

Parametric study of the impact of insulation and wall thickness in straw-reinforced adobe structures on energy performance in a Moroccan desert climate: A case study of Errachidia

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ABSTRACT

In hot and arid desert climates, the thermal performance of passive buildings is strongly influenced by external climatic factors such as solar radiation, air temperature, humidity, and wind speed. However, these challenges can be mitigated through a judicious selection of construction materials and the optimization of their properties to ensure occupant thermal comfort. This study aims to identify the optimal combinations of insulation and wall thickness in straw-reinforced adobe structures to enhance the energy performance of buildings in a Moroccan desert context, specifically in the city of Errachidia.

To achieve this aim, the study employs a validated energy model to investigate two key parameters: (1) the addition of natural fiber insulation (0.10 m) and (2) the variation of wall thickness (0.3 m to 0.5 m).

KEYWORDS

Straw-reinforced adobe structures;
Thermal comfort; Insulation;
Building energy performance;
Desert climate

The thermal simulation results indicate that adding 0.10 m of insulation significantly enhances thermal performance compared to non-insulated walls. Without insulation, wall thicknesses ranging from 0.4 m to 0.5 m reduce thermal fluctuations by 2°C. However, with insulation, a 0.3 m thick wall achieves a reduction of 3.7°C in summer indoor temperature peaks and maintains winter indoor temperatures as high as 12.1°C, even under extreme outdoor conditions. The integration of eco-friendly insulation panels also leads to a 23.18% reduction in cooling energy demand and a 40% decrease in heating needs compared to uninsulated walls.

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These findings underscore the importance of designing walls specifically tailored to the climatic conditions of desert regions, especially those near the city of Errachidia to optimize energy efficiency, lower ecological footprints, and promote sustainable architectural practices.

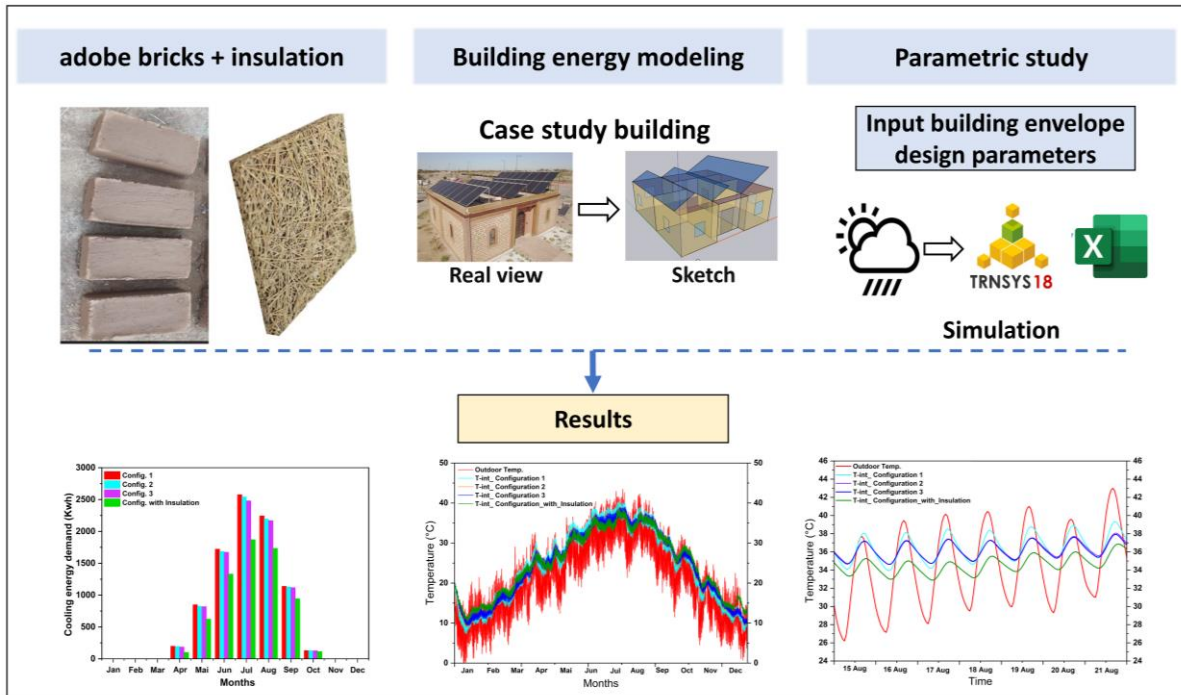
دراسة بارومتريه لتأثير العزل وسماكة الجدران في الهياكل المبنية من الطوب اللبن المدعوم بالقش على أداء الطاقة في المناخ الصحراوي في المغرب: دراسة حالة من مدينة الرشيدية

