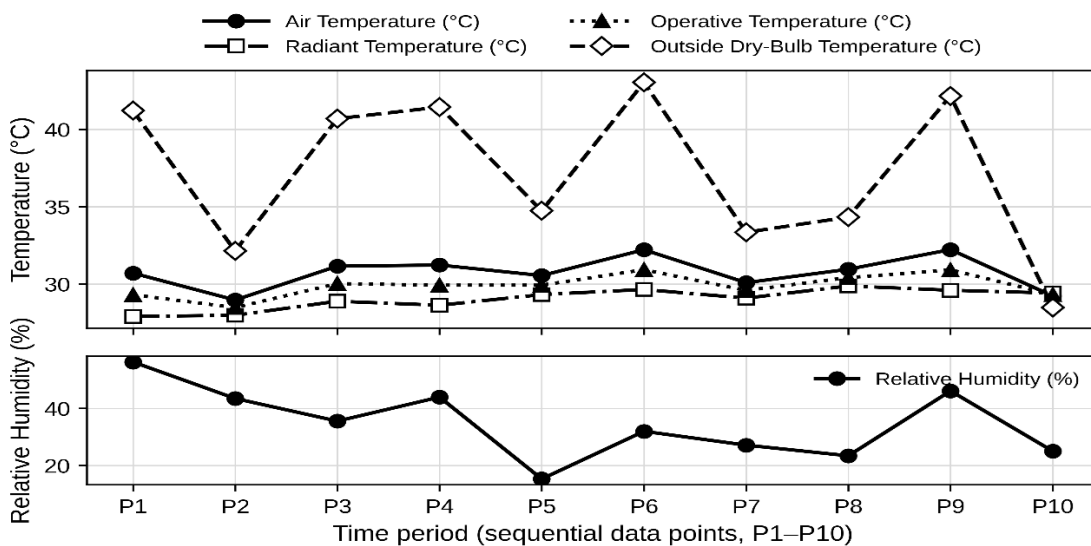


Figure 8. Hourly temperature and relative humidity profiles for the 150 cm mud-brick wall scenario during the summer period.

The concrete reference wall (30 cm) recorded indoor temperatures ranging between 32°C and 36°C, with wall heat gains reaching up to 64 W/m², indicating rapid heat transfer through the building envelope. In contrast, the 30 cm mud-brick wall exhibited lower heat gains, ranging from 9 to 31 W/m², confirming the superior thermal storage characteristics of earthen materials even at relatively small thicknesses. These findings are consistent with the experimental observations reported by Belarbi et al. (2025).

Further improvements were observed with increasing wall thickness. The 60 cm mud-brick wall reduced

wall heat gains to values ranging from 3 to 25 W/m² while maintaining a narrower indoor temperature range. A more pronounced thermal response emerged at 100 cm thickness, where wall heat gain values became negative, reaching -6 W/m². This behavior indicates that the wall was not only attenuating heat transfer but also contributing to delayed heat release due to its thermal storage capacity. The most significant thermal performance was achieved by the 150 cm Kushite wall configuration, where wall heat gains ranged from -21 to 4 W/m². Indoor temperatures varied between 29°C and 32°C, corresponding to an attenuation of approximately 11°C relative to the outdoor peak temperature of 43°C. Compared with the concrete reference case, which achieved a temperature reduction of 7°C, the massive earthen wall demonstrated substantially enhanced thermal buffering performance. These findings provide quantitative support for the “Deffufa Effect”, defined in this study as the thermal inversion phenomenon associated with wall thicknesses between 100 and 150 cm. The summer indoor temperature performance of all five wall configurations is summarized in Table 3.

Table 3: Summer indoor temperature performance across all five wall construction scenarios.

Scenario	Max Indoor Temp. (°C)	Min Indoor Temp. (°C)	Indoor Amplitude (°C)	Wall Heat Gain (W/m ²)
Concrete 30 cm	36	32	4	38 – 64
Mud 30 cm	37	33	4	9 – 31
Mud 60 cm	36	32	4	3 – 25
Mud 100 cm	34	31	3	- 6 to 18
Mud 150 cm	32	29	3	-21 to 4

3.2 Winter Thermal Performance (6–12 January)

Winter simulations were conducted to evaluate the ability of massive earthen walls to retain heat during cold desert nights. During the selected winter period, outdoor temperatures varied between 10°C and 28°C. The hourly indoor thermal profiles corresponding to the five wall configurations are illustrated in Figures 9 and 10.

