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Optimizing Passive Thermal Performance in Moroccan Residential Structures: A Comparative Study of Traditional Versus Contemporary Building Techniques

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ABSTRACT

This study presents a comparative analysis of three construction scenarios for a residential building in Morocco, maintaining consistent parameters such as building orientation, architectural layout, and occupancy schedule. The research uses dynamic thermal simulations with TRNSYS software to evaluate the influence of different wall and roof compositions on energy consumption and indoor thermal comfort. The investigation focuses on the integration of eco-friendly hemp-based materials, particularly hempcrete, recognized for its insulating properties. Simulations were conducted across four Moroccan climatic zones: Mediterranean (Al Hoceima), continental (Oujda), semi-arid (Marrakech), and desert (Ouarzazate) to capture diverse environmental conditions. Results demonstrate that the use of hempcrete can reduce heating energy demand by up to 39% and cooling demand by up to 15%, while enhancing indoor thermal comfort with an average winter temperature increase of 0.77°C and a summer decrease of 0.62°C. These findings highlight the potential of hempcrete to improve building energy performance and contribute to carbon footprint reduction in varied climatic contexts.

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تحسين الأداء الحراري السلبي في المنشآت السكنية المغربية: دراسة مقارنة بين تقنيات البناء التقليدية والمعاصرة

هشام قدوري، عبد الرحيم عبيدوش، محمد سعيدي حسني علوي، إسماعيل دريوش، فريال لطرش، وعبد الرحيم الضاوي

ملخص: تقدم هذه الدراسة تحليلاً مقارناً لثلاثة سيناريوهات بناء لمبنى سكني في المغرب، مع الحفاظ على ثبات بعض المعايير مثل اتجاه المبنى، التخطيط المعماري، وجدول إشغال المبنى. تستخدم الدراسة محاكاة حرارية ديناميكية بواسطة برنامج TRNSYS لتقييم تأثير تركيبات الجدران والأسقف المختلفة على استهلاك الطاقة والراحة الحرارية الداخلية. تركز الدراسة على دمج مواد صديقة للبيئة تعتمد على القنب، وخاصة الخرسانة القنبية (hempcrete) المعروفة بخصائصها العازلة. أُجريت المحاكاة عبر أربع مناطق مناخية مغربية هي: المتوسطية (الحسيمة)، القارية (وجدة)، شبه الجافة (مراكش)، والصحراوية (ورزازات)، لتغطية ظروف بيئية متنوعة. أظهرت النتائج أن استخدام الخرسانة القنبية يمكن أن يقلل من طلب الطاقة للتدفئة بنسبة تصل إلى 39% وللتبريد بنسبة تصل إلى 15%، مع تحسين الراحة الحرارية الداخلية بزيادة متوسط درجة الحرارة في الشتاء بمقدار 0.77 درجة مئوية وانخفاضها في الصيف بمقدار 0.62 درجة مئوية. وتبرز هذه النتائج قدرة الخرسانة القنبية على تحسين أداء الطاقة في المباني والمساهمة في تقليل البصمة الكربونية في سياقات مناخية متنوعة.

الكلمات المفتاحية: الخرسانة القنبية، استهلاك الطاقة، الراحة الحرارية، المحاكاة الديناميكية، المناطق المناخية

1. INTRODUCTION

In recent decades, the growing energy needs in the building sector and the significant environmental impact caused by the construction industry have become central topics in multidisciplinary research. This trend is largely driven by substantial energy consumption in buildings, which results from various factors: the effects of climate change, leading to rising ambient temperatures and consequently higher heating and cooling needs. Additionally, socio-economic factors such as population growth, urban migration, widespread use of new technologies, and increasing expectations for thermal comfort further contribute to this demand.

These challenges are major concerns for stakeholders and key drivers of sustainable development policies aimed at meeting the needs of present and future generations. Globally, several agreements and conventions have been signed, with the goal of supporting the transition from fossil fuels to green and renewable energies. They also aim to reduce greenhouse gas (GHG) emissions in energy-intensive sectors such as buildings, industry, and transport. Many countries now recognize this challenge as a critical development and sustainability issue, making the improvement of energy efficiency a necessity.

In Morocco, this challenge is exacerbated by the country's heavy reliance on fossil fuels. According to estimates from the Ministry of Energy, petroleum alone accounts for approximately 61% of the country’s energy needs, resulting in substantial GHG emissions. The building sector contributes significantly to these emissions, representing around 12% of the country’s total GHG emissions and 33% of total energy consumption [1]. Between 2000 and 2020, electricity consumption in residential buildings increased by 50%, with an additional 5% rise recorded during the COVID-19 lockdown in 2020 [2].

The building sector is a major energy consumer worldwide [3], and Morocco is no exception. The country’s growing urbanization and economic development have intensified energy demand, mainly due to heating, cooling, and electricity needs in buildings. To address this challenge, the Moroccan government has adopted a national energy strategy. Its goals are to reduce energy consumption, increase the share of renewable energy in the energy mix, and improve energy efficiency across all sectors, including buildings. Specifically, the target is a 15% reduction in energy consumption by 2030 [4].

This strategy includes several measures. It promotes both the renovation of existing buildings and the construction of new, energy-efficient structures. It also focuses on improving building codes to ensure better thermal insulation. Another key objective is to increase overall energy performance. These actions aim to address Morocco's energy, environmental, and economic challenges. The building sector offers significant potential for energy savings. Many studies and research projects are now focusing on reducing energy demand in buildings and improving their performance. Proposed approaches include green building practices and bioclimatic design as passive and eco-friendly solutions.

The adoption of green building concepts and the use of ecological and bio-based materials can significantly reduce buildings' energy needs while improving thermal comfort and lowering their carbon footprint. Although research on integrating bio-based materials into typical Moroccan building envelopes adapted to the country's diverse climates remains limited, several studies have addressed this issue from different perspectives.

