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Study of the Energy, Economic, Environmental, and Thermal Comfort Impact of the Integration of Hemp Concrete and Hemp Plaster in a Residential Building Envelope in Morocco

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ABSTRACT

In the building sector, the majority of efforts are aimed at achieving greater energy efficiency, a low carbon footprint, and optimum thermal comfort to make buildings more efficient, more sustainable, and more pleasant to live in. In this context, this paper aims to assess the impact of integrating environmentally friendly and green materials (lime-hemp plaster and hemp concrete) into the envelope of an existing residential building. A numerical simulation study was carried out using TRNSYS 18, in four Moroccan climates: Mediterranean, cold semi-arid, hot semi-arid, and hot and dry desert, to study the energy, economic, and environmental impact, as well as that of the thermal comfort. The proposed construction scenarios are compared with the reference scenario in terms of heating and cooling requirements, electricity bills, carbon footprint, and percentage of annual thermal discomfort. The results show that energy savings are highest in the cold semi-arid climate (Oujda) at around 24%. Hemp concrete construction is more effective in reducing heating requirements, with a reduction of up to 39.4%. For cooling, the reduction is only 15.5%. The economic and environmental study shows that using materials such as hemp concrete in an optimal construction and climatic context can reduce electricity bills by 25% and CO_2 emissions by around 23.7%. However, the reduction in terms of hours of discomfort is not yet significant enough. Hence, there is a need to combine this technique with other strategies based on bioclimatic design. The use of hemp plaster and hemp concrete for renovating existing buildings or constructing new ones represents a very promising alternative from several points of view: energy, economic, and environmental.

1. Introduction

Nowadays, the world and the entire scientific community are moving at high speed to find solutions and alternatives to the great challenge concerning energy: either at the level of the scarcity of fossil fuels, such as oil, natural gas, and coal [1], and their massive consumption, which will

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eventually lead to a total depletion of the reserves of these resources [2], or at the level of the environmental impact of the use of these hydrocarbons and their contribution to the emission of the so-called greenhouse gases (GHG) [3]. In this context, all efforts are aimed at producing green energy from natural and renewable resources [4], as well as at applying energy efficiency measures to reduce the current energy bill and rationalize energy use.

In Morocco, several efforts have been made to address the environmental problems related to energy production, especially since Morocco is likely to be one of the countries affected by the effects of climate change due to the increasing consumption of fossil fuels and GHG emissions, according to the estimates of the International Energy Agency (IAE) [5]. Indeed, during the last two decades, Morocco has always been present at various international events that take climate issues as a theme, such as participation in the Earth Summit in Rio de Janeiro, participation in the Conference of the Parties (COP21) in Paris, and the organization of the (COP22) in Marrakech.

From an energy point of view, Morocco is committed to establishing an energy policy translated into a national energy strategy that seeks to diversify energy resources by introducing green energy into the Moroccan energy context through the use of renewable energy [6]. In parallel to the renewable energy sector, energy efficiency is also one of the major concerns in the national energy strategy: the implementation of energy efficiency actions in the most energy-intensive sectors such as transport, building, and industry to save about 15% of energy by 2030 [7].

With an energy consumption of 33% and about 12% of GHG emissions at the national level [8], the building sector in Morocco is one of the most energy-consuming sectors. To address this issue, it is of crucial importance to choose optimal solutions and adequate designs to minimize the energy consumption of buildings. In this respect, the building sector has recently seen a possible transition from conventional building materials that are derived from non-renewable resources and have a high embodied energy [9], to environmentally friendly materials with low grey energy and a low carbon footprint [10-11].

Indeed, hemp represents one of the most promising alternatives in the construction industry, to produce ecological and green materials. Among these are hemp-based biocomposites, such as hemp concrete, hemp-lime concrete, and hemp plaster, which are often composed of a natural or synthetic binder for toughness and mechanical strength, and hemp plant components such as fibers for insulation due to their porous microstructure [12]. Furthermore, construction with hemp can be used for the insulation of various envelope elements, i.e., exterior and interior walls, floors, and roofs. This depends on the nature of the mixture [13], the manufacturing and compacting process [14], and the nature of the binding material [15].

To improve these materials, various researchers have been concerned with the thermal, mechanical, and hygroscopic properties of several hemp-based biocomposites:

i) A body of work (Arnaud in 2000 [16], Bevan and Woolley in 2008 [17], Stevulova *et al.,* in 2013 [18], Arizzi *et al.,* in 2015 [19], and Evrard *et al.,* in 2020 [20]) has shown that hemp concrete has a fairly low thermal conductivity (from 0, 05 W/m.K to 0.13 W/m.K) as well as a relatively low density (from 200 Kg/m^3 to 1000 Kg/m^3), which makes this material an excellent choice for thermal insulation against heat loss in winter and heat gain in summer.

ii) Mechanical properties have been widely discussed in several works (Bledzki in 1999 [21], Elfordy *et al.,* in 2008 [22], de Bruijn *et al.,* in 2009 [12], Arnaud and Gourlay in 2012 [23], Shea *et al.,* in 2012 [24]), which have shown that hemp concrete has low compressive and tensile strengths, respectively, compared to other building materials, which precludes its use as a load-bearing element of the envelope.

iii) The porous nature of hemp increases its permeability to water vapor contained in the air (Cerezo in 2005 [25]), which makes it a good moisture regulator as well as prevents the formation of moulds (Walker and Pavia in 2014 [26])

iv) The demand for ecological hemp-based materials is increasing worldwide, due to their various characteristics: low density, easy to use, quick hardening, adaptation to all kinds of climates, natural thermal and acoustic insulation, and better water vapor permeability. In addition, hemp is a material with very good environmental performance, as it is environmentally friendly. To this end, several research works have been carried out (di Capua *et al.,* in 2021 [27], Pretot *et al.,* in 2014 [28], Arrigoni *et al.,* in 2017 [29], Sinka *et al.,* in 2014 [30]) to evaluate and quantify the environmental impact of several hemp walls according to several parameters (type of wall, wall properties, construction method...).

Even though Morocco is one of the major cannabis-producing countries, from an energy point of view, this substance has not yet received enough attention. A very limited amount of research work has been done on the integration of hemp in typical Moroccan building envelopes and for the most abundant climates in Morocco, such as our studies carried out for the Mediterranean climate of the city of Al-Hoceima [31-32]. Charai *et al.,* (2021) [33] studied the thermal insulation potential of hemp-gypsum biocomposites and their contribution to energy savings in a typical building in cold and hot semi-arid climates represented by the cities of Oujda and Marrakech, while (Dlimi *et al.,* in 2023 [34]) tried to evaluate the thermal performances of a hollow brick wall filled with hemp concrete and their potential (3E: Energetic, Economic and Environmental) at the scale of a typical building located in Meknes. In another work (Essaghouri, and MaoXiaodong in 2023 [35]), a comparative study was carried out using life cycle assessment (LCA) of three models of exterior walls of a residential building located in Marrakech, of which the three constructions are, respectively, a wall with a biocomposite (hemp concrete), a wall with double hollow clay bricks, and another composite wall insulated with extruded polystyrene to highlight the low carbon footprint of the building constructed with hemp concrete.

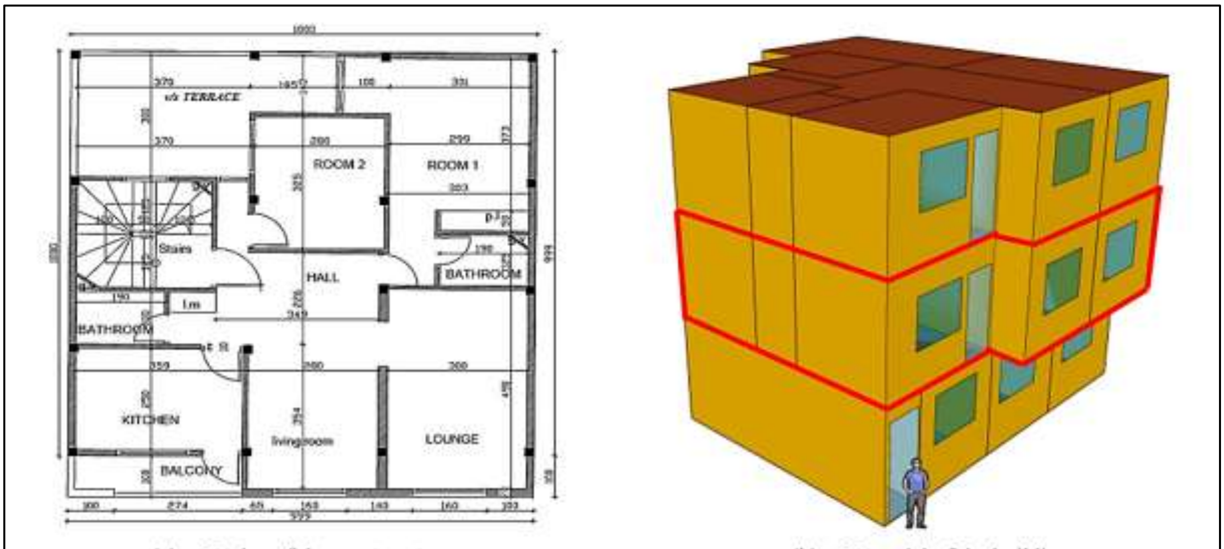
Previous research on the use of hemp-based composite materials in the Moroccan building sector has mainly been limited to studies focusing on a single climatic zone or on specific aspects such as energy performance. In contrast to these approaches, our study offers a comprehensive parametric analysis of bio-sourced materials such as hemp concrete and hemp plaster, covering the energy, thermal, environmental and economic aspects of a Moroccan residential building. In addition, our research includes significant geographical diversity by representing four climatic zones in line with the Moroccan construction standards. This multi-climate approach makes our work particularly relevant to professionals in the construction sector, providing them with usable data for the renovation and design of new projects in these specific zones.