عبد المنعم عليوي، يونس أزالم، محمد بنفارس، المعطي بن دادة، مصطفى مبروكي

ملخص: في المناخات الصحراوية الحارة والقاحلة، يتأثر الأداء الحراري للمباني السلبية بشدة بالعوامل المناخية الخارجية مثل الإشعاع الشمسي ودرجة حرارة الهواء والرطوبة وسرعة الرياح. ومع ذلك، يمكن التخفيف من حدة هذه التحديات من خلال الاختيار الحكيم لمواد البناء وتحسين خصائصها لضمان الراحة الحرارية للسكان. تهدف هذه الدراسة إلى تحديد التوليفات المثلى للعزل وسماكة الجدران في الهياكل المبنية من الطوب اللبن المدعوم بالقش لتعزيز أداء الطاقة في المباني في سياق صحراوي مغربي، وتحديدًا في مدينة الرشيدية. ولتحقيق هذا الهدف، توظف الدراسة نموذجًا للطاقة تم التحقق من صحته للتحقق من متغيرين رئيسيين: (1) إضافة عازل من الألياف الطبيعية (0.10 م) و (2) تباين سماكة الجدار (0.3 م إلى 0.5 م). تشير نتائج المحاكاة الحرارية إلى أن إضافة 0.10 م من العزل يعزز الأداء الحراري بشكل كبير مقارنةً بالجدران غير المعزولة. بدون العزل، تقلل سماكة الجدران التي تتراوح من 0.4 متر إلى 0.5 متر من التقلبات الحرارية بمقدار درجتين مئويتين. ومع ذلك، مع العزل، يحقق الجدار بسماكة 0.3 متر انخفاضًا قدره 3.7 درجة مئوية في ذروة درجات الحرارة الداخلية في الصيف ويحافظ على درجات حرارة داخلية في الشتاء تصل إلى 12.1 درجة مئوية، حتى في ظل الظروف الخارجية القاسية. يؤدي دمج الألواح العازلة الصديقة للبيئة أيضًا إلى انخفاض الطلب على طاقة التبريد بنسبة 23.18% وانخفاض احتياجات التدفئة بنسبة 40% مقارنةً بالجدران غير المعزولة. تؤكد هذه النتائج على أهمية تصميم جدران مصممة خصيصًا للظروف المناخية للمناطق الصحراوية، خاصة تلك القريبة من مدينة الرشيدية لتحسين كفاءة الطاقة وخفض الآثار البيئية وتعزيز الممارسات المعمارية المستدامة.

الكلمات المفتاحية: الطوب اللبن المدعوم بالقش؛ الراحة الحرارية؛ العزل؛ أداء الطاقة في المباني؛ المناخ الصحراوي

The graphical abstract:



1. INTRODUCTION

Today, Africa's population is experiencing rapid demographic growth, coupled with a high rate of construction, which increases the demand for decent housing that provides satisfactory thermal comfort conditions for residents [1]. In hot regions, the need for cooling is particularly significant to adapt to current heat conditions, making thermal regulation a key aspect of housing design. This challenge is further amplified by the fact that nearly one-third of global energy is consumed by the building sector, which also accounts for 40% of all CO₂ emissions, highlighting the urgent need for sustainable and energy-efficient construction solutions [2-4]. Moreover, heating, ventilation, and air conditioning (HVAC) systems alone account for half of the total energy consumption in residential buildings, highlighting the urgent need for energy-efficient solutions [5, 6]. To reduce heating and cooling demands, recent and efficient traditional construction techniques, such as earthen buildings, can be employed. This involves adapting the building envelope by adding ecological insulation or enhancing earthen building materials with natural fibers [4]. Clay is one of the oldest and most widely used building materials, valued for its exceptional hygrothermal properties, natural abundance, and outstanding ecological benefits, particularly in conserving non-renewable resources [7].

Adobe bricks are traditionally composed of a mixture of sand, clay, and water. The bricks are formed by molding the clay-water mixture into desired shapes and allowing them to dry naturally in open air. To enhance their properties, extensive research has been conducted on incorporating natural additives into adobe bricks and evaluating their impact on thermal, mechanical, and durability characteristics. Notable additives studied include straw [7,8], alfalfa fibers [9], Alfa fibers [10], sawdust [11, 12], palm fibers [13], fonio straw [14], dry grass fibers [15]. These natural reinforcements aim to improve the bricks' performance, making them more suitable for modern sustainable construction.

In addition to enhancing the properties of adobe bricks, the integration of environmentally friendly thermal insulation materials into building walls has become a key strategy for improving energy efficiency and indoor comfort. For instance, the integration of thermal insulation in concrete walls has been shown to significantly reduce heat conduction across the envelope, thereby enhancing indoor thermal stability and lowering energy consumption [16]. Thermal insulation plays a vital role in reducing heat transfer, which is particularly critical in climates with extreme temperatures, such as hot desert regions. Research has shown that natural insulation materials, including bio-composites and fibers such as date palm fibers [17], hemp fibers [18], coconut fibers, cellulose fibers [19], and Sugarcane Bagasse [20], can significantly reduce temperature fluctuations and enhance the thermal stability of buildings. For example, a study evaluated recycled insulation panels made of cork, rice husk, and coffee chaff, achieving a thermal conductivity as low as 0.08 W/m.K and a Global Warming Potential of only 2.6 kg CO₂ eq/m², highlighting their strong environmental and thermal performance [21]. Another study assessed the effect of insulation and thermal mass on the thermal performance of a stabilized compressed earth block wall in a hot, dry tropical climate. The results indicated that a wall thickness of 0.14 m, with insulation, provided the best thermal efficiency, reducing the external temperature range by 22% [22].

In that scope, this paper aims to explore and propose construction solutions tailored to warm climates by optimizing the properties of building materials to enhance the thermal performance

of buildings. The study focuses on combining earth-stabilized bricks reinforced with straw and ecological thermal insulation panels applied to walls to improve energy efficiency. A detailed parametric analysis, conducted through simulations using TRNSYS software, investigates the impact of adding thermal insulation to earth walls. The originality of this research lies in the use of locally sourced materials, such as clay bricks reinforced with straw, which not only contribute to reducing indoor overheating but also minimize the ecological footprint of the construction process. In this context, the straw fibers incorporated in the adobe mix were collected from the Beni Mellal region in central Morocco, underlining the importance of valorizing renewable, regionally available resources. Overall, this study contributes to the advancement of sustainable and eco-friendly architecture that meets thermal comfort requirements while limiting the exploitation of natural resources.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Clay Bricks