Charai et al. [5] explored the thermal insulation properties of hemp and plaster-based biocomposites and their impact on energy savings in buildings located in cold and hot semi-arid zones, such as Oujda and Marrakech. Benfars et al. [6] evaluated the impact of roof insulation using a cardboard and straw-based biocomposite on the energy efficiency of residential buildings in the semi-arid climate of Beni Mellal. Dlimi et al. [7] investigated the thermal performance of hollow brick walls filled with hempcrete and analyzed their energy, economic, and environmental potential in a typical building in Meknes. Essaghouri et al. [8] conducted a life cycle assessment (LCA) comparing three exterior wall models for a residential building in the hot semi-arid climate of Marrakech, highlighting the low carbon footprint of hempcrete walls. Kaddouri et al. [9] investigated the use of hemp as a building material in the Mediterranean climate. Furthermore, in other studies, Kaddouri et al. [10] and Abidouche et al. [11] explored the combined impact of insulation and other passive design strategies on the energy performance of buildings in Morocco's Mediterranean climate.

Beyond academic research, real-world case studies further reinforce the relevance of hempcrete as a high-performance, low-carbon building material. In the United Kingdom, the Triangle Development (2022) achieved a 55% reduction in energy consumption and a 65% decrease in operational carbon emissions compared to conventional buildings [12]. In Morocco, the Bioclimatic Villa Prototype in Marrakech, developed by IRESEN in 2023, demonstrated passive cooling performance with an indoor temperature range of 24–26°C, even under peak external temperatures of 38°C [13].

At the policy level, global frameworks are actively promoting the use of bio-based materials like hempcrete. France's "Plan Bâtiment Durable" targets a 30% integration of such materials in new buildings by 2030, with detailed hemp strategies outlined in national guidelines [14]. Similarly, Canada's upcoming National Building Code (NBC) 2025 revision formally recognizes hempcrete as an alternative insulating material, aligning with ASTM C1186 moisture resistance standards [15].

These developments are supported by both market dynamics and regulatory trends. The European Union has seen an 18% compound annual growth rate (CAGR) in hempcrete adoption between 2020 and 2023, while in the United States, twelve states including California have amended building codes to include hempcrete, guided by ICC-ES evaluation protocols. As part of the present study, dynamic thermal simulations were carried out using the TRNSYS software to evaluate the thermal performance of a residential building envelope. The analysis focused on the impact of three distinct construction scenarios, characterized by different configurations and eco-friendly materials, to assess their influence on indoor temperature and heating and cooling energy needs. These simulations were conducted across four Moroccan climatic zones, allowing the adaptation of results to regional specificities and the development of optimized solutions to enhance both energy efficiency and occupant thermal comfort.

2. MATERIALS AND METHODS

To assess the impact of construction characteristics on the building's energy performance and indoor thermal conditions, three distinct construction scenarios were defined and simulated. To ensure the comparability of the results, certain parameters such as building orientation, architectural layout, occupancy schedule, and the operation of lighting and electrical equipment were systematically kept constant. The only variables were the composition of the building envelope, specifically the exterior walls, roofs, and floors.

The energy demand for heating and cooling was calculated using setpoint temperatures of 20 °C for winter and 26 °C for summer, across four climatic zones representative of the Moroccan territory. Additionally, a detailed analysis of indoor air temperature variations was carried out, based on two representative days for each season: January 15 and 16 for winter, and July 15 and 16 for summer, corresponding to periods of extreme climatic conditions.

This methodological approach aims to provide a comprehensive evaluation of how different construction configurations influence both energy consumption and thermal comfort under contrasting seasonal contexts.

2.1. Meteorological data

According to the Moroccan Thermal Regulation for Buildings (RTCM) [16], Morocco has been thermally zoned to reflect the country's diverse climate. This zoning divides the national territory into six distinct climatic zones. To conduct a thermal simulation that accurately reflects these diverse climatic conditions, four cities were selected to represent Morocco's main climatic zones: Al Hoceima for the Mediterranean zone, Oujda for the continental zone, Marrakech for the semi-arid zone, and Ouarzazate for the desert zone.

Meteorological data for these locations were obtained using the Meteonorm software [17], which generates accurate and location-specific climate information based on a Typical Meteorological Year (TMY). These data were essential for modeling the thermal behavior of buildings in accordance with regional climatic characteristics, thereby ensuring a reliable and context-sensitive energy analysis.

Figure 1 illustrates the geographical location of the studied sites on the RTCM climate map, highlighting their spatial distribution and potential influence on buildings' thermal performance.

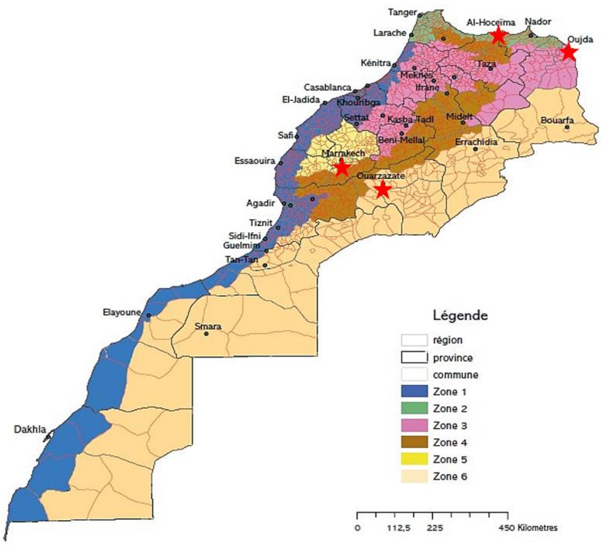

Figure 1: Location of study sites on the RTCM climate map.

Figure 2 highlights the variations in ambient temperature across the four studied sites, each representing a distinct climatic zone. The analysis of hourly temperature profiles underscores the importance of tailoring building design and energy strategies to the specific characteristics of each climate. Data collected from Oujda, Marrakech, Al Hoceima, and Ouarzazate reveal significant differences directly linked to the unique climatic conditions of each region.