Our study aims to provide a comprehensive framework for assessing the performance of hemp-based composites, in order to effectively guide sustainable construction practices in Morocco. It focuses on the sustainable and environmentally friendly use of hemp concrete and plaster for thermal insulation of residential buildings in Morocco. The main objective is to assess the energy, economic and environmental impacts and thermal comfort of integrating these materials into building envelopes in four different climatic zones: Al-Hoceima, Oujda, Marrakech and Ouarzazate. This assessment is based on a dynamic thermal simulation using TRNSYS software and a model validated with real data from the Moroccan Thermal Building Regulations (RTCM). It explores two scenarios: the renovation of existing buildings and the design of new buildings with low energy consumption and a low carbon footprint, adapted to the Moroccan construction context.

2. Data

2.1 Building Data

Our study building is a single-family Moroccan apartment. The apartment is 3m high and has a surface area of 91.5 m^2. The interior space is divided as follows: two bedrooms, a living room, a sitting room opening onto a hall, a kitchen, and a bathroom. The house is occupied by a family of three members. The 2D and 3D architectural plans are shown in Figure 1.



(a) : 2D plan of the apartment (b) : 3D model of the building

Fig. 1. Architectural plans of the building

2.1.1 Building materials

The elements of the envelope of our building, such as the external walls, the internal walls, the high floor, and the low floor are constructed using the materials mentioned in Table 1. It should be noted that the thermophysical properties of these selected materials were taken from the BINAYATE prescriptive software developed by AMEE (Moroccan Agency for Energy Efficiency) (Table 2) [36].

Table 1
Composition of the reference building envelope

Walls	Layers	Thickness (cm)
Exterior Wall	Cement mortar	1,5
	Brick (12 holes)	20
	Cement mortar	1,5
Interior Wall	Cement mortar	1,5
	Brick (8 holes)	10
	Cement mortar	1,5
Floors	Plaster coating	1
	Hollow slab	16
	Heavy concrete	7
	Floor tiles	2

Table 2
Thermophysical properties of materials [34]

Materials	Thermal conductivity (W/m.K)	Thermal capacity (kJ/kg.K)	Density (kg/m^3)
Cement mortar	1,30	1,00	1900
Brick (12 holes)	0,22	0,74	664
Brick (8 holes)	0,19	0,74	918
Floor tiles	1,30	0,84	2300
Mortar	1,00	1,00	1700
Heavy concrete	2,00	1,00	2450
Plaster coating	0,56	1,00	1350
Hollow slab	1,04	1,00	1513

The Window/Wall Ratio (WWR) is 10%. The windows are single-glazed with a factor U = 5.69 W/m^2.K and a solar heat gain coefficient g = 0.82.

2.1.2 Thermal zoning of the building

Our study apartment is subdivided into seven thermal zones as shown in Figure 2. It should be noted that several other thermal zoning assumptions would have been possible.

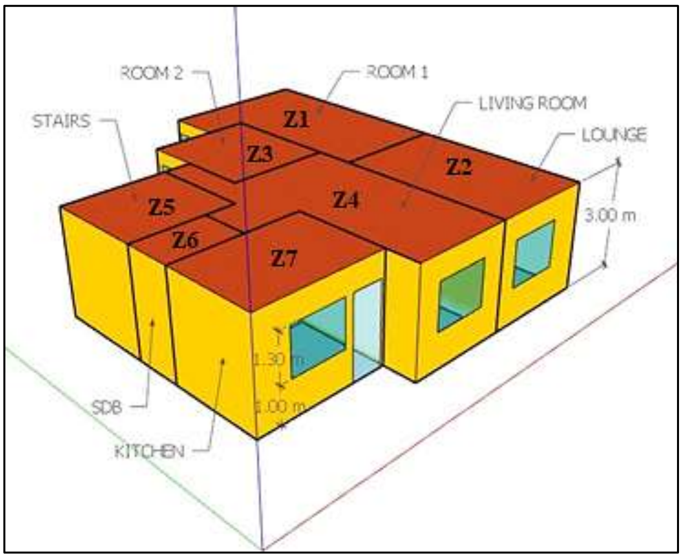


Fig. 2. Thermal zoning of the apartment

2.1.3 Internal energy loads

To take into account the activities of the occupants of our study building, and to make our simulation closer to reality, it is necessary to take into account the internal thermal gains in the energy balance of the building. To do this, the gains taken into consideration are:

i) Thermal gains due to people
ii) Thermal gains due to lighting
iii) Thermal gains due to electrical equipment

The calculation of these gains must be done according to schedules: occupancy - lighting - use of electrical equipment, as well as being standardized. Our simulation software TRNSYS allows the determination of the thermal load internal heat gains due to the occupants according to the NM ISO 7730 standard [37]. Table 3 shows the various schedules for each room in the building.

Table 3
Planning: Occupancy - Lighting - Equipment

Element	Type of gain	Daily Schedule of use	Internal gains (W)
Lounge	Lighting	7h00 – 8h00 / 19h00 – 21h00 (5 days a week)	36W
	TV	12h00 – 13h00 / 18h00 – 21h00 (5 days a week)	100W
	2 persons	7h00 – 8h00 / 12h00 – 13h00 / 18h00 – 21h00 (5 days a week)	166W
Living room	Lighting	7h00 – 8h00 / 19h00 – 21h00 (2 days a week)	36W
	TV	12h00 – 13h00 / 18h00 – 21h00 (2 days a week)	100W
	2 persons	7h00 – 8h00 / 12h00 – 13h00 / 18h00 – 21h00 (2 days a week)	166W
Kitchen	Lighting	7h00 – 8h00 / 19h00 – 21h00 (all week)	12W
	Refrigerator	24h (all week)	300W
	Washing M	19h00 – 21h00 (1 time per week)	2200W
	1 person	7h00 – 8h00 / 12h00 – 13h00 / 19h00 – 21h00 (all week)	126W
Room 1	Lighting	21h00 – 23h00 (all week)	12W
	Laptop	21h00 – 23h00 (all week)	40W
	2 persons	in activity : 21h00 – 23h00 (all week)	166W
		Sleeping : 23h00 – 7h00 (all week)	144W
Room 2	Lighting	21h00 – 23h00 (all week)	12W
	Laptop	21h00 – 23h00 (all week)	40W
	1 person	in activity: 21h00 – 23h00 (all week)	83W
		Sleeping: 23h00 – 7h00 (all week)	72W

2.2 Meteorological Data

For the realization of a thermal simulation covering the majority of the Moroccan territory, four study cities were selected to represent four climates in Morocco (Climates: Mediterranean, cold semi-arid, hot semi-arid, and hot desert). Meteorological data for these four locations were obtained using Meteonorm software [38] for a typical meteorological year (TMY). They are then exported to our dynamic thermal simulation software TRNSYS. Table 4 shows the main geographical and meteorological data of the selected locations.

Table 4
Locations and climates of the study sites [38,39]

Location	Al-Hoceima	Oujda	Marrakech	Ouarzazate
Latitude	35,18°N	34,8°N	31,7°N	30,9°N
Longitude	− 3,85°E	− 1,9°E	− 8,1°E	− 6,9°E
Altitude (m)	14	470	403	1140
Köppen climate classification	(Csa) Mediterranean	(BSk) semi-arid cold	(BSh) semi-arid hot	(BWh) hot desert

Figure 3 shows the hourly distribution of ambient temperature for a typical meteorological year in the four study areas: Al-Hoceima, Oujda, Marrakech, and Ouarzazate. It can be seen that these data show remarkable differences, making it necessary to study each zone separately.

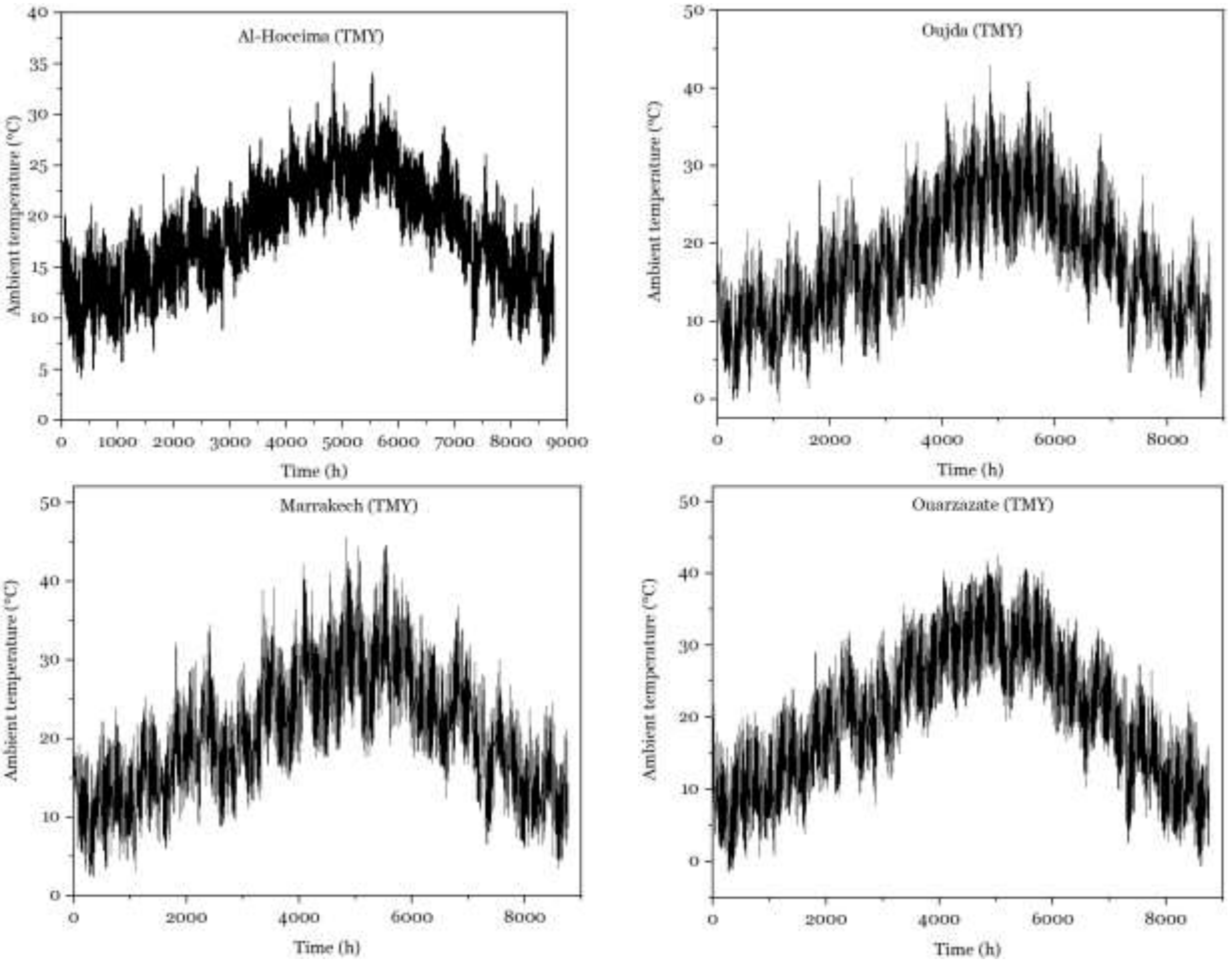


Fig. 3. Hourly distribution of ambient temperature in the four locations studied for a typical weather year