The main raw material used in this study is natural clay extracted from the Beni Mellal region in north-central Morocco. It was employed during the summer season to produce adobe bricks reinforced with 2% straw by weight, as shown in Figure 1. The addition of straw enhances both the thermal insulation and mechanical performance of the bricks. To evaluate the workability and plasticity of the clay, the Atterberg limits were determined. These limits help assess the suitability of the clay for construction purposes. The corresponding values are presented in Table 1. Furthermore, Figure 2 presents the X-ray diffraction (XRD) analysis of the studied clay, revealing a range of minerals including quartz (Q), illite (I), kaolinite (K), calcite (C), dolomite (D), feldspar (Fp), and chlorite (Ck), with quartz identified as the predominant phase. The **high presence of silicon dioxide (SiO_2) indicates that the clay is suitable for construction [7], as SiO_2 is associated with enhanced mechanical strength, reduced water absorption, and improved thermal insulation properties—key characteristics for building materials [23].** In addition, this is further supported by the chemical composition of the clay shown in Figure 3. The **significant presence of aluminum oxide (Al_2O_3) confirms the clayey nature of the soil [24].** Moreover, the **elevated concentrations of calcium oxide (CaO) and potassium oxide (K_2O) suggest that the clay belongs to the kaolinite and illite mineral types [25].**



Figure 1. Sample clay brick

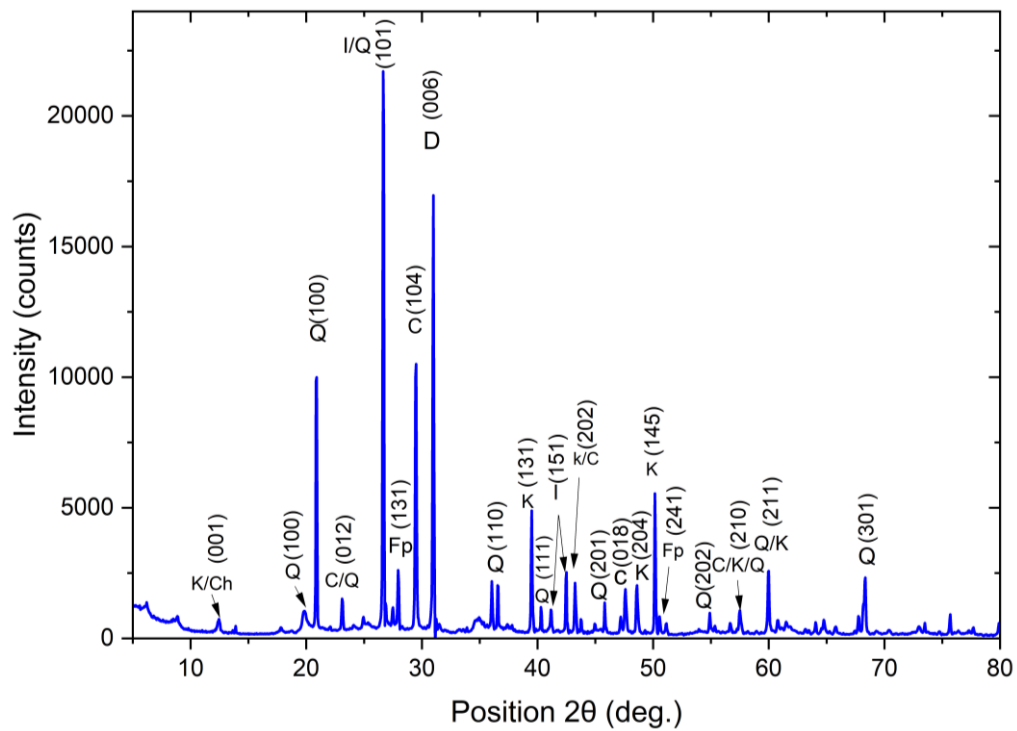


Figure 2. XRD pattern of the studied clay. Indexes: Q – quartz, C – calcite, K – kaolinite, I – illite, D – dolomite, Fp – feldspat, Ch – Chlorite [7].

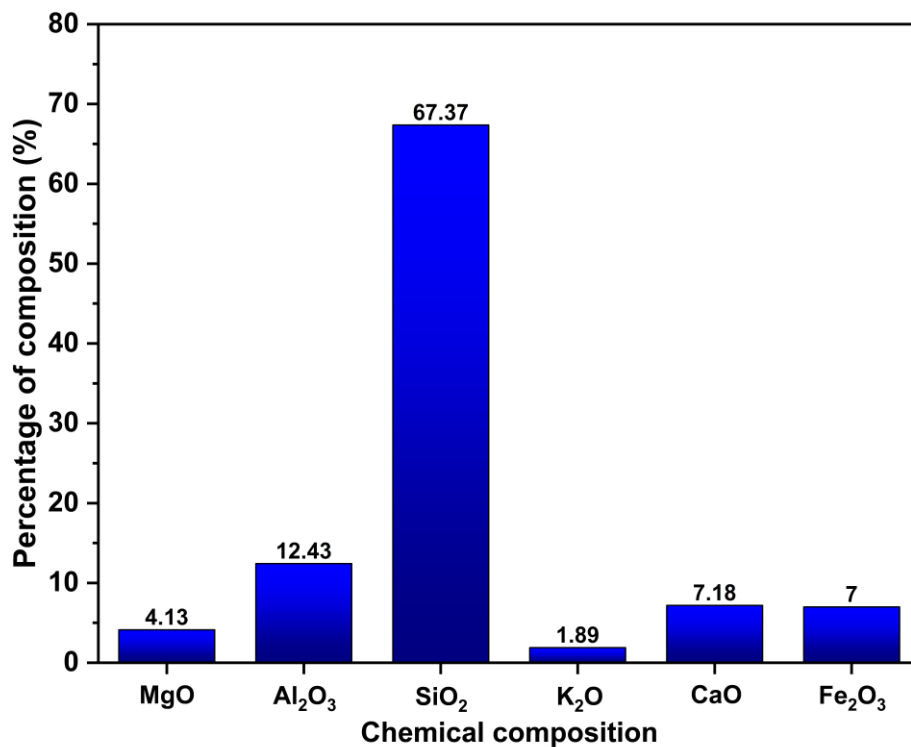


Figure 3. The chemical composition of the studied clay [7].