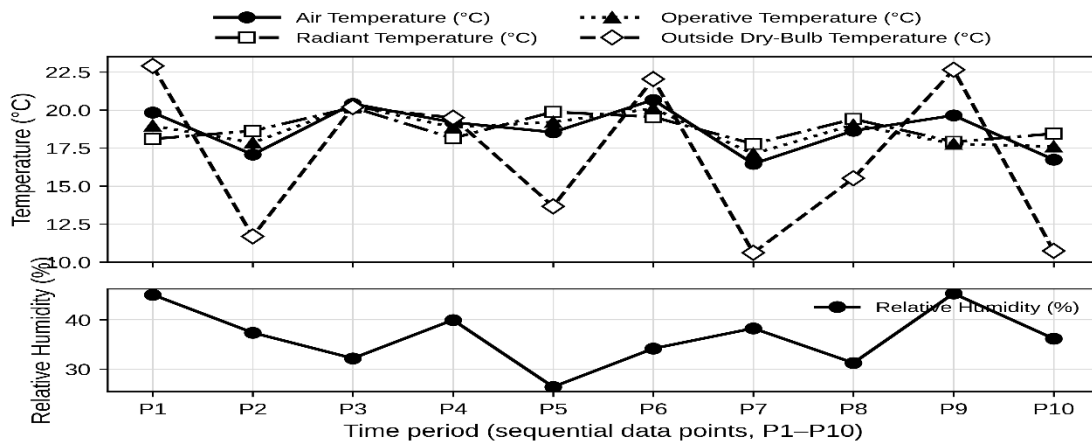


Figure 9. Hourly temperature and relative humidity profiles for the 30 cm concrete wall scenario during the winter period.

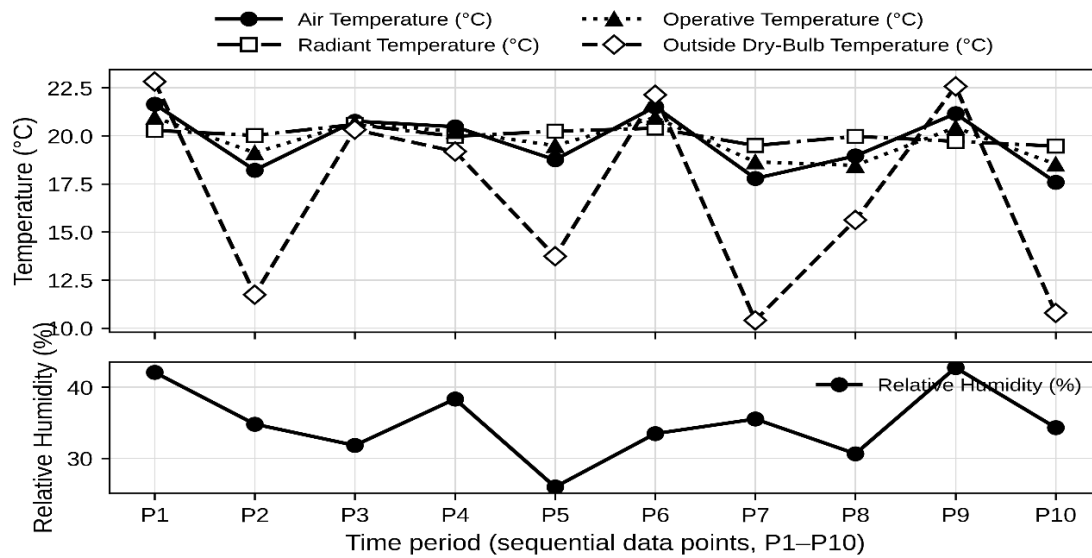


Figure 10. Hourly temperature and relative humidity profiles for the 150 cm mud-brick wall scenario during the winter period.

Unlike summer conditions, where thermal mass primarily attenuated heat gains, winter simulations demonstrated the capacity of massive mud-brick walls to retain heat and moderate nocturnal temperature drops. The reinforced concrete wall exhibited more pronounced temperature fluctuations, resulting in lower indoor temperatures during nighttime hours.

The 150 cm mud-brick wall maintained indoor temperatures approximately 2°C higher than those observed in the concrete reference case, indicating improved thermal stability and reduced heat losses. Similar trends were observed for the 100 cm wall configuration, although with a less pronounced effect. These findings demonstrate that thick earthen walls contribute not only to passive cooling during summer but also to passive heat retention during winter conditions.

The winter thermal performance indicators for all wall configurations are summarized in Table 4.

Table 4: The winter indoor thermal performance of all five scenarios.