3. Methodology

In this paper, the working methodology is well detailed in Figure 4, starting from the design phase of the study building, followed by the details and assumptions of the simulation, to the results and their discussion. Finally, a summary of the work is presented in the form of a conclusion.

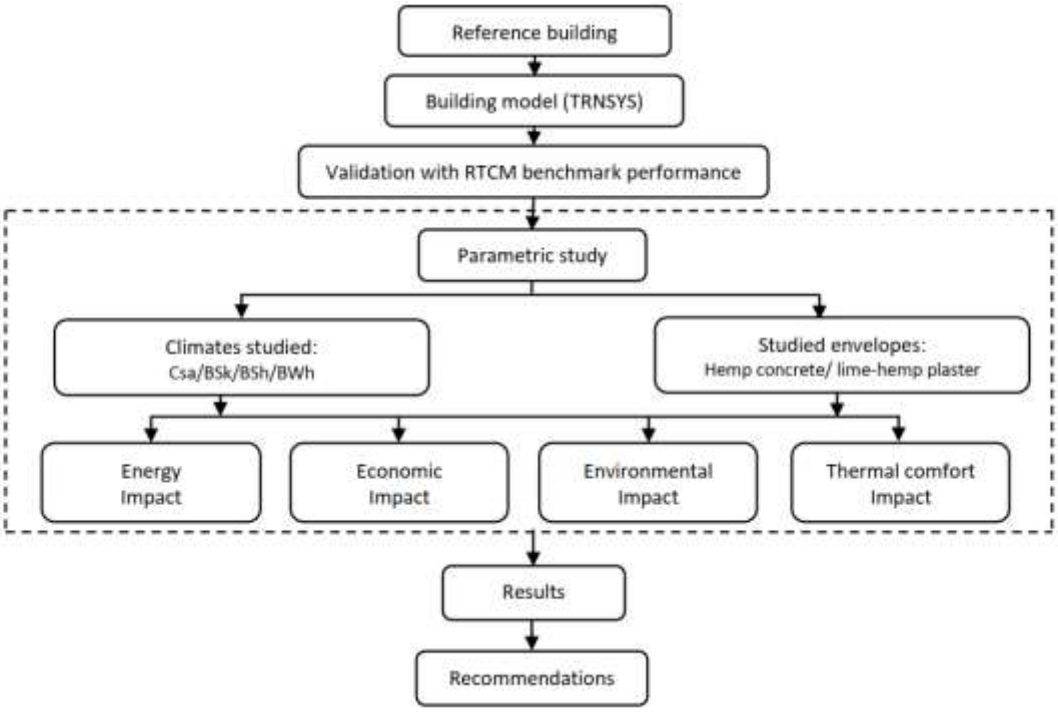


Fig. 4. Work organization chart

3.1 Building Energy Simulation: Physical and Mathematical Models

Our simulation study using TRNSYS software aims to achieve energy efficiency measures within a building. The simulation model includes the design of the building structure in the SketchUp environment as well as the use of TRNSYS type 56 (TRNBUILD) to properly describe the building structure in terms of building materials (thicknesses, thermophysical parameters), air infiltration, occupancy planning, lighting, etc.

The three modes of heat transfer within our building are:

i) Heat transfer by conduction

The various walls of the building are modeled using the Conduction Transfer Function method (Stephenson and Mitalas), from which the phenomenon of heat conduction through the walls of the building is expressed:

$$\dot{q}_{so} = \sum_{k=0}^{n_a} a^k T_{s,o}^k - \sum_{k=0}^{n_b} b^k T_{s,i}^k - \sum_{k=1}^{n_d} d^k \dot{q}_{s,o}^k \tag{1}$$

$$\dot{q}_{si} = \sum_{k=0}^{n_b} b^k T_{s,o}^k - \sum_{k=0}^{n_c} c^k T_{s,i}^k - \sum_{k=1}^{n_d} d^k \dot{q}_{s,i}^k \tag{2}$$

$\dot{q}_{so}$ and $\dot{q}_{si}$ respectively represent the outlet and inlet heat flows in the wall. While $T_{s,o}$ and $T_{s,i}$ represent the temperatures of the internal and external surfaces of the wall (Figure 5).

Expressions (1) and (2) are time series based on heat fluxes and surface temperatures where the exponent k refers to the term of these two series ($k = 0$ represents the current hour and $k = 1$ represents the previous hour). While a, b, c and d are the coefficients of the equations of these time series.

From a thermal point of view, a window is considered to be an external wall with a low thermal mass. However, when calculating the energy balance for each thermal zone using TRNSYS type 56, the window is modeled with a 2-node model.

ii) Heat transfer by convection

The expressions for the heat flows exchanged by convection near the inner and outer sides of the wall:

$$\dot{q}_{c,s,o} = h_{outside}(T_{a,s} - T_{s,o}) \tag{3}$$

$$\dot{q}_{c,s,i} = h_{inside}(T_i - T_{s,i}) \tag{4}$$

h_{inside} and $h_{outside}$ represent the convective heat transfer coefficients for the inside and outside surfaces respectively. While $T_{a,s}$ and T_i represent the ambient air temperatures outside and inside the thermal zone respectively (Figure 6).

iii) Heat transfer by radiation

The expression for the heat flux exchanged by radiation is:

$$\dot{q}_{r,s,o} = \sigma \varepsilon_{s,o}(T_{s,o}^4 - T_{fsky}^4) \tag{5}$$

σ and $\varepsilon_{s,o}$ are the Stephan-Boltzmann constant and the long-wave emissivity of the outer surface of the wall, respectively. While T_{fsky} represents the fictive sky temperature concerning the exchange of long-wave radiation.

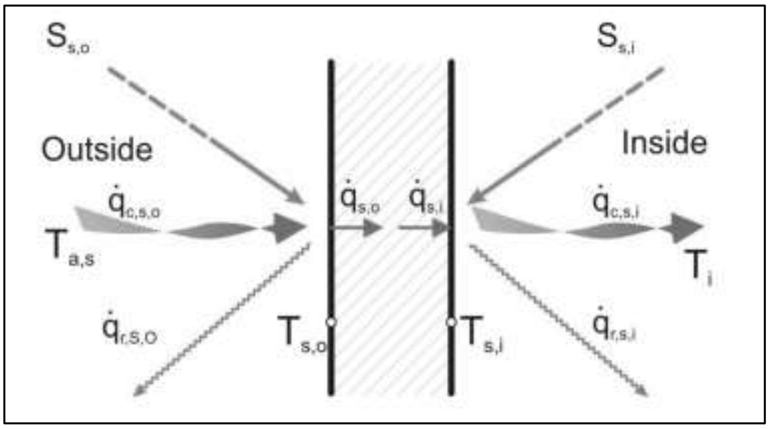


Fig. 5. Heat fluxes and temperatures near a wall

3.2 Calculation of Heating and Cooling Energy

The simulation process in TRNSYS is based on whether the thermal study of the building is mono-zone or multi-zone, while each thermal zone is described by an air node i as having a network of nodes covering the whole conditioned space of the building.

The overall energy balance of the building (of the network of nodes) is expressed as follows:

$$\dot{Q}_{Global} = \sum_{i=1}^{n} \dot{Q}_i \tag{6}$$

where:

n: Number of nodes or thermal zones in the building (if each air node represents a single thermal zone).