Among these cities, Marrakech exhibits the highest temperatures, with summer peaks regularly exceeding 45 °C, characteristic of a semi-arid climate marked by particularly hot and dry summers. In contrast, Al Hoceima, representing the Mediterranean climate, shows the most moderate temperature range, with summer highs not exceeding 35 °C and winter lows generally between 5 °C and 10 °C. This reduced thermal amplitude is primarily attributed to the moderating influence of the Mediterranean Sea, which dampens seasonal temperature fluctuations.

The comparison between Marrakech, Al Hoceima, and the other sites thus illustrates the wide thermal contrasts across Moroccan territory from the harsh semi-arid and desert climates of the interior to the milder coastal Mediterranean climate.

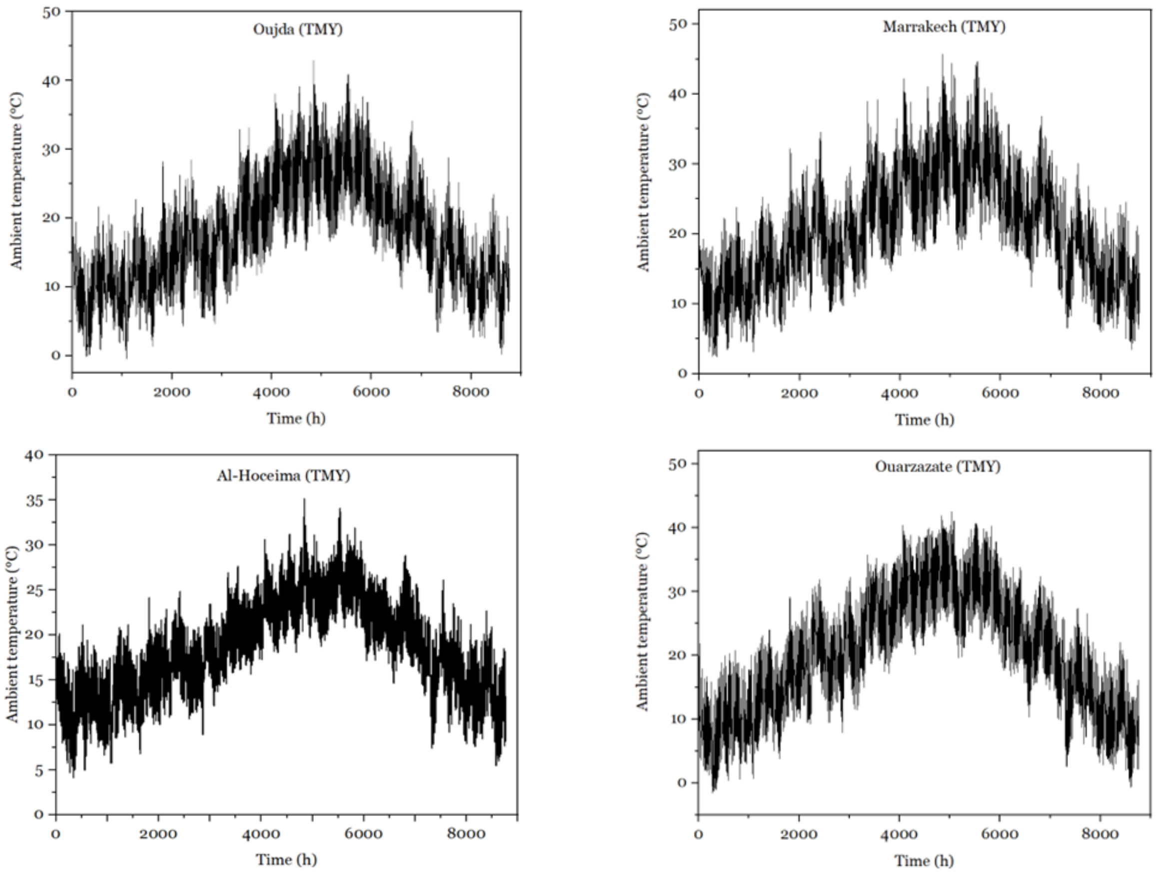

Figure 2: Hourly distribution of ambient temperature at the four sites studied for a typical meteorological year.

2.2. Building and occupancy schedule

Our study focuses on an apartment in a two-story residential building. Each floor has a height of 3 meters and an area of 91.5 m². The interior layout consists of two bedrooms, a living room, a lounge open to a hall, a kitchen, and a bathroom. The apartment is occupied by a family of three. Figure 3 illustrates the different rooms that make up the apartment.

In this study, three construction scenarios are examined:

- Scenario 1: Conventional construction without energy efficiency measures.
- Scenario 2: Conventional construction with renovation using hemp plaster.

- Scenario 3: Eco-friendly construction with hempcrete.