Table 1. The Atterberg limits of the soil [9].

Atterberg limits	Value
Plasticity limit (%)	16
Liquidity limit (%)	30
Plasticity index	14

2.1.2. Preparation of bricks samples

The adobe brick depicted in Figure 1 was fabricated using a traditional technique widely employed in southern Morocco. First, natural soil was mixed with water at 19% of the soil's dry mass. The mixture was then cured for 72 hours to ensure uniform moisture distribution. Subsequently, varying proportions of straw fibers were thoroughly incorporated into the hydrated clay matrix to form adobe bricks. The samples were then air-dried for four weeks under ambient conditions to achieve complete drying.

Once dried, the bricks' thermal properties were analyzed using an HFM Lambda 446 thermal flow meter. This instrument applies Fourier's law to determine thermal conductivity, as expressed in Equation (1) [26]:

$$Q = \lambda \times A \times \frac{\Delta T}{\Delta x} \quad (1)$$

The equation (1) represents heat flow (Q , in Watts) measured by a heat flow meter, where:

λ : thermal conductivity of the material (W/m.K)

A : cross-sectional area (m²)

ΔT : temperature difference (K) across the sample

Δx : thickness of the sample (m).

2.1.3. Thermal Insulation

The thermal insulation material employed in this study is a bio-composite made from cardboard and date palm fibers. These natural fibers were chosen for their durability, local availability, and superior thermal insulation properties, as noted by Bennallel et al. [17]. The bio-composites were transformed into eco-friendly panels and integrated between adobe walls to assess their effectiveness in reducing thermal fluctuations and improving energy efficiency.

2.2. Methodology

The methodology of this study consists in a comprehensive parametric analysis of adobe walls reinforced with straw, supplemented by ecological thermal insulation panels, to evaluate their thermal performance in hot desert climates. The thermal behavior of the reinforced adobe walls is examined in three configurations, as shown in Table 2, first by varying their thickness between 0.4 m, 0.45 m and 0.5 m. Then, Thermal insulation panels are placed between two adobe walls to determine the optimal balance between material efficiency and thermal stability. Simulations are performed using TRNSYS software to evaluate the impact of different insulation thicknesses on energy efficiency and indoor thermal comfort. These simulations allow the analysis of key parameters such as surface temperature fluctuations, indoor temperature stability and energy demand for heating and cooling. The results are then used to identify optimal wall and insulation configurations, minimizing thermal variations, improving interior comfort and reducing energy consumption. To clarify this methodology, a flowchart is presented in Figure 4, which outlines the key steps of the research process. The first part shows the design and modeling steps of the reference building, including the creation of the architectural model and its thermal simulation in TRNSYS 18, followed by validation according to the RTCM. The second part illustrates the comparative analysis of thermal performance between traditional adobe walls and insulated walls. The diagram shows the different configurations tested and the parameters

measured, including indoor temperatures and energy requirements. This approach has identified the most efficient insulation thickness, suitable for designing and building energy-efficient buildings adapted to hot desert climates while promoting environmentally friendly architecture.

Table 2. The wall configurations of the study.

Wall configurations	Materials	Thickness
Configuration 1	Reinforced adobe brick	0.40 m
Configuration 2	Reinforced adobe brick	0.45 m
Configuration 3	Reinforced adobe brick	0.50 m
Configuration with insulation	Reinforced adobe brick+ insulation+ Reinforced adobe brick	(0.15 + 0.1 + 0.15) m

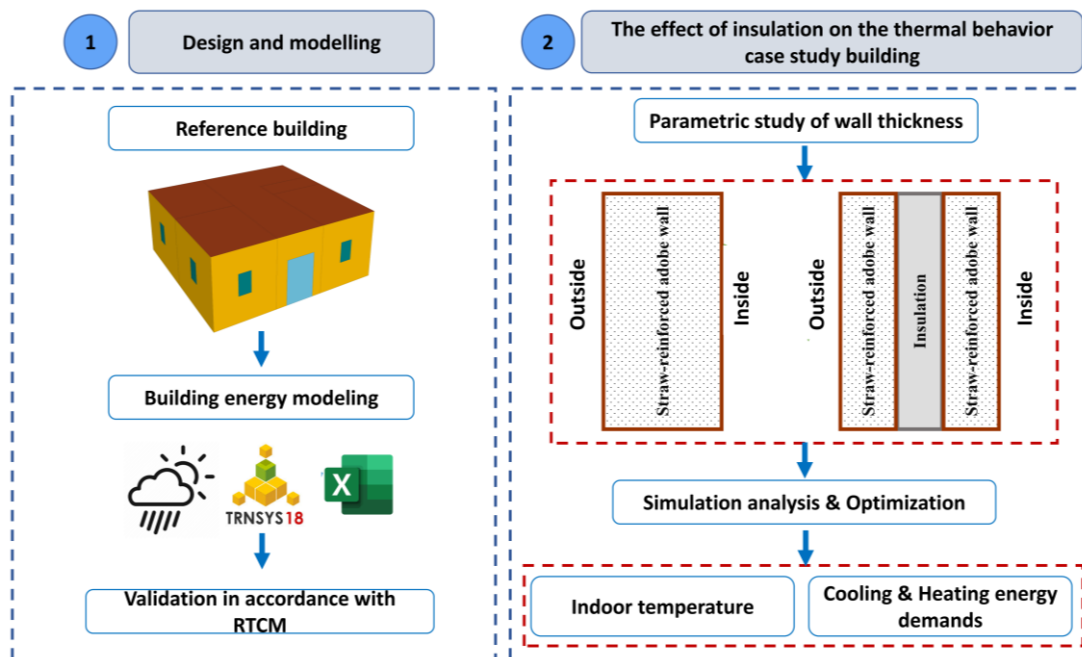


Figure 4. Flow chart of the study.