$\dot{Q}_i$: Energy flow corresponds to the thermal zone i. The energy balance in this thermal zone is expressed as follows [40]:

$$\dot{Q}_i = \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{cplg,i} + \dot{Q}_{Surf,i} + \dot{Q}_{g,c,i} + \dot{Q}_{solair,i} + \dot{Q}_{ishcci,i} \tag{7}$$

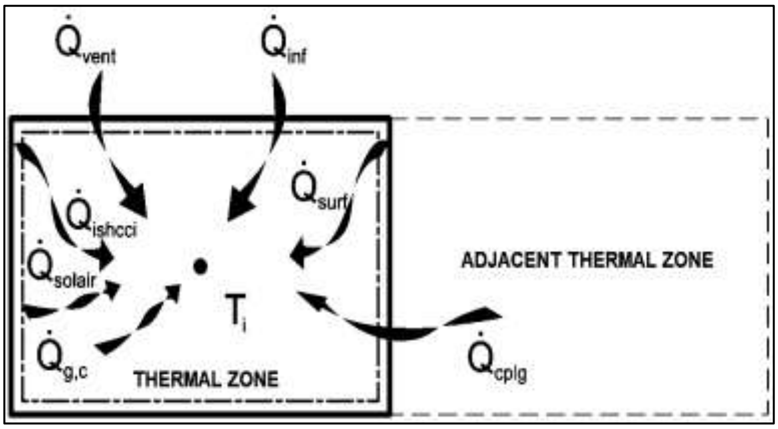


Fig. 6. Heat balance for a thermal zone

where:

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

$$\dot{Q}_{inf,i} = \dot{V}_{inf}\, \rho\, C_p (T_{outside,i} - T_i) \tag{8}$$

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

$$\dot{Q}_{vent,i} = \dot{V}_{vent}\, \rho\, C_p (T_{vent,i} - T_i) \tag{9}$$

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

$$\dot{Q}_{cplg,i} = \dot{V} \rho\, C_p (T_{zone,adjacente} - T_i) \tag{10}$$

iv) $\dot{Q}_{surf,i}$: The energy flow due to convection caused by the opaque surfaces of the thermal zone i is expressed as:

$$\dot{Q}_{surf,i} = UA(T_w - T_i) \tag{11}$$

v) $\dot{Q}_{g,c,i}$: The energy flow is due to internal gains (including occupants, lighting, equipment...) in the thermal zone i.

vi) $\dot{Q}_{solair,i}$: The energy flow is due to the amount of solar radiation entering the thermal zone i through the glass panes.

vii) $\dot{Q}_{ishcci,i}$: The energy flux is due to the amount of solar radiation absorbed by the internal shading devices of the thermal zone i.

where:

$\dot{V}$, ρ , C_p : Are respectively the air flow rate in (m^3/s), the air density in (Kg/m^3) and the specific heat capacity of air at constant pressure in (J/Kg.K).

U : Are respectively the thermal transmittance in (W/m^2.K) and the area in (m^2).

The thermal load of each zone (air node) is deduced from the heat balance of this thermal zone:

$$\frac{dE_i}{dt} = C_i \frac{dT_i}{dt} = \dot{Q}_i \tag{12}$$

where:

$\frac{dE_{int}}{dt}$ and $\frac{dT_i}{dt}$ are respectively the time variations of the internal energy and the internal temperature of the thermal zone i and $C_i = v_i \rho C_p$ is the heat capacity of the interior space of volume v_i in (kJ/K).

3.2 Calculation of Temperature

According to equation (12), the temperature of a zone is calculated from the time variation of the internal energy of a floating thermal zone. Furthermore, the energy flux $\dot{Q}_i$ corresponding to the thermal zone i is a function of its temperature T_i and the temperatures of the other adjacent thermal zones. Due to simplification, we consider that the energy flux $\dot{Q}_i$ remains constant during a simulation time step Δt as well as the temperature is linear, hence the solution of the differential equation (7) is written as:

$$T_{i,t} = T_{i,t-\Delta t} + \frac{\overline{\dot{Q}_{i,\Delta t}}}{C_i} \tag{13}$$

During the time step Δt the average temperature is expressed as:

$$\bar{T}_i = \frac{T_{i,t} + T_{i,t-\Delta t}}{2} \tag{14}$$

If we determine the expression for $T_{i,t}$ from expression (14) and substitute it into Eq. (13) and Eq. (7), we obtain:

$$\frac{2\, C_i(\bar{T}_i - T_{i,t-\Delta t})}{\Delta t} = \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{cplg,i} + \dot{Q}_{Surf,i} + \dot{Q}_{g,c,i} + \dot{Q}_{solair,i} + \dot{Q}_{ishcci,i} \tag{15}$$

After solving equation (15) using the method for determining the temperature of the floating air node for a naturally ventilated building, the final temperature of zone i is equal to:

$$T_{i,t} = 2\overline{T}_i - T_{i,t-\Delta t} \tag{16}$$

3.3 Simulation Assumptions

During the simulation period, several assumptions were taken into consideration, namely:

i) During the simulation, we neglect any kind of natural ventilation or air coupling within our study building.
ii) Doors and windows are considered closed.
iii) The infiltration rate is estimated at 0.6 vol/h.
iv) The solar absorption percentage of the building walls is estimated at 0,5.
v) The thermal simulation was carried out with a step of 1 hour.
vi) Each air node describes a thermal zone in the building.
vii) The simulation does not take into account thermal bridges.
viii) The set temperatures are: heating is 20°C and cooling is 26°C according to the Moroccan standard NM ISO 7730 [37].
ix) The initial air temperature and humidity in each thermal zone were set at 20°C and 50% respectively.
x) To predict the ground temperature of our building we resort to the use of TRNSYS type 77 based on the Kusuda correlation:

$$T = T_{mean} - T_{amp} \times exp\left[-depth \times (\frac{\pi \alpha_{Soil}}{365})^{0,5}\right] \times \cos\left[\frac{2\pi}{365} \times \left(t_{now} - t_{shift} - \frac{depth}{2} \times (\frac{365\alpha}{\pi})^{0,5}\right)\right] \qquad (17)$$

xi) The convective exchange coefficient inside the building is obtained using an internal calculation model in the form of a correlation taking into account the surface and air temperatures [40]:

$$h_{inside} = C(T_{s,i} - T_i)^n \qquad (18)$$

where:
C , n : Are parameters depending on the type of surface, their values are grouped in Table 5.

Table 5
The values of n and C according to the type of surface

Type of surface	Condition	$\boldsymbol{C}$ (W.m^{-2}.K^{-n-1})	$\boldsymbol{n}$
Vertical: wall	---	1,60	0,30
Horizontal: Ground	$T_{s,i} - T_i > 0$	2	0,31
	$T_{s,i} - T_i < 0$	1,07	
Horizontal: Roof	$T_{s,i} - T_i > 0$	1,07	0,31
	$T_{s,i} - T_i < 0$	2	

xii) The convective exchange coefficient outside the building is obtained using an internal calculation model in the form of a correlation taking into account the surface and air temperatures [40]:

$$h_{outside} = C(T_{s,o} - T_{a,s})^n \qquad (19)$$

where:
C, n: Are parameters depending on the type of surface, their values are grouped in Table 6.

Table 6
The values of n and C according to the type of surface

Type of surface	Condition	C (W.m^{-2}.K^{-n-1})	n
Vertical: wall	---	2,11	0,31
Horizontal: Ground	$T_{s,o} - T_{a,s} > 0$	2,11	0,31
	$T_{s,o} - T_{a,s} < 0$	1,87	0,25
Horizontal: Roof	$T_{s,o} - T_{a,s} > 0$	2,11	0,31
	$T_{s,o} - T_{a,s} < 0$	1,87	0,25

4. Results

4.1 Heating and Cooling Demands of the Reference Building

In this section, we present the energy needs or demands of our reference building, so that the calculations of these needs have been made based on the set points or comfort of 20°C and 26°C heating and cooling, respectively. Table 7 presents the building's total energy demand, including heating and cooling requirements. It also specifies the energy performance values required by the RTCM for buildings constructed before 2014. This data allows for a comparison between the building's actual consumption and the standards in effect at that time, providing an assessment of its energy efficiency.

Table 7
Annual energy requirements of the reference building

Location	Al-Hoceima	Oujda	Marrakech	Ouarzazate
Heating (kWh)	2498,8	4564	2317,7	4217,2
Cooling (kWh)	5604,3	6167,1	9000,8	8331,1
Total energy demand (kWh)	8103,1	10731,1	11318,5	12544,3
Total area of the building (m^2)	91,5	91,5	91,5	91,5
Energy performance of the building (kWh/m^2. years)	88,5	117,2	123,7	137,1
Reference energy performance according to RTCM (kWh/m^2.years)	82	130	125	125

The building under study is an apartment built before the application of the Moroccan Thermal Building Regulations (RTCM) in 2015, which means that our building does not have any energy efficiency measures, in other words, it is non-regulated. Unfortunately, there is no monitoring data for this building to calibrate or validate our simulation model. In this respect, the RTCM's performance-based approach requires baseline values for the energy performance of non-regulatory buildings. To verify the similarity of the energy performance of our apartment with the RTCM reference performance. In addition, to test the reliability of our numerical calculation code, a comparison of the results was carried out as shown in Figure 7. It should be noted that a validation of the TNSYS software numerical code was carried out in the same way on an old building [41].

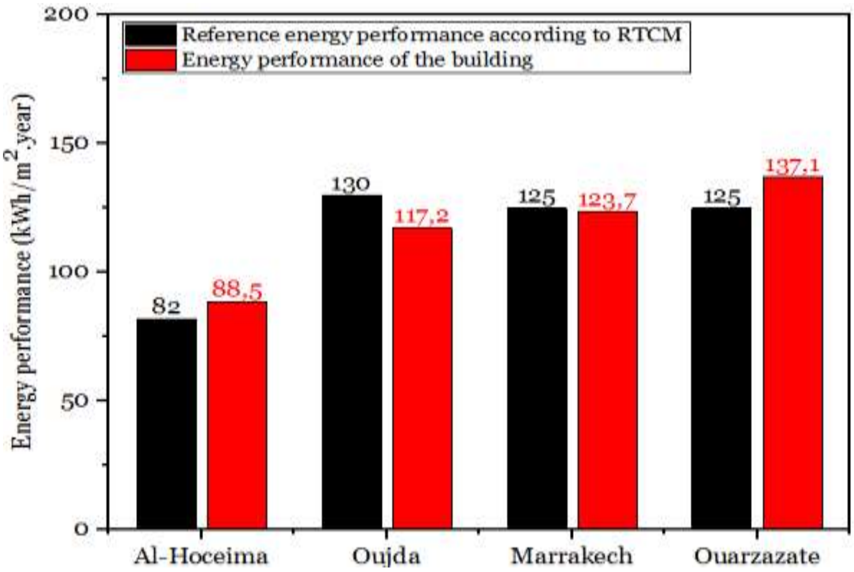


Fig. 7. Comparison of simulation results with reference performance according to RTCM

4.2 Scenarios Studied

Moroccan buildings are generally constructed using a combination of materials based on hollow bricks, heavy or light concrete, cement mortars, and plaster. These constructions are often under the effect of the external environment, which can influence their energy performance as well as their interior comfort state. The present study aims to propose the use of new materials to enrich the Moroccan construction library and to measure their impact on the energy loads, the carbon footprint, and the interior comfort of the building. For this purpose, two scenarios were simulated, one of renovation with lime-hemp plaster and one of construction with hemp concrete.