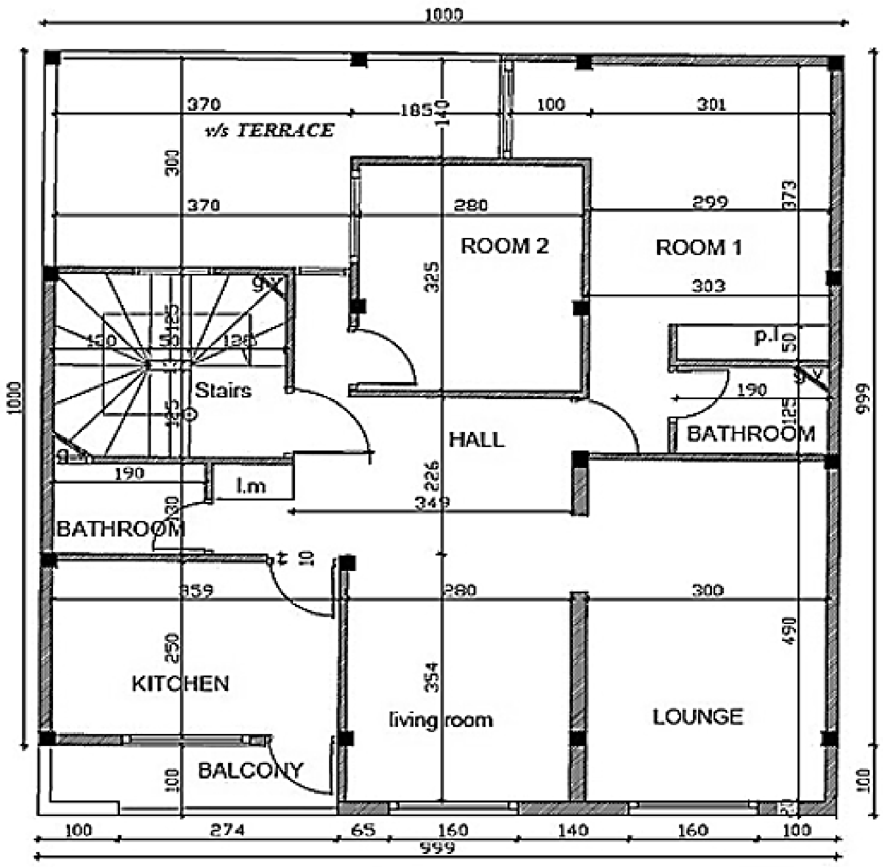

Figure 3: 2D plan of the apartment

The three construction scenarios are detailed in Table 1.

Table 1. Construction scenarios

Building components	Scenario 1		Scenario 2		Scenario 3	
	Materials	Thickness (cm)	Materials	Thickness (cm)	Materials	Thickness (cm)
Exterior Wall	Mortar Brick 1 Mortar	1,5 20 1,5	Hemp plaster Mortar Brick 1 Mortar Hemp plaster	2 1,5 20 1,5 2	Mortar Brick 2 Hempcrete Brick 2 Mortar	1,5 7 5 7 1,5
Interior Wall	Mortar Brick 2 Mortar	1,5 10 1,5	Mortar Brick 2 Mortar	1,5 10 1,5	Mortar Brick 2 Mortar	1,5 10 1,5
Roof	Plaster coating Hollow slab Heavy concrete Tiles	1 16 7 2	Hemp plaster Plaster coating Hollow slab Heavy concrete Tiles	2 1 16 7 2	Plaster coating Hollow slab Hempcrete Heavy concrete Tiles	1 16 5 6 2
Floor	Plaster coating Hollow slab Heavy concrete Tiles	1 16 7 2	Plaster coating Hollow slab Heavy concrete Tiles	1 16 7 2	Plaster coating Hollow slab Heavy concrete Tiles	1 16 7 2

Table 2. Thermophysical properties of materials [18] [19] [20]

Materials	Thermal conductivity (W/m.K)	Thermal capacity (kJ/kg.K)	Density (kg/m3)
Cement mortar	1,30	1,00	1900
Brick 1	0,22	0,74	664
Brick 2	0,19	0,74	918
Tiles	1,30	0,84	2300
Heavy concrete	2,00	1,00	2450
Plaster coating	0,56	1,00	1350
Hollow slab	1,04	1,00	1513
Hempcrete	0,082	1,00	317
Hemp plaster	0,21	1,09	761

Table 3 illustrates a schedule of occupancy and use of lighting and electrical equipment.

Table 3: Schedule of occupancy and equipments

Element	Type of gain	Number of hours of daily use	Internal gains (W)
lounge	Lighting TV 2 persons	3h (Monday to Friday) 4h (Monday to Friday) 5h (Monday to Friday)	36W 100W 166W
Living room	Lighting TV 2 persons	3h (Saturday and Sunday) 4h (Saturday and Sunday) 5h (Saturday and Sunday)	36W 100W 166W
Kitchen	Lighting Refrigerator Washing M 1 person	3h (all week) 24h (all week) 3h (1 time per week) 4h (all week)	12W 300W 2200W 126W
Room 1	Lighting Laptop 2 persons	3h (all week) 3h (all week) in activity : 2h (all week) Sleeping : 8h (all week)	12W 40W 166W 144W
Room 2	Lighting Laptop 1 person	3h (all week) 3h (all week) in activity: 2h (all week) Sleeping: 8h (all week)	12W 40W 83W 72W

2.3. Simulation: physical model and assumptions

Using the TRNSYS software, the building is modeled as a multi-zone system employing Type 56. The building consists of seven thermal zones, where the heat balance for each zone is represented by the following equation [21]:

$$\dot{Q} = \dot{Q}_{inf} + \dot{Q}_{vent} + \dot{Q}_{cplg} + \dot{Q}_{Surf} + \dot{Q}_{g,c} + \dot{Q}_{solair} + \dot{Q}_{ishcci} \quad (1)$$

Where:

- $\dot{Q}_{inf}$: The energy flow due to infiltration of air from outside the thermal zone (node), expressed as :

$$\dot{Q}_{inf} = \dot{V}_{inf}\, \rho\, C_p (T_{outside} - T_{air}) \quad (2)$$

With $\dot{V}_{inf}$ is the air infiltration rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in (kJ.kg^{-1}.K^{-1}), $T_{outside}$ is the outside temperature of the thermal zone in (K).

- $\dot{Q}_{vent}$: The energy flow due to ventilation of the thermal zone, expressed as :

$$\dot{Q}_{vent} = \dot{V}_{vent}\, \rho\, C_p (T_{vent} - T_{air}) \tag{3}$$

With $\dot{V}_{vent}$ is the air ventilation rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in (kJ.kg^{-1}. K^{-1}), T_{vent} is the temperature of the ventilated air entering the thermal zone in (K).