2.2.1. Description of the building and materials

The studied structure is a single-story building covering a total area of 74 m² with an internal height of 3 meters. The building is segmented into four distinct thermal zones, as illustrated in the sketch provided in Figure 5.

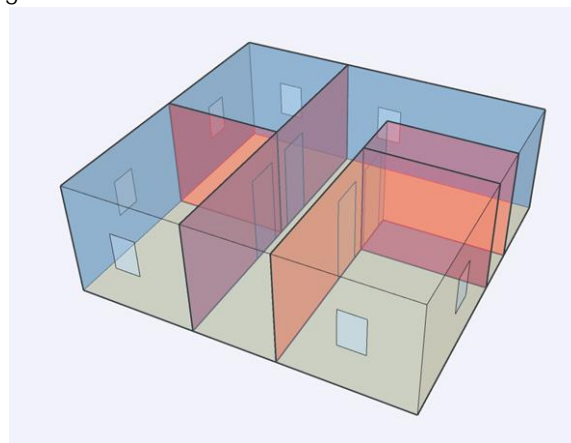


Figure 5. The sketch of case study building

This architectural sketch was created using SketchUp software and subsequently integrated into the TRNSYS simulation environment to define the thermal model. Each zone represents a specific usage area (e.g., living room, kitchen, bedroom, and rooms), which allows for more accurate simulation of internal thermal behavior and energy consumption. To ensure a comprehensive analysis, the thermophysical characteristics of the construction materials, such as thermal conductivity, density, and specific heat capacity, are detailed in Table 3.

Table 3. Thermophysical Properties of Wall-Building Materials

Materials	Density (Kg/m ³)	Thermal conductivity (W/ m K)	Thermal capacity (kJ/kg K)
Clay-straw (2%)	1703	0.40	0.75
Insulation panel	265.7	0.081	1.411

2.2.2. Climatic Conditions

The study area, Er-Rachidia, situated on the edge of the Moroccan Sahara Desert, experiences a hot desert climate. Summer is extremely hot, with temperatures often exceeding 43°C, while winter is relatively cool, with nighttime temperatures frequently dropping to around -1°C. The annual temperature profile of Er-Rachidia, depicted in Figure 6, highlights the pronounced seasonal variations and the thermal challenges characteristic of this harsh environment.

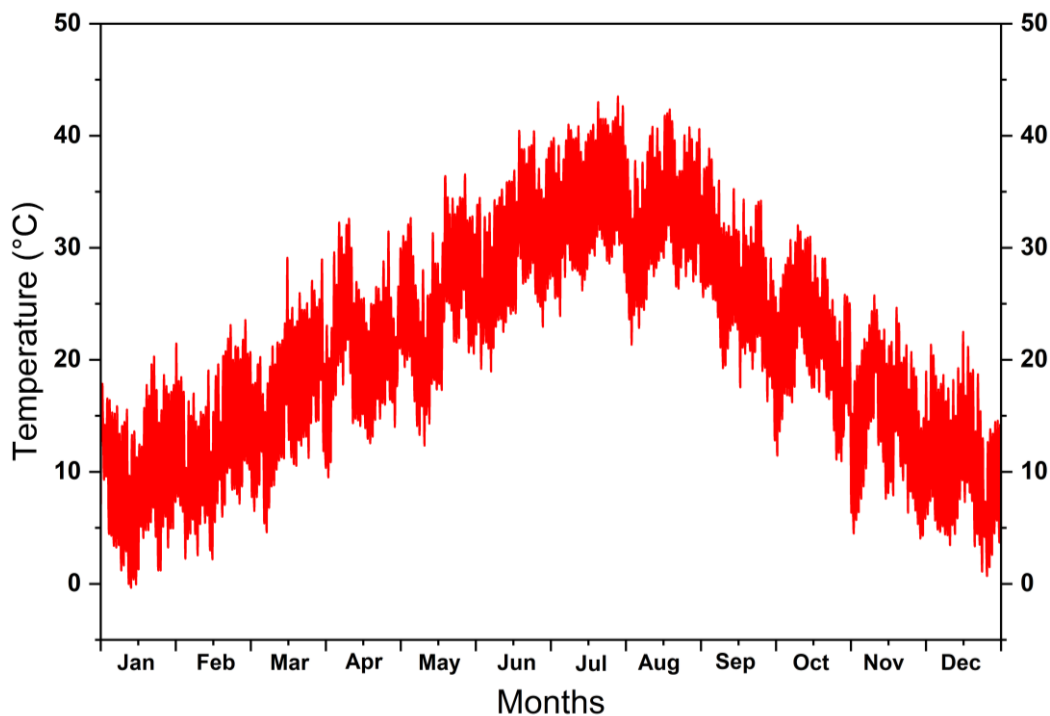


Figure 6. Outdoor air temperature of Er-rachidia city in 2024, showing extremes ranging from -1 °C (winter) to 43 °C.