The construction scenario of the reference building is illustrated in Table 8 and 9. While the two proposed, scenarios are:

i) **Scenario 1:** In this scenario, the building is renovated by applying a lime-hemp plaster to the external walls and the high floor.

Table 8
Composition of the external wall and high floor (Scenario 1)

Walls	Layers	Thickness (cm)
Exterior Wall	Lime-hemp plaster	2
	Cement mortar	1,5
	Brick (12 holes)	20
	Cement mortar	1,5
	Lime-hemp plaster	2
High Floor	Lime-hemp plaster	2
	Plaster coating	1
	Hollow slab	16
	Heavy concrete	7
	Floor Tiles	2

ii) **Scenario 2:** In this scenario, the building is constructed using hemp concrete for the external walls and the high floor.

Table 9
Composition of the external wall and high floor (Scenario 2)

Walls	Layers	Thickness (cm)
Exterior Wall	Cement mortar	1,5
	Brick (8 holes)	7
	Hemp concrete	5
	Brick (8 holes)	7
	Cement mortar	1,5
High Floor	Plaster coating	1
	Hollow slab	16
	Hemp concrete	5
	Heavy concrete	6
	Floor tiles	2

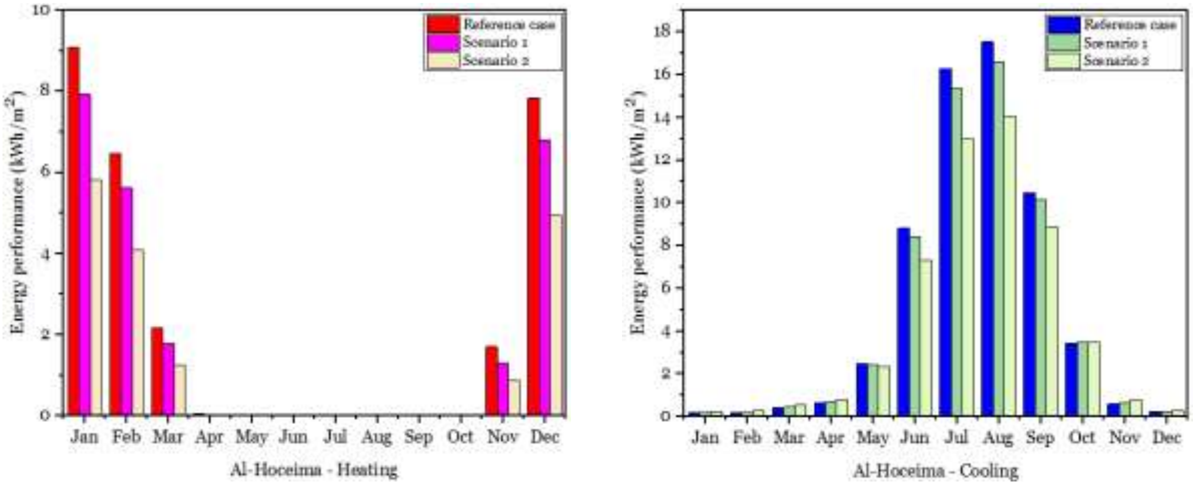
The thermophysical properties of the bio-sourced materials used in the building construction scenarios are shown in Table 10.

Table 10
Thermophysical properties of bio-sourced materials

Materials	Thermal conductivity (W/m.K)	Heat Capacity (J/kg. K)	Density (kg/m^3)
Hemp concrete [42]	0,082	1000	317
Lime-hemp plaster [43]	0,21	1090	761

4.2.1 Impact on the energy demand of the building

In this section, we will examine the effect of integrating lime-hemp plaster and hemp concrete into the building envelope on the building's energy requirements. Figure 8 shows the monthly heating and cooling requirements for the three scenarios (reference case, scenarios: 1, and 2).



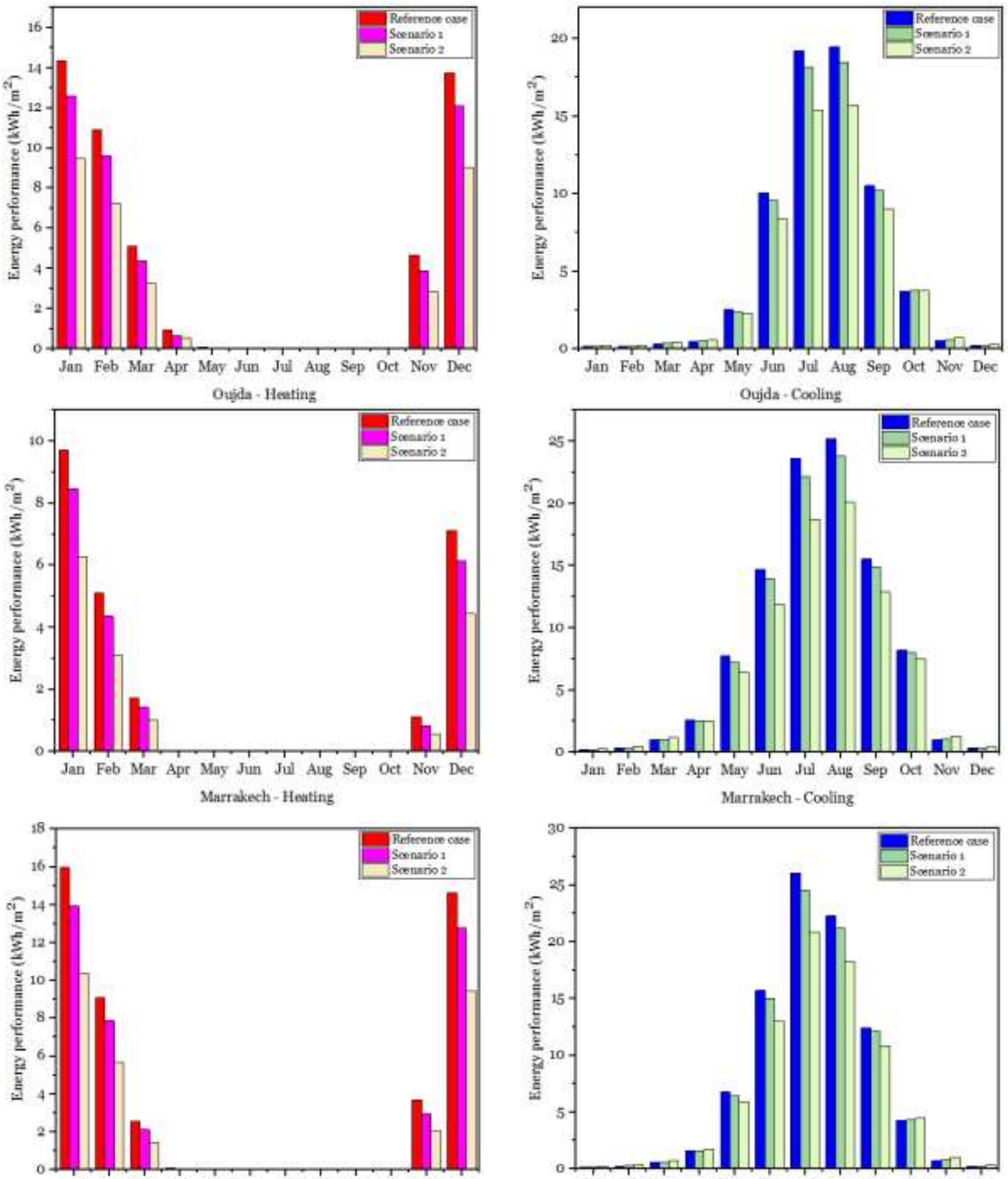


Fig. 8. Monthly evolution of the building heating and cooling needs for the three scenarios

For the reference case, the following results were obtained:

i) For the Al-Hoceima region (Mediterranean climate, hot summer), the results show a predominance of cooling needs with a peak demand of about 17.5 kWh/m^2 for the month of August.
ii) For the Oujda region (semi-arid climate), the results show a predominance of cooling needs with a peak demand of about 19.5 kWh/m^2 for the month of August.

iii) For the region of Marrakech (semi-arid climate), the results show a predominance of cooling needs with a peak demand of about 25.2 kWh/m^2 for the month of August.
iv) For the Ouarzazate region (hot and dry desert climate), the results show a predominance of cooling needs with a peak demand of about 26 kWh/m^2 for the month of July.

Indeed, the estimated annual energy demands of the reference building are 27.3 kWh/m^2.year, 49.8 kWh/m^2.year, 25.3 kWh/m^2.year and 46 kWh/m^2.year for heating, 61.2 kWh/m^2.year, 67.4 kWh/m^2.year, 98.3 kWh/m^2.year and 91 kWh/m^2.year for cooling in Al-Hoceima, Oujda, Marrakesh, and Ouarzazate respectively.

Table 11 summarizes the energy savings achieved in the building for two different scenarios. Scenario 1, involving a lime-hemp plaster renovation, reduced heating demands by 14.2% in Al-Hoceima, 13.1% in Oujda, 16.3% in Marrakech, and 14% in Ouarzazate. Additionally, cooling demands decreased by 4.1%, 4.3%, 3%, and 4.2% respectively in these cities. In comparison, Scenario 2, based on construction using hemp concrete, showed greater energy efficiency, with heating reductions of 37.9% in Al-Hoceima, 35% in Oujda, 39.4% in Marrakech, and 37% in Ouarzazate. Cooling demands were also reduced by 15.2% in Al-Hoceima, 15.5% in Oujda, 15% in Marrakech, and 14.6% in Ouarzazate. These results highlight the significant impact of these construction solutions on the building's energy efficiency across various climate zones.