Scenario	Max Indoor Temp. (°C)	Min Indoor Temp. (°C)	Indoor Amplitude (°C)
Concrete 30 cm	21	16	5
Mud 30 cm	20	17	3
Mud 60 cm	21	17	4
Mud 100 cm	21	18	3
Mud 150 cm	22	18	4

3.3 Comparative Summary

A comparative assessment of the five wall configurations reveals a clear relationship between wall thickness and thermal performance. Increasing wall thickness resulted in reduced indoor temperature fluctuations, lower wall heat gains, and improved thermal stability. The overall comparison among the simulated configurations is illustrated in Figure 11.

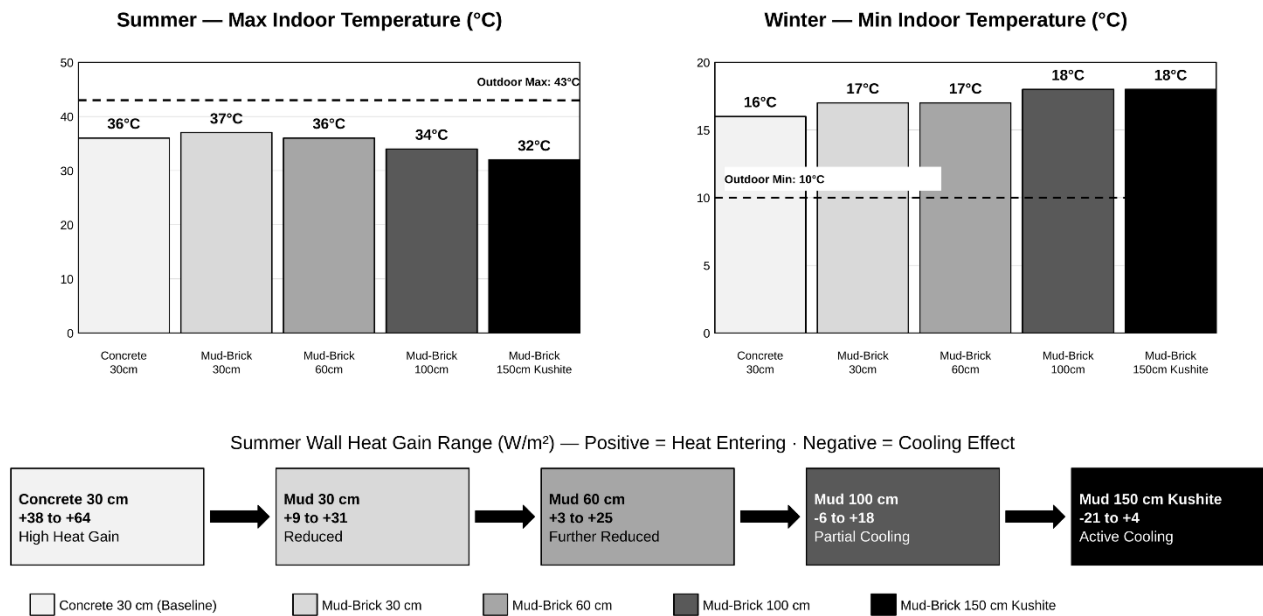


Figure 11. Comparative summary of key thermal performance indicators for the five wall scenarios.

The reinforced concrete wall exhibited the highest heat gains and the largest indoor temperature fluctuations. By contrast, all mud-brick configurations demonstrated improved thermal performance, with progressively greater benefits observed as wall thickness increased. The 100 cm and 150 cm walls achieved the best overall performance, characterized by reduced temperature amplitudes, increased time lag, and lower decrement factors.

The comparative thermal indicators for all wall configurations are summarized in Table 5.

Table 5: Comparative Thermal Mass Performance — Summer and Winter Combined summer and winter thermal performance summary for all wall, Time Lag and Decrement Factor scenarios.

Scenario	Summer Max Indoor (°C)	Summer Reduction from Outdoor	Winter Min Indoor (°C)	Wall Heat Gain Summer (W/m²)	Time Lag (hr)	Decrement Factor
Concrete 30 cm	36	7°C	16	38 – 64	~2	0.27
Mud 30 cm	37	6°C	17	9 – 31	~3	0.27
Mud 60 cm	36	7°C	17	3 – 25	~5	0.27
Mud 100 cm	34	9°C	18	-6 – 18	~8	0.20
Mud 150 cm	32	11°C	18	-21 – 4	~11	0.20

Overall, the results demonstrate that increasing thermal mass significantly enhances indoor thermal stability under hot-arid climatic conditions. These findings provide quantitative evidence supporting the environmental efficiency of Kushite mud-brick architecture and highlight its potential relevance for contemporary low-energy building design.