- $\dot{Q}_{cplg}$: The energy flow due to convection caused by air flows between neighbouring thermal zones (air coupling) is expressed as :

$$\dot{Q}_{cplg} = \dot{V} \rho\, C_p (T_{zone} - T_{air}) \tag{4}$$

With $\dot{V}$ is the air coupling flow rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in (kJ.kg^{-1}. K^{-1}), T_{zone} is the temperature of the thermal zone air in (K), while T_{air} is the temperature of the air from an adjacent zone in (K).

- $\dot{Q}_{surf}$: The energy flow due to convection caused by opaque surfaces in the thermal zone is expressed as :

$$\dot{Q}_{surf} = UA(T_w - T_{air}) \tag{5}$$

Where U and A are the thermal transmittance coefficient in (W/m^2.K) and the surface area in (m^2), respectively. T_w and T_{air} are the ambient indoor and outdoor air temperatures in (K), respectively.

- $\dot{Q}_{g,c}$: Energy flow due to internal gains in the thermal zone.
- $\dot{Q}_{solair}$: The energy flow due to the amount of solar radiation entering the thermal zone through the glazing.
- $\dot{Q}_{ishcci}$: The energy flow due to the amount of solar radiation absorbed by the thermal zone's internal shading devices.

In fact, the heat balance of each thermal zone represents the variation in internal energy in that zone:

$$\dot{Q} = \frac{dE_{int}}{dt} = C_{int} \frac{dT_{air}}{dt} \tag{6}$$

Where $\frac{dE_{int}}{dt}$ and $\frac{dT_{air}}{dt}$ represent the time variations of the internal energy and the indoor air temperature of the thermal zone, respectively, and C_{int} is the heat capacity of the indoor space of the thermal zone, expressed in (kJ/K).

Finally, based on the thermal balance of the thermal zone, its thermal load is determined for the imposed heating and cooling setpoint temperatures.

$$\dot{Q} - P = C_{int} \frac{dT_{air}}{dt} \tag{7}$$

Where P is the thermal zone output power required to maintain the zone interior at the set temperature.

During the simulation, the following assumptions were taken into account:

- The thermal simulation is performed with a time step of 1 hour.
- The infiltration rate is set at 0.6 air changes per hour (ACH).
- The solar absorption coefficient of the walls and roof is estimated at 0.5.
- The ground temperature is derived using Kusuda's correlation [22].
- The setpoint temperatures are 20°C for heating and 26°C for cooling [23].
- The internal and external convective heat transfer coefficients are calculated based on the

following correlation:

$$h_{inside,outside} = a(T_{surf} - T_{air})^b \quad (8)$$

Table 4: a and b values

Type of surface	Condition	h_{inside}		$h_{outside}$	
		a (W.m-2.K-n-1)	b	a (W.m-2.K-n-1)	b
Wall	---	1,60	0,30	2,11	0,31
Ground	$T_{surf} - T_{air} > 0$	2	0,31	2,11	0,31
	$T_{surf} - T_{air} < 0$	1,07		1,87	0,25
Roof	$T_{surf} - T_{air} > 0$	1,07	0,31	2,11	0,31
	$T_{surf} - T_{air} < 0$	2		1,87	0,25

3. RESULTS AND DISCUSSION

3.1. Effect of envelope composition on energy demand

The results highlight the impact of different construction scenarios, in particular the use of ecological and bio-sourced materials. The heating and cooling requirements are illustrated in Figures 4.a and 4.b.

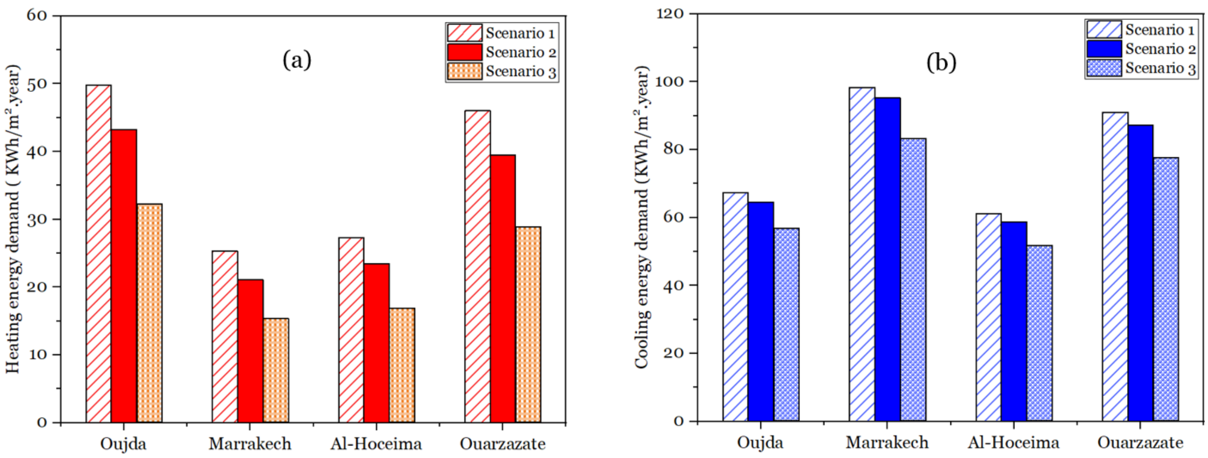

Figure 4: Annual variation in building energy demand for the three construction scenarios: (a) heating, (b) cooling

Figure 4.a illustrates the building's annual heating energy demand under three construction scenarios across the four studied cities. The results indicate that heating needs are particularly pronounced in Oujda and Ouarzazate, with a peak consumption of 49.8 kWh/m².year observed in Oujda due to the specific climatic conditions of these regions, which require greater heating demand. The impact of construction choices on energy performance is also significant: Scenario 1, which does not incorporate any energy efficiency measures, exhibits the highest heating demand, while Scenarios 2 and 3 demonstrate improved performance through the integration of insulating materials. Scenario 2 uses hemp-lime plaster, while Scenario 3 incorporates hempcrete, both known for their thermal properties, resulting in a notable reduction in heating needs. For instance, in Marrakech, Scenario 2 achieves a maximum reduction of 16.3% compared to Scenario 1, while Scenario 3 reaches a reduction of up to 39%, confirming the superior thermal insulation performance of hempcrete.