Table 11
Heating and cooling energy savings compared with the reference scenario

Location	Scenarios	Heating	Cooling
Al-Hoceima	Scenario 1	14,2%	4,1%
	Scenario 2	37,9%	15,2%
Oujda	Scenario 1	13,1%	4,3%
	Scenario 2	35%	15,5%
Marrakech	Scenario 1	16,3%	3%
	Scenario 2	39,4%	15%
Ouarzazate	Scenario 1	14%	4,2%
	Scenario 2	37%	14,6%

Regarding total needs (heating and cooling), Figure 9 shows that renovation with hemp plaster reduced total heating and cooling demand by 7.1%, 8%, 5.7%, and 7.6% respectively in Al-Hoceima, Oujda, Marrakech, and Ouarzazate. Integrating hemp concrete into the building envelope reduced the building's energy demand by 22.1%, 23.8%, 20%, and 22.3% respectively.

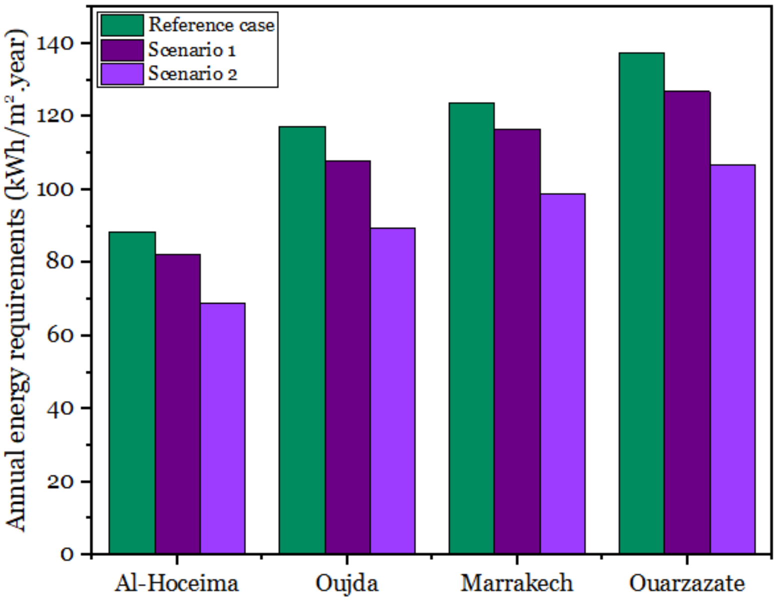


Fig. 9. Total requirements for the three construction scenarios

Consequently, in winter, renovation with hemp plaster or the use of hemp concrete for the construction of external walls and floors leads to a reduction in the building's heating requirements due to the improvement in both the thermal inertia and thermal resistance of the envelope, which respectively leads to the storage of external (solar) and internal (equipment, people) heat gains, as well as minimizing heat loss through the walls by the phenomenon of conduction.

In summer, there is a slight reduction in cooling requirements, which is explained by the effect of hemp in reducing the temperature difference between the outside and inside of the building. On the other hand, the increase in the thermal resistance of the walls has a negative impact on the interior comfort of unconditioned rooms such as the kitchen, because of the barrier effect caused by the thermal insulation, which makes this room overheated due to the heat trapped by the internal gains from the equipment and occupants and the external gains from solar radiation.

4.2.2 Impact on the building's energy bill

After carrying out numerical simulations for the three scenarios mentioned above to minimize the energy demand of our reference building, an economic study can be carried out, as the energy savings have a direct impact on the energy bill.

The savings in heating and cooling requirements within a building affect the electricity bill of the building. To determine the price of the monthly electricity consumption of the building for the three scenarios and for the different climates studied, Table 12 gives the unit price rates of a kilowatt-hour in Morocco.

Table 12
Unit price of a kWh under the band system [44]

Brackets	0 à 100 kWh	101 à 150 kWh	151 à 200 kWh	201 à 300 kWh	301 à 500 kWh	> 500 kWh
Price per kWh in MAD	0.9010	1.0732	1.0732	1.1676	1.3817	1.5958

where : 1MAD = 0,1 USD

The graphs in Figure 10 summarize the building electricity bills for the three construction scenarios (reference scenario, scenario 1, and scenario 2) for the four study regions. The electricity bill for the reference construction is 12532 MAD/year, 16675 MAD/year, 17878 MAD/year, and 19650 MAD/year, respectively for Al-Hoceima, Oujda, Marrakech, and Ouarzazate. On the one hand, scenario 1 allowed for reductions in the electricity bill by 7.3%, 7.9%, 6.6%, and 7.4% respectively. On the other hand, scenario 2 allowed reductions in the electricity bill by 25%, 24%, 21.6% and 24.7% respectively.

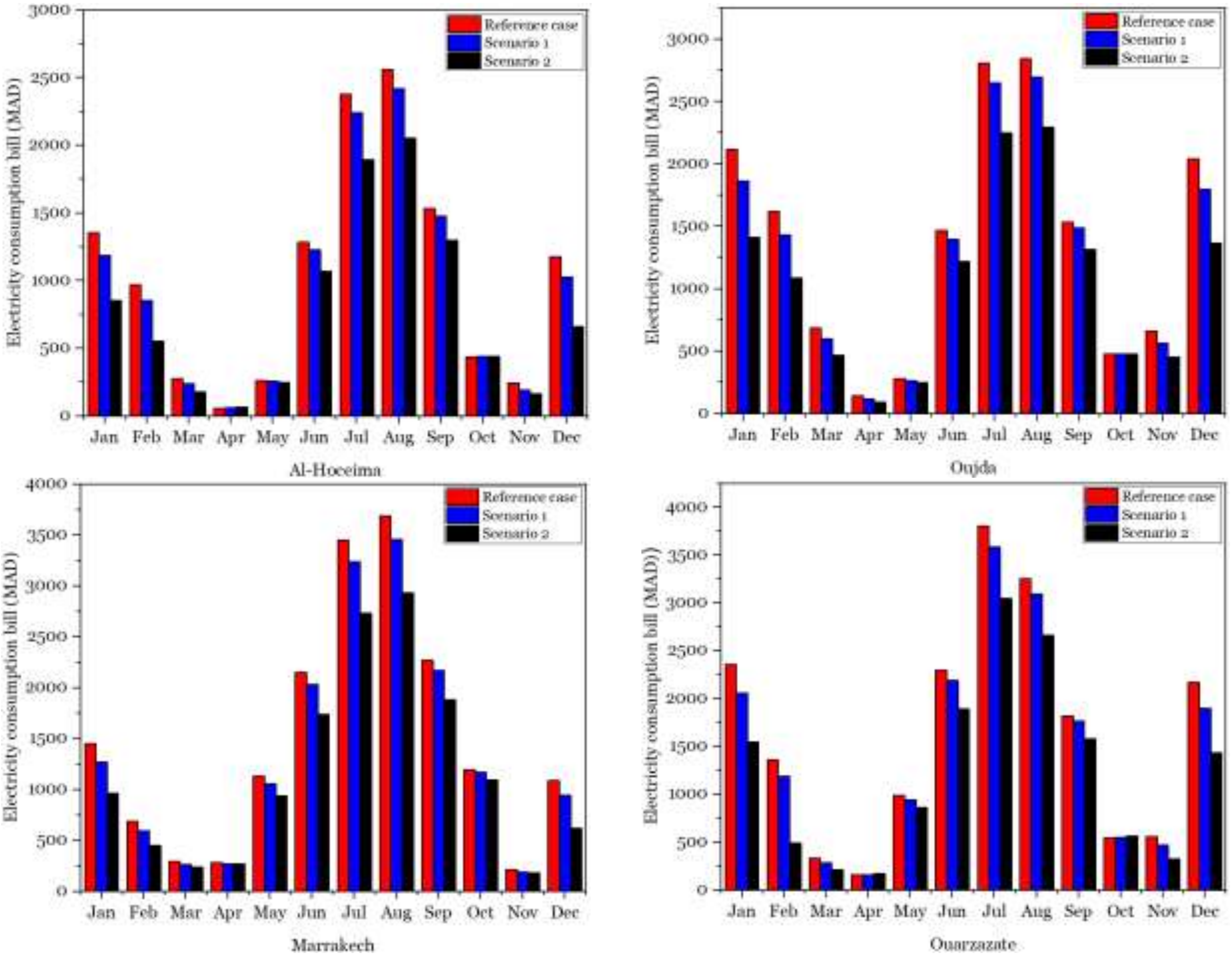


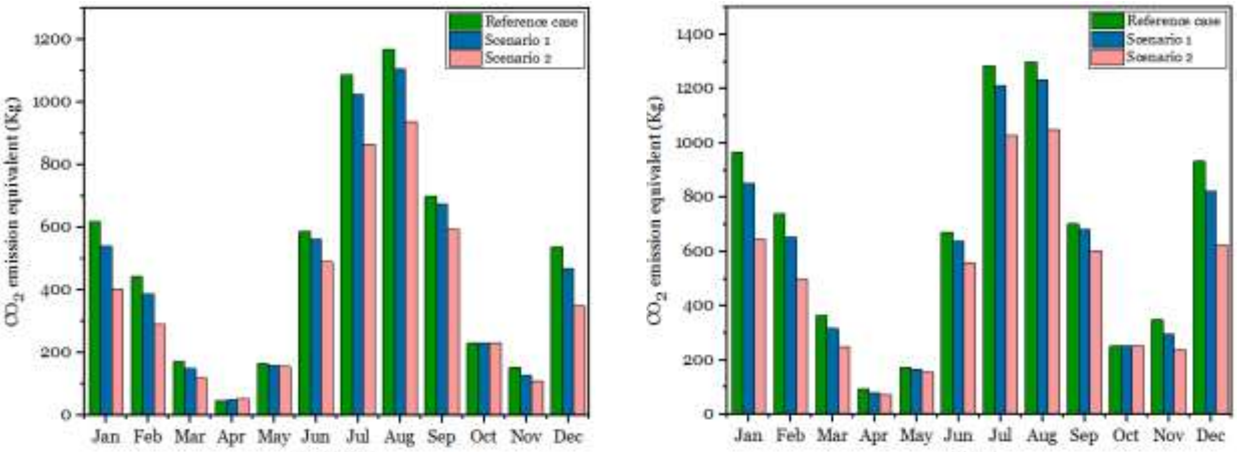
Fig. 10. Monthly evolution of the building electricity bill for the three scenarios

4.2.3 Impact on the carbon footprint of the building (GHG emissions)

For the study to be complete, it is necessary to consider the environmental impact of the building and not only the energy performance, which is quantified by an equivalent amount of GHG emissions.