4. Discussion

The simulation results presented in this study provide compelling empirical evidence that the massive mud-brick construction of Kushite architecture represents a highly effective passive thermal regulation system. The findings are discussed below in relation to existing literature across four key themes.

4.1 Thermal Performance of Massive Earthen Walls

The results demonstrate that increasing wall thickness substantially improves indoor thermal stability and reduces heat transfer under hot-arid climatic conditions. Compared with the reinforced concrete reference case, all mud-brick configurations exhibited lower temperature fluctuations and enhanced thermal buffering capacity. These findings confirm the effectiveness of thermal mass as a passive design strategy and are consistent with previous investigations on earthen architecture conducted in hot climates.

The progressive reduction in wall heat gains observed in the present study reflects the capacity of thick earthen walls to absorb and delay heat transmission. As wall thickness increased from 30 cm to 150 cm, heat gain values decreased significantly, eventually reaching negative values. This behavior indicates that

the wall acted as a thermal storage medium, releasing previously accumulated heat with a considerable time delay.

Similar thermal responses have been reported in studies of vernacular earthen buildings, which emphasize the role of thermal mass in maintaining stable indoor conditions and reducing cooling loads. Therefore, the thermal behavior observed in the Western Deffufa should be understood as a consequence of the interaction between wall thickness, thermal inertia, and the hot-arid climatic context rather than as an isolated architectural phenomenon.

These findings are particularly relevant in the context of contemporary concerns regarding energy efficiency and climate adaptation. In hot-arid environments, reducing heat transfer through the building envelope represents one of the most effective passive strategies for minimizing cooling demands. The thermal response observed in the present study suggests that the massive walls of Kushite architecture provided an inherent mechanism for indoor temperature regulation without relying on external energy inputs. Such characteristics demonstrate that traditional earthen construction systems can offer practical lessons for developing resilient and environmentally responsive buildings under increasingly extreme climatic conditions.

4.2 Time Lag and Decrement Factor

The calculated time lag and decrement factor values further demonstrate the superior performance of massive earthen walls. Higher wall thicknesses resulted in longer thermal delays and lower decrement factors, indicating a greater ability to attenuate outdoor temperature fluctuations.

The 100 cm and 150 cm wall configurations exhibited the most favorable thermal responses, providing substantial delays in heat transmission and maintaining more stable indoor temperatures throughout the day. These findings are consistent with previous studies that identified thermal inertia as one of the principal advantages of earthen construction in desert environments.

From a building physics perspective, the observed behavior confirms that thermal mass plays a critical role in regulating heat flow and improving passive thermal comfort without increasing energy demand.

In addition, the increase in time lag associated with thicker earthen walls contributes to shifting peak heat transfer to periods characterized by lower outdoor temperatures. This delay mechanism is particularly advantageous in hot-arid regions, where significant diurnal temperature variations occur. Lower decrement factors further indicate the ability of massive walls to dampen temperature oscillations and maintain more stable indoor environments. Consequently, the combined effect of thermal inertia, delayed heat transmission, and reduced temperature amplitudes enhances thermal comfort and reinforces the suitability of earthen construction as a passive design strategy for energy-efficient buildings.

These findings also highlight the importance of considering dynamic thermal behavior rather than relying solely on steady-state thermal properties. While conventional insulation strategies primarily aim to reduce heat transfer, thermal mass provides an additional mechanism capable of delaying and attenuating temperature fluctuations. This characteristic becomes particularly valuable in desert climates, where large diurnal temperature variations can be utilized to improve indoor comfort through passive means. Similar observations regarding the interaction between thermal mass, overheating mitigation, and the beneficial role of temperature attenuation have also been reported in different climatic contexts (Sun et al., 2022).

4.3 The Deffufa Effect

One of the most significant findings of this study is the identification of a thermal inversion phenomenon occurring between wall thicknesses of 100 and 150 cm. At these thicknesses, wall heat gains became negative, indicating a reversal in heat flow behavior associated with delayed thermal release.

This phenomenon, referred to in the present study as the “Deffufa Effect,” represents a measurable threshold at which massive earthen walls exhibit enhanced thermal buffering performance. Rather than functioning merely as passive barriers, the walls behave as dynamic thermal storage systems capable of moderating indoor temperatures over extended periods.