Figure 4.b presents the building's annual cooling energy demand under the three construction scenarios for the four studied cities. Cooling needs are particularly high in Marrakech and Ouarzazate, with a peak consumption of 98.3 kWh/m².year recorded in Marrakech due to the hot and arid climate, which intensifies air conditioning demand. The influence of construction scenarios on energy performance is also noticeable: Scenario 1 shows the highest cooling demand, while Scenarios 2 and 3 help to reduce consumption, although the impact is less significant compared to heating savings. However, Scenario 3 stands out by achieving annual cooling demand reductions three times greater than those observed in Scenario 2. In Oujda, for example, Scenario 2 achieves a maximum reduction of 4.5% compared to Scenario 1, while Scenario 3 reaches a 15% reduction, confirming the effectiveness of hempcrete in limiting heat gains and improving summer comfort.

A comparison with previous studies highlights that the use of bio-based and ecological insulation materials enables significant energy savings. For example, a study on the integration of 4 cm thick hemp-gypsum composite panels in the roofs of residential buildings in Oujda and Marrakech [5] reported energy demand reductions of 4.7% and 5.4%, respectively. In contrast, our results indicate higher savings, reaching nearly 8% in Oujda and 6.8% in Marrakech for Construction Scenario 2. These findings suggest that our approach is not only comparable but potentially more efficient in terms of energy performance. Moreover, they emphasize the importance of selecting insulating materials not only to reduce heating needs but also to limit cooling energy consumption, while enhancing the building's resilience to extreme climatic conditions.

3.2. Effect of envelope composition on indoor temperature

The results highlight the impact of the different construction scenarios, particularly the use of ecological and bio-based materials. The temperature assessments during both the summer and winter periods are illustrated in Figures 5 and 6.

Figure 5 illustrates the variations in indoor temperature for three different construction scenarios during the two typical days in winter. Analysis of the graphs clearly shows that Scenario 3 has the greatest impact on the building's indoor air temperature, followed by Scenario 2. The temperature difference between Scenario 3 and Scenario 1 reaches approximately 0.77°C in Ouarzazate, 0.63°C in Oujda, 0.60°C in Al-Hoceima, and 0.53°C in Marrakech. These results indicate a slight improvement in thermal comfort inside the buildings, although the temperature remains within a range considered comfortable for the winter season.

For instance, in Marrakech, the indoor air temperature in the building under Scenario 3 ranges between 18.9°C and 19.4°C, while in the reference building (Scenario 1), it fluctuates between 18.5°C and 19.02°C. The temperature variation amplitude in the reference building is approximately 0.48°C, whereas in the building under Scenario 3, it is reduced to 0.39°C. This decrease in amplitude can be attributed to the use of hempcrete, a material that promotes better thermal regulation and consequently helps maintain a more stable indoor temperature.

Regarding summer conditions, the results presented in Figure 6 show that Scenario 3 remains the one that causes the greatest deviation compared to the reference scenario (Scenario 1). The maximum temperature difference reaches 0.62°C in Marrakech, while the minimum deviation occurs in Al-Hoceima, with only 0.27°C. Although all scenarios show thermal improvement compared to the reference scenario during the summer, this improvement is less pronounced than that observed in winter. This suggests that, although Scenarios 2 and 3 provide enhancements, they remain insufficient for optimal thermal management during the summer season.

These observations highlight the crucial importance of selecting an appropriate construction scenario to optimize the indoor temperature of buildings throughout the year. This choice should consider local climatic variations, particularly in regions as diverse as those studied, to ensure optimal thermal comfort in both winter and summer.