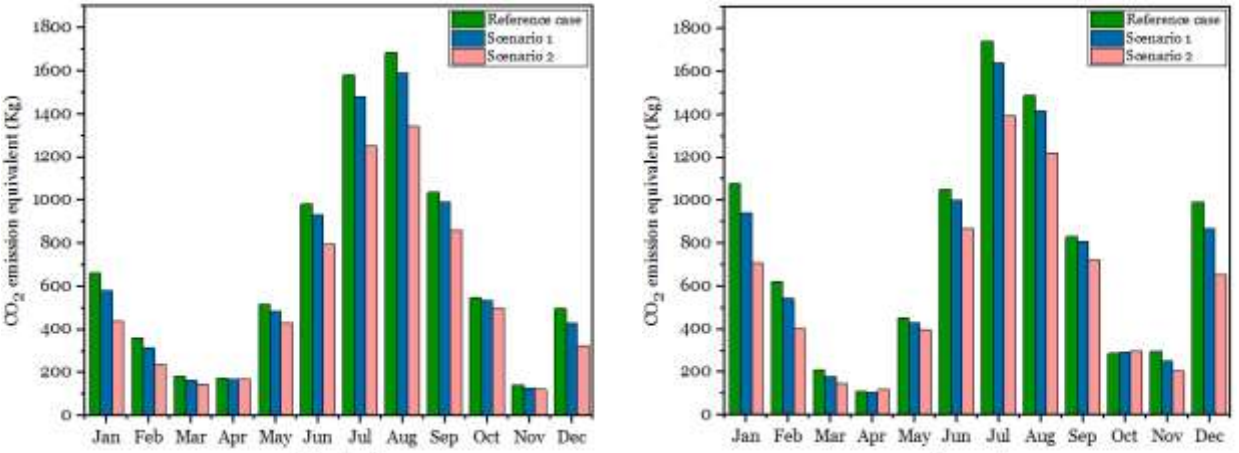
In this section, we are interested in the environmental impact due to the various energy demands of the building including heating and cooling. The quantification of this impact is based on the fact that the process of producing one kWh of electricity is accompanied by an emission of 0.743Kg of CO_2-equivalent [45]. The amount of CO_2-equivalent is calculated for the three scenarios studied and for the different study climates.

After calculating the CO_2 emissions for the three construction scenarios studied, the results are shown in the graphs in Figure 11. The CO_2 emissions of the buildings studied showed the following reductions: scenario 1 led to reductions of 7.1%, 8%, 6.8%, and 7.4% respectively for Al-Hoceima, Oujda, Marrakech, and Ouarzazate. Scenario 2 achieved reductions of 22.1%, 23.7%, 21% and 22% respectively.



Al-Hoceima

Oujda



Marrakech

Ouarzazate

Fig. 11. Monthly evolution of CO_2 emissions from buildings for the three scenarios

4.2.4 Impact on thermal comfort within the building

The last step of this analysis is devoted to the impact of the proposed construction scenarios on the thermal comfort within our building. Indeed, the thermal comfort or the state of the interior environment of the building represents one of the most important elements of study for thermal engineers, as reaching a good level of comfort allows to improve the productivity of the occupants as well as their satisfaction. In other words, it is to seek an energy balance in the building for which none of the occupants has extreme sensations in terms of cold and heat [46].

Indeed, this part aims to measure the impact of the integration of ecological materials from nature (based on hemp waste) on the thermal comfort level of the building. Consequently, the temperature felt by the occupants or the operative temperature represents a good index of comfort. It is expressed as [47]:

$$T_{op} = \frac{h_r T_{mr} + h_c T_{air}}{h_r + h_c} \tag{20}$$

where:

i) h_c: Convective heat transfer coefficient.

ii) h_r: Linear radiative heat transfer coefficient.
iii) T_{air}: Indoor air temperature.
iv) T_{mr}: Mean radiative temperature.

For the interior space of a building, the operative temperature can be calculated by the simplified expression:

$$T_{op} = \frac{T_{mr}+T_{air}}{2} \tag{21}$$

The operative temperature calculations were used to plot the graphs in Figures 12 and 13, which show the variation in comfort temperature in our building for the three construction scenarios in the four sites studied during a typical week. Only the variations in operative temperature in room 1 are shown for reasons of visibility, as illustrated in the eight graphs:

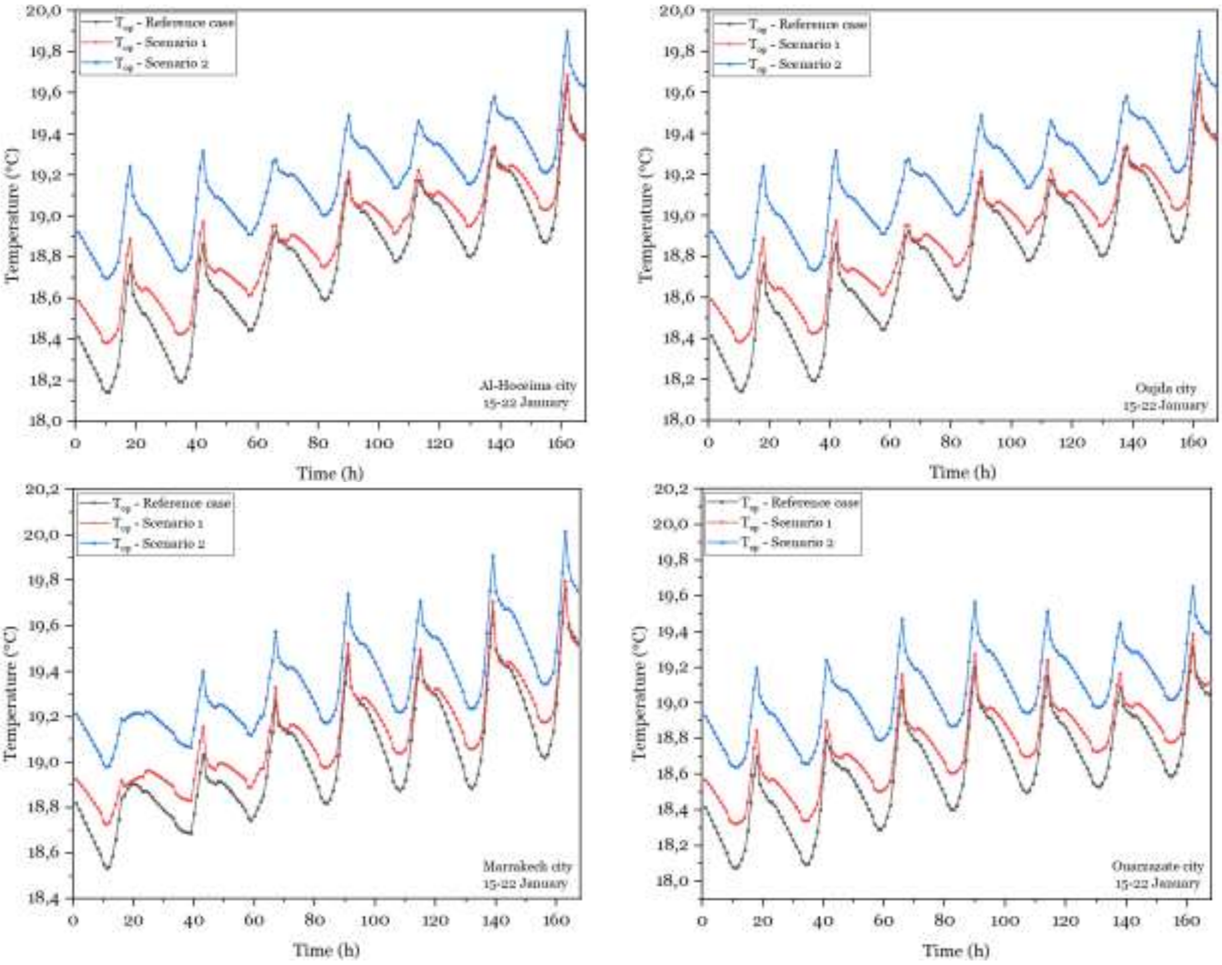


Fig. 12. Operative temperatures as a function of three scenarios for a typical week in January

For a typical week in January, Figure 12 shows the variations in operative temperature for the three construction scenarios. A careful analysis of the four graphs in Figure 12 reveals that the scenario with the greatest impact on the temperature felt by occupants is scenario 2, followed by scenario 1. The difference in temperature between scenario 2 and the reference scenario can reach around 0.56°C in Ouarzazate, 0.54°C in Oujda, 0.45°C in Al-Hoceima and 0.44°C in Marrakech.

These results indicate a slight improvement in thermal comfort inside the building, although the temperature still fluctuates around the range considered comfortable for winter. This observation highlights the important nuances between different building scenarios and underlines the importance of choosing appropriate materials and design strategies to optimise thermal comfort in a variety of Moroccan climates.

Similarly, for a typical week in July, the study analyzed the variations in operative temperature for the same three construction scenarios. The results presented in Figure 13 show that the maximum deviation of the operative temperature from the reference scenario is observed in the case of scenario 2, recording a difference of 0.62°C in Ouarzazate, while the minimum deviation is observed in Al-Hoceima, with a difference of 0.4°C.