3. RESULTS AND DISCUSSION

3.1. Annual Indoor air Temperature

The results of the dynamic thermal simulation for the four envelope configurations are

presented in Figure 7. These findings clearly demonstrate that the insulated configuration significantly enhances indoor thermal comfort compared to the reference configuration (Configuration 1), even under the extreme climatic conditions typical of the study area, characterized by intense summer heat and cold winter temperatures.

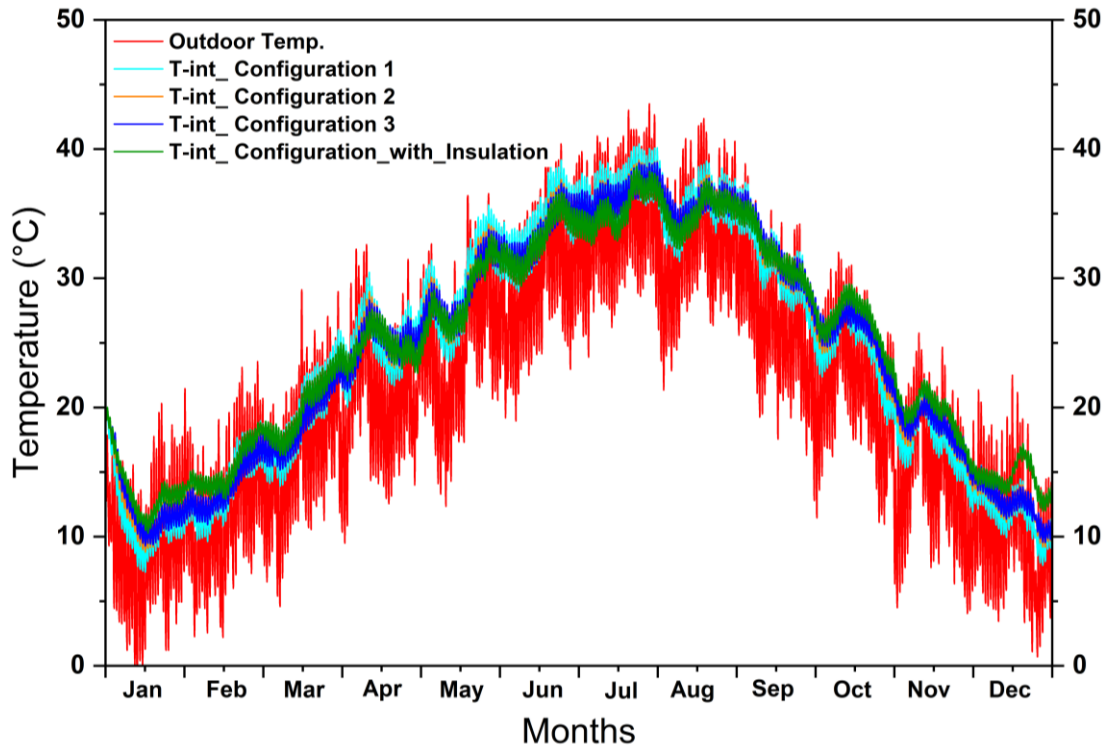


Figure 7. Annual variation in indoor and outdoor temperatures in 2024.

3.2. Summer and winter indoor temperature

During the winter period (Figure 8), the insulated configuration consistently outperforms the other configurations by maintaining higher indoor temperatures, despite outdoor temperatures dropping as low as -1°C . The minimum indoor temperatures recorded for the four configurations are 7.2°C , 8.7°C , 9.2°C , and 12.1°C , respectively, highlighting the superior thermal retention capacity of the insulated configuration. Similarly, during the summer period (Figure 9), when outdoor temperatures often exceed 43°C , the insulated configuration demonstrates a significant reduction in maximum indoor temperatures. The maximum indoor temperatures for the four configurations are recorded at 40.3°C , 39.1°C , 38.3°C , and 36.6°C , respectively. These results underscore the critical role of insulation in minimizing heat ingress and improving indoor thermal comfort during hotter periods.

Moreover, the analysis reveals that integrating locally sourced ecological insulation materials significantly enhances thermal regulation. The reduction in indoor temperature fluctuations observed in insulated adobe buildings, compared to those constructed with adobe alone, highlights improved thermal stability. This performance underscores the effectiveness of insulation in optimizing energy efficiency and thermal comfort for traditional adobe constructions in extreme climatic conditions.