Although further experimental validation is required, the results suggest that this phenomenon may provide valuable insights for the development of contemporary passive cooling strategies in hot-arid climates.

4.4 Implications for Contemporary Sustainable Architecture

The findings of this study demonstrate that ancient Kushite construction principles remain relevant to contemporary sustainable architecture. The thermal efficiency achieved by massive mud-brick walls highlights the potential of earthen materials as low-carbon and climate-responsive alternatives for hot-arid regions.

Beyond their historical significance, the architectural principles embodied in the Western Deffufa provide quantitative evidence supporting the integration of traditional knowledge into modern building practices. Such approaches may contribute to reducing cooling demands and improving indoor environmental quality while preserving cultural identity and promoting sustainable development.

The increasing demand for energy-efficient buildings has renewed interest in passive design strategies that rely on locally available materials and environmentally responsible construction techniques. In this context, earthen architecture offers several advantages, including low embodied energy, reduced carbon emissions, and compatibility with local climatic conditions. These characteristics are particularly important in developing countries, where access to advanced cooling technologies may be limited and construction costs

remain a significant concern. Previous simulation studies conducted in hot-arid regions have similarly demonstrated the potential of passive strategies and thermally responsive envelopes to reduce cooling demands and improve indoor environmental conditions (Dabaieh et al., 2015). Furthermore, the findings of the present study suggest that lessons derived from Kushite architecture may support future applications of sustainable earthen construction in residential and public buildings. By combining traditional thermal principles with contemporary engineering approaches, it may be possible to develop building systems capable of improving thermal comfort while reducing energy consumption. Such strategies are consistent with current international efforts aimed at promoting climate-responsive and low-carbon architecture. Recent review studies have similarly emphasized the environmental and thermal advantages of earthen construction systems and highlighted the importance of integrating monitoring and simulation approaches to optimize their performance under different climatic conditions (Carrobé et al., 2021; Mora-Ruiz et al., 2025).

5. Conclusion

This study investigated the thermal performance of Kushite mud-brick architecture using the Western Deffufa of Kerma as a representative case study. Through DesignBuilder/EnergyPlus simulations, five wall configurations were evaluated under representative summer and winter conditions characteristic of the hot-arid climate of northern Sudan.

The results demonstrated a clear relationship between wall thickness and thermal performance. Increasing wall thickness led to reduced indoor temperature fluctuations, lower wall heat gains, and enhanced thermal stability. Among the investigated configurations, the 150 cm mud-brick wall exhibited the highest thermal buffering capacity, maintaining indoor temperatures substantially below outdoor peak temperatures during summer and retaining heat more effectively during winter conditions.

The analysis further revealed a thermal inversion phenomenon occurring at wall thicknesses between 100 and 150 cm, where wall heat gains became negative due to delayed thermal release. This behavior, referred to in the present study as the “Deffufa Effect,” represents a measurable passive thermal response associated with massive earthen construction.

The findings provide quantitative evidence supporting the environmental efficiency of Kushite architecture and contribute to filling an important gap in the literature regarding the thermal performance of ancient Nubian monuments. More importantly, the study demonstrates that traditional earthen construction principles can inform contemporary low-energy building strategies for hot-arid regions.

From a broader perspective, the study highlights the importance of re-evaluating vernacular architectural knowledge through quantitative approaches capable of linking historical construction practices with present-day sustainability challenges. The results indicate that traditional earthen materials should not be regarded solely as heritage elements but also as valuable resources for developing climate-responsive and energy-efficient buildings.

Although the findings are based on numerical simulations and require further experimental validation, they provide a foundation for future investigations involving field measurements, hygrothermal monitoring, and the optimization of contemporary earthen construction systems. Further research may also explore the integration of traditional thermal mass principles with modern technologies and sustainable building materials to enhance thermal comfort and reduce energy demand in hot-arid regions.

Overall, the present study demonstrates that the architectural legacy of ancient Kush offers valuable insights for contemporary sustainable design and emphasizes the continuing relevance of earthen construction as a low-carbon and climate-responsive building strategy.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study were generated through numerical simulations. The datasets and simulation parameters used in this research are available from the corresponding author upon reasonable request.

Institutional Review Board Statement

Not applicable. This study did not involve human participants, animal subjects, or personal data requiring ethical approval.

CRedit Author Statement

Shaza Yousif Taha: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Visualization, Writing – Original Draft, and Writing – Review and Editing.

Ahmed Osman Ibrahim: Writing – Review and Editing.

All authors have read and approved the final manuscript.

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