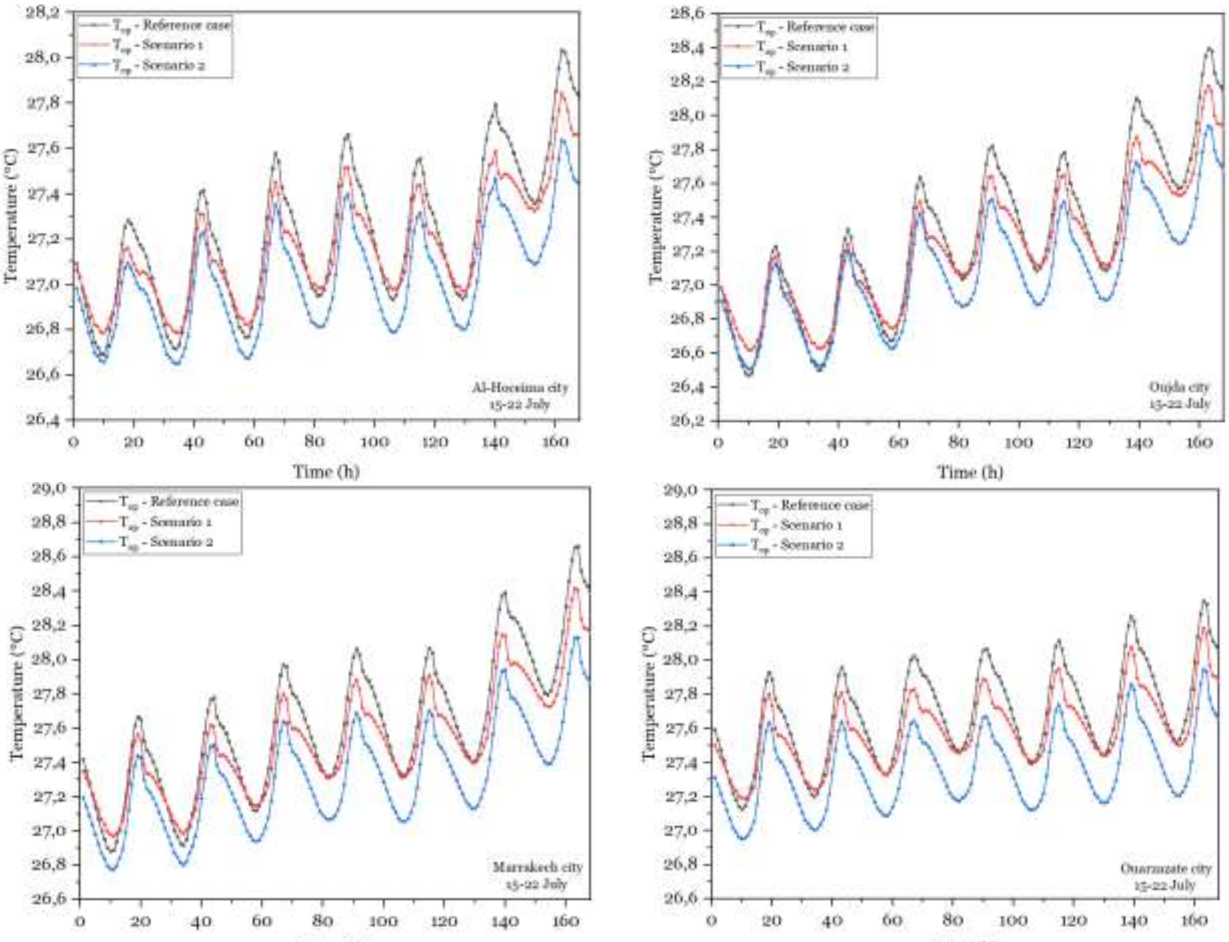


Fig. 13. Operative temperatures as a function of three scenarios for a typical week in July

As in winter, the building shows a slight improvement in thermal comfort in the summer. These observations highlight the subtle but significant variations in the thermal performance of different building scenarios according to Moroccan summer weather conditions. This highlights the importance of choosing appropriate design strategies to maintain comfortable indoor conditions throughout the year, particularly in climatically varied regions such as those studied.

Figure 14 shows the annual percentage of hours of discomfort experienced by occupants. Note that this percentage is calculated by the expression:

$$\%\ \text{discomfort} = \frac{\text{Number of hours of discomfort}}{8760} \times 100 \tag{22}$$

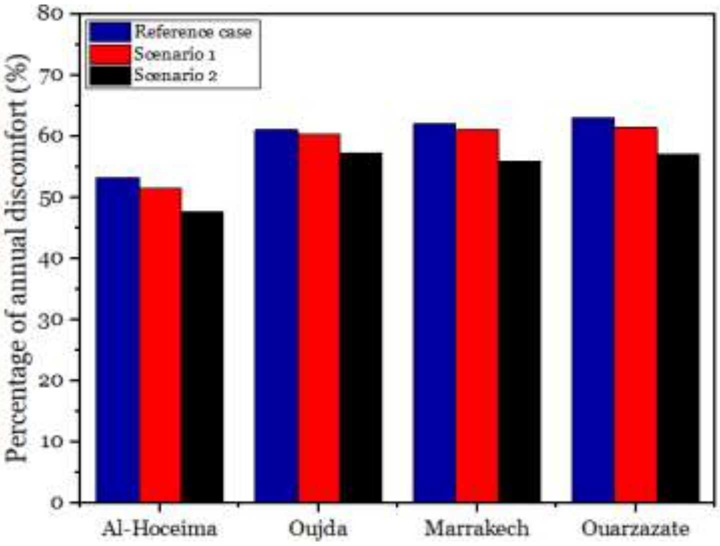


Fig. 14. Percentage of annual discomfort for room 1

The results clearly show that thermal comfort inside the building has improved in the four climates studied and for the two scenarios proposed. However, the reduction in terms of hours of discomfort is still not significant enough, because only insulating the walls of the building with hemp plaster and hemp concrete is insufficient to prevent overheating of the room and generally the whole building.

5. Discussion

The results of our simulations highlight the effectiveness of hemp plaster and hemp concrete as bio-based materials for the thermal insulation of building envelopes. This approach aims to significantly reduce energy consumption and the associated carbon footprint, while improving thermal comfort inside buildings across the different climatic zones defined by Morocco's thermal regulations.

By integrating these natural materials into the design of building envelopes, our study shows how they can help to improve overall energy performance and create more comfortable and sustainable indoor conditions. This well-known approach could potentially influence construction practices to promote more sustainable and efficient solutions in the Moroccan building sector, in line with the objectives of reducing carbon emissions and improving energy efficiency.

In comparison with the study conducted by Charai *et al.,* [33] on the integration of 4cm hemp plasterboards in the ceiling of a residential building for two Moroccan cities, namely; Oujda and Marrakech, which shows savings in terms of total energy demand of about 4.7% and 5.4% respectively which is around our scenario 1 results estimated at 8.03% and 6.78% respectively in Oujda and Marrakech. Whereas our results for scenario 2 indicate total energy demand savings estimated at 23.8% for a building constructed in the third climatic zone of the RTCM against a 41.5% reduction in total energy for a building with double partitioning based on hollow bricks filled with hemp concrete separated by a 5cm air gap and a roof insulated with 7cm of hemp wool through a study conducted by Dlimi *et al.,* [34]. These results highlight the high insulating capacity and thermal inertia of hemp material, making it a good bio-sourced thermal insulator, as already announced in a study by Dhakal *et al.,* [48].

Although this study presents other results concerning the improvement of the carbon footprint and thermal comfort inside the building, these conclusions are in agreement with those of the studies carried out by Essaghouri and Mao Xiaodong [35] on environmental aspects, as well as with that of Tran Le *et al.,* [49] which examines the impact of hemp-based materials on indoor air quality in buildings.

6. Conclusions

The major challenge of energy prices and the environmental impact caused by greenhouse gas emissions during the manufacturing process of conventional building materials have prompted scientists to look for solutions and alternatives aimed at optimizing buildings in terms of energy savings, carbon footprint, energy bills, and of course, occupant comfort. Among the various passive strategies, the building envelope remains a fundamental parameter on which we can act to create energy-efficient, sustainable, and environmentally friendly buildings.

This article aimed to study the impact of integrating ecological materials based on hemp waste into the envelope of an existing Moroccan building, using a TRNSYS simulation. Firstly, the building's heating and cooling requirements were calculated and compared with the RTCM reference energy performance. Next, two building construction scenarios using hemp rendering and hemp concrete were studied for different Moroccan climatic zones (a Mediterranean climate, a cold semi-arid climate, a hot semi-arid climate, and a hot desert climate):

i) Impact on energy demand
Using hemp plaster to renovate the walls of existing buildings can lead to maximum reductions of 16.3% and 4.3% for heating and cooling respectively. Using hemp concrete in walls and high floors can reduce these requirements by 39.4% and 15.5% respectively. Buildings using these materials have a greater impact on heating requirements, so this technique is better suited to climates that require more heating.

ii) Impact on the electricity bill
The economic study carried out for both scenarios shows that renovating the envelope of an existing building with hemp plaster can reduce electricity bills by up to 8%. Integrating hemp concrete into the walls of a new building can reduce energy costs by up to 25%.

iii) Impact on the carbon footprint (GHG emissions)
Reducing energy requirements for heating and cooling reduces the amount of CO_2 emitted. To achieve this, the carbon footprint was also calculated. The results show that scenario 1 leads to reductions in CO_2 emissions of up to 8%. Scenario 2 can contribute to a maximum reduction of around 23.7%.

iv) Impact on thermal comfort
Thermal comfort was evaluated by calculating the operative temperature for each construction scenario. The results obtained show that the two proposed construction scenarios offer a slight improvement in thermal comfort compared with the reference scenario. However, the internal state of the building in the four sites studied requires sufficient comfort, which can be achieved by adding other bioclimatic design strategies.

The results show that renovating existing buildings or constructing new ones using hemp plaster and hemp concrete is a very promising alternative for reducing energy needs, particularly for heating. It will also reduce electricity bills and the carbon footprint of buildings, as well as make them more comfortable to live in throughout most of Morocco.

Finally, it would be very useful to further complete this work by studying a combination of this building strategy based on bio-sourced materials with other passive strategies such as building orientation, glazing system, natural ventilation, and shading techniques, among others.

Acknowledgement

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