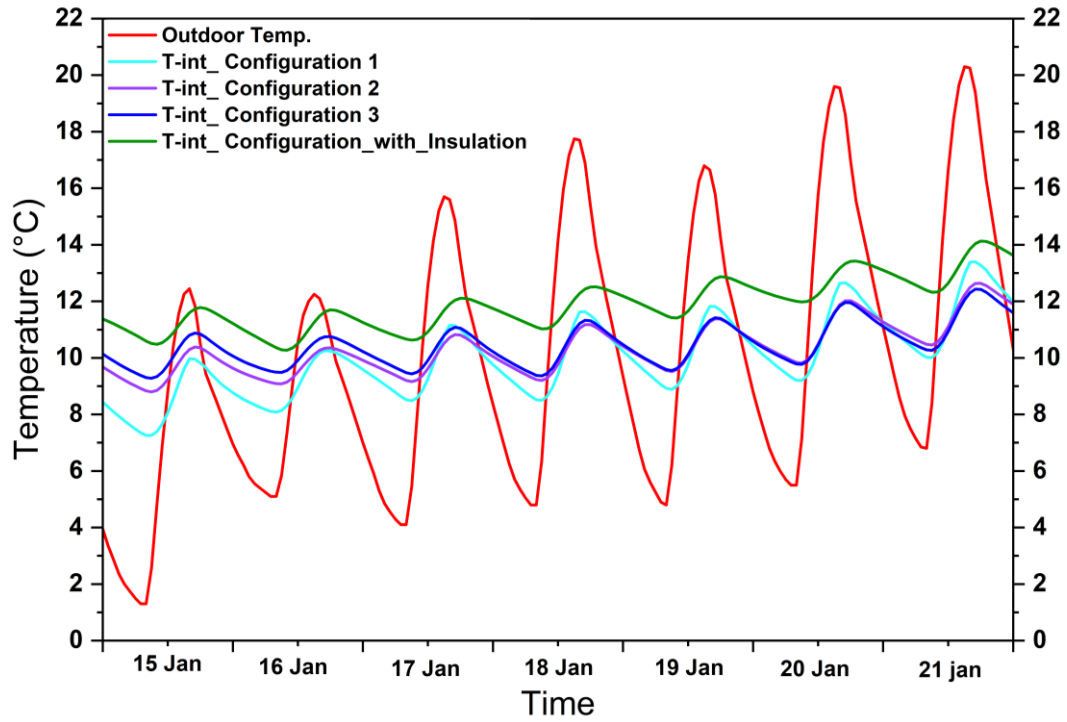


Figure 8. Indoor air temperature during the winter from January 15 to 21, 2024, under extreme outdoor conditions ranging from -1 °C to 22.5 °C.

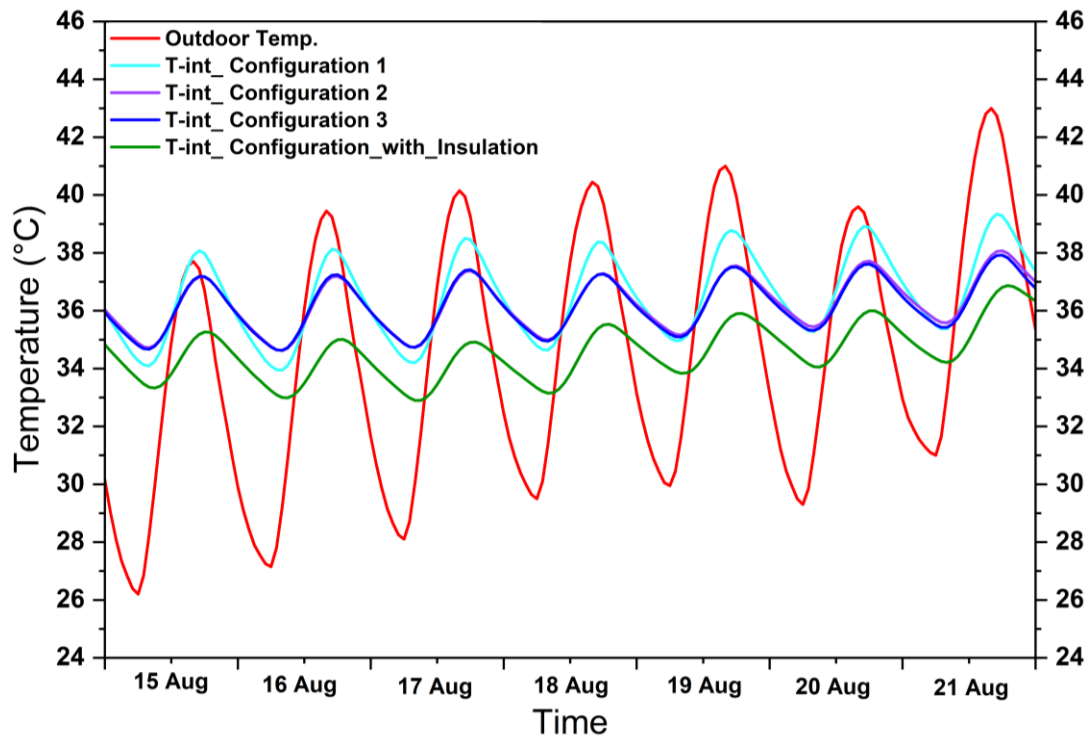


Figure 9. Indoor air temperature during the winter from August 15 to 21, 2024, under extreme outdoor conditions ranging from 26.2 °C to 43 °C.

3.3. Effect of Insulation on energy requirements

Figures 10 and 11 present the annual and monthly energy requirements for cooling and heating, respectively, across the various wall configurations studied. A detailed analysis of the results reveals that integrating 0.1 m thick thermal insulation panels between two layers of adobe

significantly lowers energy demand, particularly for cooling. The insulated configuration decreases cooling requirements from 8,855 to 6,802.3 kWh, representing a 23.18% improvement compared to the initial configuration (Configuration 1). Similarly, heating requirements drop from 7,265 to 4,359.38 kWh, marking a 40.00% reduction.

These findings emphasize the effectiveness of insulation panels in enhancing the thermal performance of walls, especially in hot, dry climates. In contrast, walls without insulation (Configurations 1, 2, and 3) exhibit lower performance, with only modest reductions achieved through increased wall thickness. Thus, incorporating ecological insulation between two layers of adobe proves to be an optimal solution for improving energy efficiency and thermal comfort in traditional buildings.