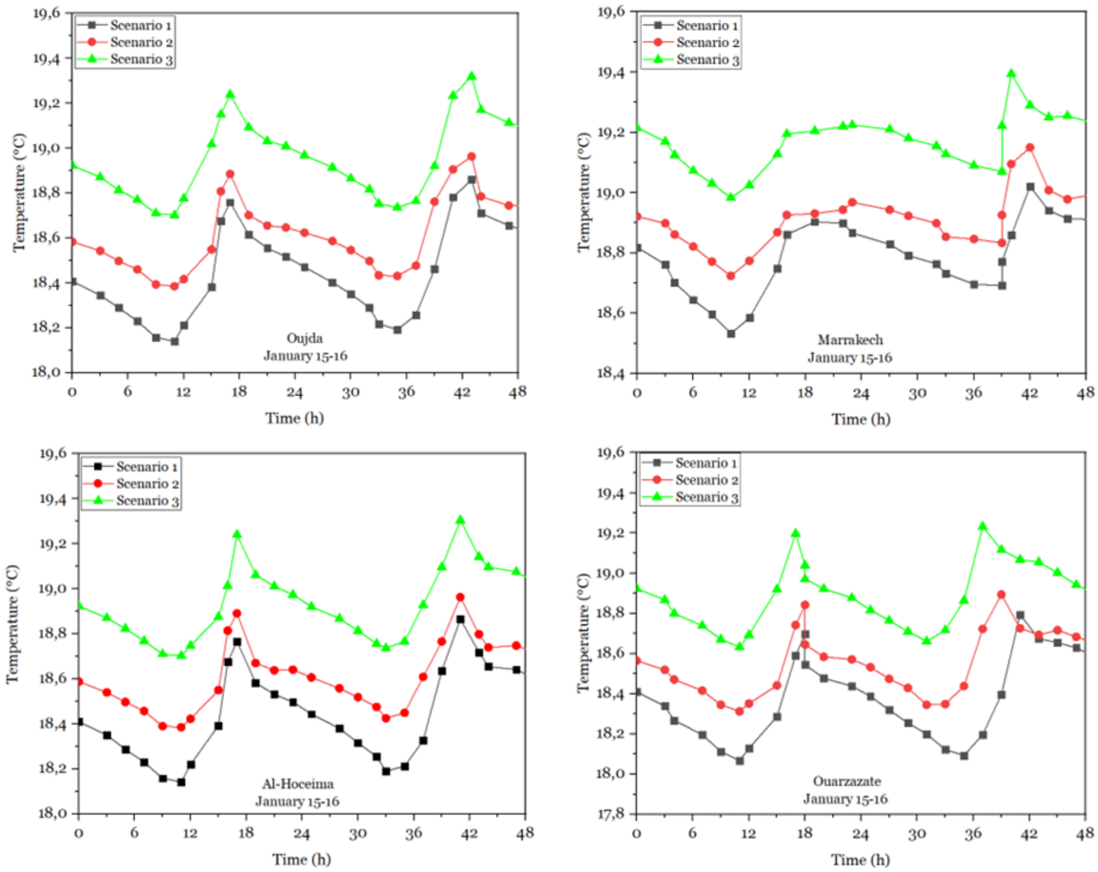

Figure 5: Indoor temperatures for the three construction scenarios during January 15 and 16

By comparing our results with previous studies, it appears that the use of bio-based and eco-friendly materials for thermal insulation not only contributes to energy savings but also significantly improves indoor thermal comfort. Indeed, a study conducted by Eddib and Lamrani [24] on a building located in Marrakech, insulated with 8 cm of wood fiber, revealed an increase in indoor air temperature of 0.26°C in January and a decrease of 0.49°C in July.

In comparison, our results show even more significant improvements, reaching nearly 0.53°C in January and 0.62°C in July for the same Marrakech climate under Construction Scenario 3. These differences suggest that our approach, although potentially based on a different insulation thickness, could offer better thermal regulation. This highlights the importance of choosing eco-friendly materials and their impact not only on the energy performance of buildings but also on occupants' comfort, by reducing thermal fluctuations and promoting a more stable and pleasant indoor environment, particularly in regions subject to extreme climatic conditions.

To further deepen the quantitative analysis of indoor temperature evaluation, it is essential to calculate the annual thermal discomfort percentage. This parameter quantifies the proportion of hours during which occupants perceive thermal discomfort throughout the year. Figure 7 shows the annual percentage of discomfort hours recorded in Room 1 for the four cities studied. This percentage is determined from the simulated indoor air temperature values in Room 1 over the entire year, by comparing these temperatures with the recommended thermal comfort ranges. This analysis makes it possible to assess the thermal performance of the building and identify critical periods of discomfort in both winter and summer.

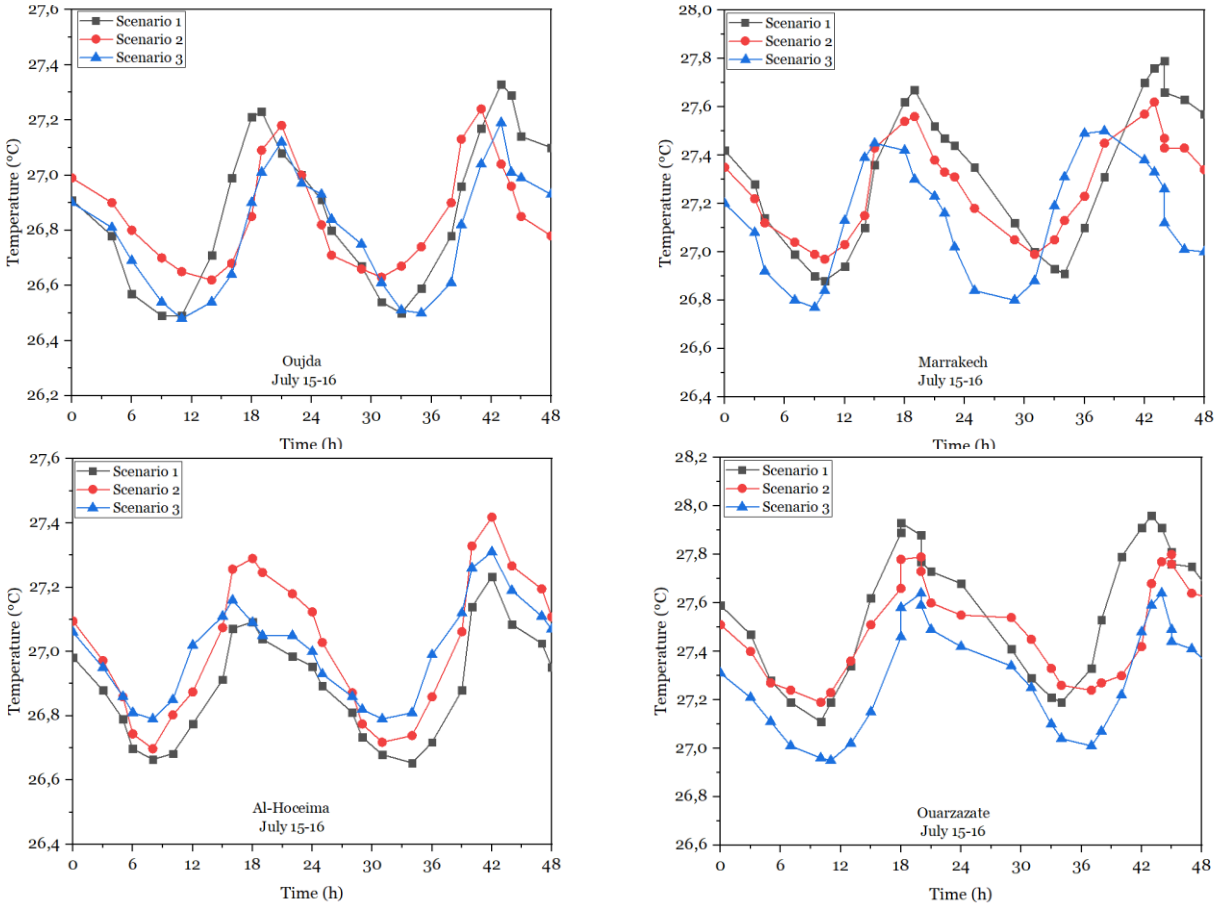

Figure.6 : Indoor temperatures for the three construction scenarios during July 15 and 16