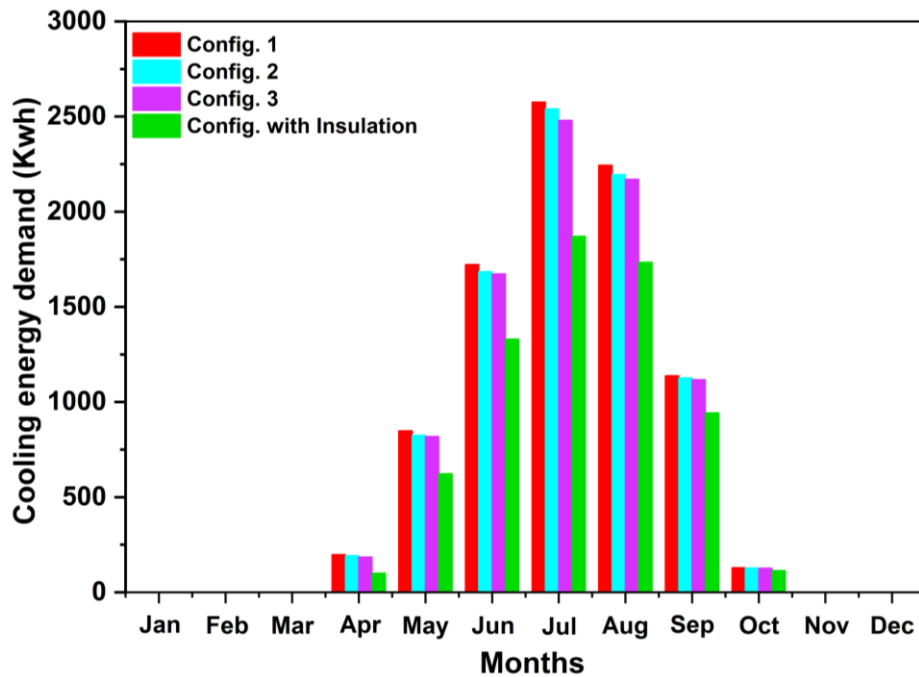


Figure 10. Energy requirements for cooling in 2024 for the city of Errachidia.

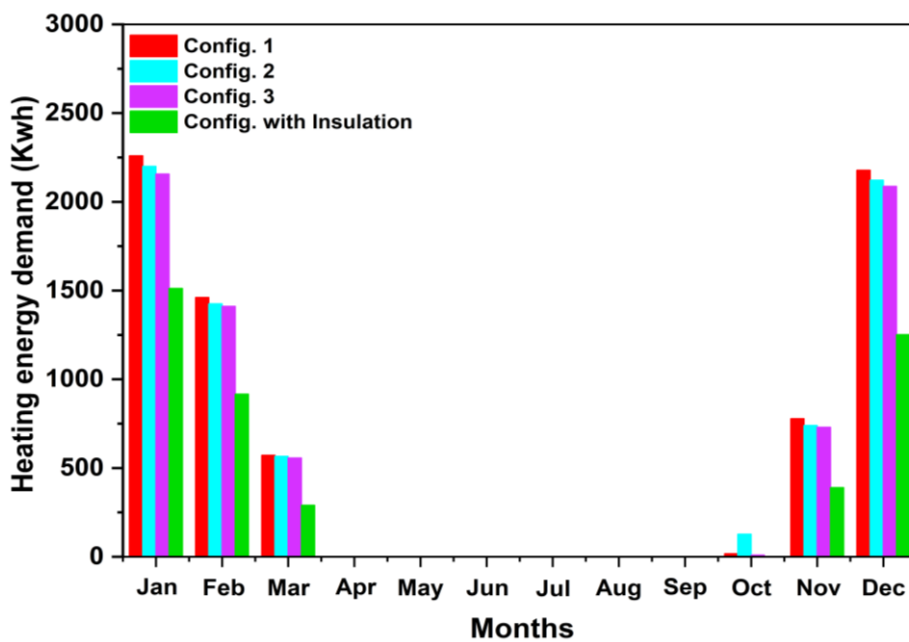


Figure 11. Energy requirements for heating in 2024 for the city of Errachidia.

4. CONCLUSION

This study highlights the advantages of integrating eco-friendly insulation panels with traditional adobe walls to enhance thermal performance and energy efficiency in hot desert climates. The simulations demonstrate that adding 0.1 meters of insulation between adobe layers significantly improves indoor thermal comfort, reducing summer indoor temperature peaks by up to 3.7°C and maintaining winter temperatures at levels as high as 12.1°C, even under extreme outdoor conditions. The energy demand analysis further confirms the effectiveness of this approach, with cooling requirements reduced by 23.18% and heating needs by 40% compared to non-insulated configurations. These findings underscore the superior thermal regulation provided by insulated adobe walls, particularly in climates with significant temperature fluctuations.

Moreover, the use of locally sourced materials, such as adobe and bio-composite insulation made from date palm fiber and cardboard, supports sustainable construction practices. This method not only enhances building performance but also minimizes environmental impact, aligning with the principles of environmentally responsible architecture.

However, this study is limited to the thermal performance of insulated adobe walls in single-story buildings under a hot desert climate. Future research should extend its scope to multi-story buildings and assess performance under real-time climatic variations. This could involve integrating adaptive insulation strategies that respond dynamically to seasonal changes, thereby improving the general applicability of these solutions. Additionally, the combination of bio-based insulation with phase change materials (PCMs) could be explored to further enhance thermal inertia and energy efficiency. Finally, a life cycle assessment (LCA) and a cost-benefit analysis should be conducted to evaluate the long-term environmental and economic impact of these solutions, ensuring their scalability for widespread adoption in sustainable construction.

In summary, this study offers valuable insights into optimizing traditional construction techniques with modern, sustainable solutions. It provides practical guidelines for designing energy-efficient, climate-resilient structures suitable for desert regions.

Author Contributions: Abdelmounaim Alioui: Writing – original draft, Data curation, Methodology, Conceptualization; Youness Azalam: Data curation, Software, Methodology, Conceptualization, Mohammed Benfars: Writing – original draft Software, Methodology; El Maati Bendada: Project administration, Supervision; Mustapha Mabrouki: Project administration, Supervision, Writing – review & editing.

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