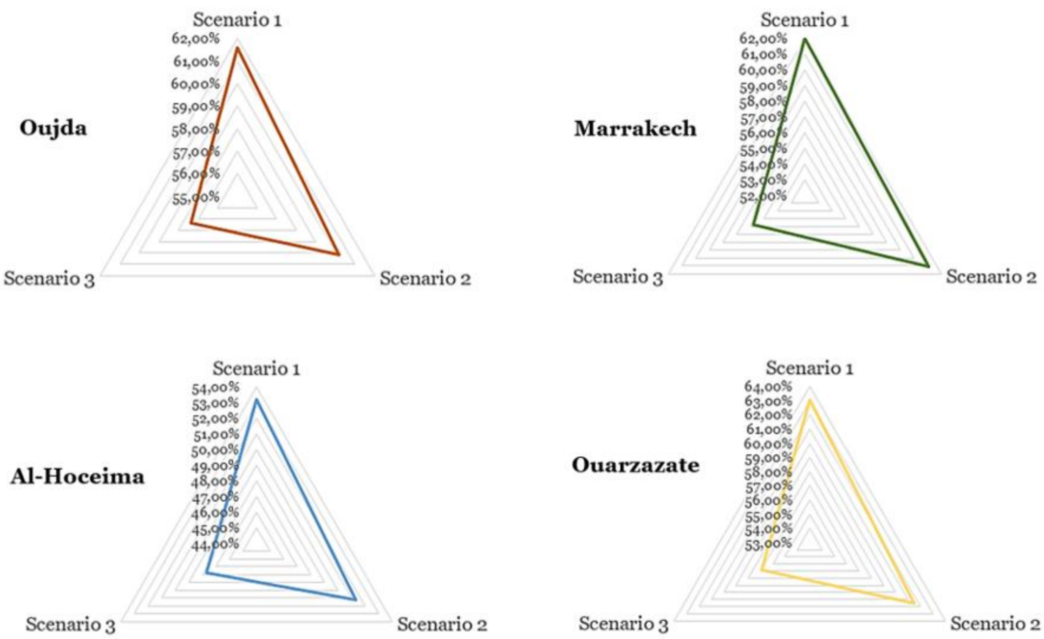

Figure 7 : Annual proportion of thermal discomfort hours in Room 1

The results obtained demonstrate an improvement in indoor thermal comfort across the four studied climates following the application of the three proposed construction scenarios. This improvement is reflected in a reduction in the thermal discomfort hours experienced by the occupants. However, this reduction remains relatively moderate, suggesting that thermal insulation achieved solely with hemp plaster and hempcrete is insufficient to effectively mitigate indoor overheating, particularly during summer periods.

The impact of insulation varies depending on the applied scenario and the climatic characteristics of each region. In Al-Hoceima, the reduction in discomfort hours reaches 1.9% for Scenario 2 and rises to 5.5% for Scenario 3, indicating progressive improvement with the addition of extra insulating materials. In the Oujda region, the results show a decrease of 0.9% for Scenario 2 and 3.7% for Scenario 3, revealing more limited effectiveness due to the harsher climatic conditions. In Marrakech, the recorded reduction is 0.9% for Scenario 2, while it reaches 6.2% for Scenario 3, illustrating the more pronounced effect of insulation strategies in hot climates. Finally, in Ouarzazate, the reductions amount to 1.6% for Scenario 2 and 6.2% for Scenario 3, confirming that bio-based materials can contribute to improving thermal comfort, although their effectiveness remains insufficient to completely eliminate overheating risks.

These findings highlight the need to adopt combined solutions, such as enhancing natural ventilation, using solar protections, or adding complementary insulation, to optimize the building's thermal performance and ensure sustainable indoor comfort in different climatic contexts.

4. CONCLUSION

In this study, transient energy simulations were conducted to evaluate the energy demand and indoor temperature variations of a typical residential building under three construction scenarios utilizing hemp plaster and hempcrete as insulation materials. The study covered four Moroccan climate zones, specifically the cities of Al Hoceima, Oujda, Marrakech, and Ouarzazate. To ensure the simulation closely reflects real conditions, a schedule of internal loads related to occupants, lighting, and electrical equipment was incorporated. The building's energy needs were calculated based on setpoint temperatures of 20°C for heating and 26°C for cooling, using the TRNSYS 18 multizone model (Type 56).

The simulation results demonstrated that the use of these materials significantly reduces energy demand for heating. Scenario 3, involving the use of hempcrete, emerged as the most efficient solution, achieving energy savings of up to 39.4% compared to the reference scenario. Regarding cooling demand, although the insulating materials had a less pronounced effect, hempcrete contributed to reducing energy needs by up to 15.5%.

Furthermore, the analysis of indoor temperatures confirmed the capacity of hempcrete to enhance thermal comfort, particularly during the winter season, with a reduction of approximately 0.77°C in thermal amplitude and improved indoor temperature stability. However, its effect on summer overheating remained moderate, indicating the need to combine hempcrete with complementary passive strategies, such as natural ventilation and solar shading. Finally, a comparison with previous studies revealed that bio-based materials offer superior energy performance while contributing to the reduction of buildings' carbon footprints. These findings highlight the importance of material selection in improving energy efficiency and thermal comfort, while enhancing building resilience to extreme climatic conditions.

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