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Impact of Insulation using Bio-sourced Materials on the Thermal and Energy Performance of a Typical Residential Building in Morocco

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ABSTRACT

Among the measures to be taken to design and construct buildings with envelopes that are more energy-efficient, sustainable, and environmentally friendly is thermal insulation using a very wide range of insulating materials, either synthetic or of natural origin or derived from biomass. The present work represents a thermal and energy study aimed at improving the thermal comfort levels and energy requirements of a typical residential building located in the city of Al-Hoceima, Morocco. To this end, a series of numerical simulations were carried out using TRNSYS software to assess the impact of applying three bio-based insulation materials, namely hemp wool, wood fiber, and expanded cork, in the wall layer of the building. Different insulation scenarios were studied to make a choice that would ensure optimum comfort in the building with low energy demand. The results of this study show that insulating the roof with 8 cm of hemp wool contributes to energy savings of up to 36.7% and 35.2% for cooling and heating demand respectively. In thermal terms, improvements in the temperature inside the building have been achieved: in January, the maximum temperature recorded is 20.94°C, while in July, the maximum temperature is around 26.80°C.

1. Introduction

In Morocco, population growth and urbanization are having a direct impact on the considerable increase in energy consumption and greenhouse gas (GHG) emissions. The building sector alone is responsible for 33% of energy consumption and 12% of greenhouse gas emissions at the national level [1]. To meet these energy and environmental challenges, the Moroccan government has put in place a national energy strategy to move towards efficient and sustainable solutions, such as integrating green and renewable energies into the national energy mix and implementing energy efficiency measures in energy-intensive sectors. The strategy aims to achieve a 52% contribution from renewable energies and a 15% reduction in final energy consumption [2].

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What's more, most people's lives take place inside buildings, where they carry out their daily tasks and activities. To do this, these buildings need to be comfortable, because achieving a good level of thermal comfort helps to improve occupants' productivity and increase their satisfaction. In other words, the aim is to achieve an energy balance in the building where none of the occupants experience extreme sensations in terms of cold and heat [3]. On the other hand, the use of air conditioning systems increases the energy bill for buildings, making it one of the most energy-intensive sectors. Hence, there is a need to take action to ensure adequate indoor thermal comfort while optimizing energy consumption.

Energy consumption and thermal comfort in the building sector represent a major area of research that has developed considerably in recent years. The thermal performance of the building envelope is the key element influencing energy consumption. Consequently, energy consumption can be reduced by incorporating thermal insulation into the building envelope [4,5]. In this respect, various research studies have investigated the effect of insulation on the energy performance of buildings and their state of indoor comfort.

Eddib and Lamrani [6] carried out a simulation study using TRNSYS software to evaluate the effect of four types of insulation and to determine their optimum thicknesses. The study focused on the thermal and energy performance of the envelope of a residential building in Marrakech. The results show that the best insulation is wood fiber, with a thickness of 7 cm, which saves 7% and 14% respectively on heating and cooling requirements. What's more, in January, the indoor temperature is raised by 0.26°C, while in July it is lowered by 0.49°C.

Guechchati *et al.,* [7] carried out a simulation study using TRNSYS software to quantify the impact of different thermal insulation installations on the energy demand of a psycho-educational center located in the city of Oujda. The study concluded that the best scenario was to insulate the roof and the outside of the walls with 6 cm of expanded polystyrene 035, resulting in a 16.36% reduction in energy demand.

Boursas and Labidine [8] carried out a comparative study to assess the impact of expanded polystyrene insulation on the energy performance of a residential building located in the North African region, represented respectively by the cities of Casablanca, Tunis, and Constantine. The energy requirements of these three cases are simulated as a function of several insulation thicknesses ranging from 1 to 10 cm using TRNSYS software. For the three sites selected, the results show that the greatest energy savings are obtained by insulating the roof first, followed by the external walls while insulating the low floor leads to an increase in energy requirements.

In addition, several studies have looked at the effect of insulation on energy consumption in the Egyptian building sector. For example, Ahmed [9] carried out a thermal study on the integration of thermal insulation materials into the building envelope of the Faculty of Engineering at El Fayoum University using DesignBuilder software. The study examined four scenarios: roof insulation - double roof - external wall insulation - double wall. The results showed that the roofs require a double ceiling including 20cm of insulation, while the external walls must contain 7cm of polyurethane insulation. In another work, Morsy *et al.,* [10] carried out an energy efficiency study aimed at improving the energy demand and thermal comfort levels for a five-floor university building. The simulation study using DesignBuilder software examined the performance of eight thermal insulations, namely: celton, expanded polystyrene, extruded polystyrene, perlite, vermiculite cement, vermiculite, polyurethane 0.026 and polyurethane 0.045. The results showed that to achieve optimum thermal comfort and reasonable energy consumption, the ground and fourth floors require a thick layer of insulation, whereas a thin layer will suffice for the other floors of the building. In addition, expanded polystyrene is the most recommended insulation for the lowest energy consumption, while vermiculite cement is the best choice for improved thermal comfort inside the building.

Muhieldeen *et al.,* [11] evaluated the temperature variation inside a test room for several forms of thermal insulation, such as polyethylene, expanded polystyrene, and rock wool. The results showed that 5.2 cm of rock wool insulation offered the best temperature reduction inside the test room, at 3.85%, followed by 2.3 cm of expanded polystyrene and 0.5 cm of polyethylene insulation, with interior temperature reductions of 2.49% and 0.89% respectively.

In a similar vein, and concerning insulation using so-called biomass materials, several studies have dealt with materials such as hemp waste, walnut shell waste, wood waste, and waste from wheat straw and date palms [12-15].

Charai *et al.,* [16] studied the thermal insulation potential of hemp-gypsum biocomposites and their contribution to energy savings in a typical building for cold and hot semi-arid climates represented by the cities of Oujda and Marrakech using Energyplus software. The results of this study showed that insulating the roof with a 5 cm thick hemp-gypsum board reduces total energy demand (heating and cooling) by 4.7% and 5.4% in Oujda and Marrakech respectively.

Dlimi *et al.,* [17] attempted to evaluate the energy performance of a typical residential building located in the city of Meknes and constructed with double partition walls made of hollow bricks filled with hemp concrete and insulated on the roof with 7cm of hemp wool. The results of thermodynamic simulations carried out using TRNSYS software showed that the total energy demand (heating and cooling) was reduced from 73.92 kWh/m^2 to 27.19 kWh/m^2.

Lachheb *et al.,* [18] examined the thermal performance and insulating properties of a biocomposite made from plaster and coffee grounds. Using this material as a 4 cm false ceiling in a typical residential building in Marrakech reduced energy demand by 27% and 21.6% for heating and cooling respectively.

Unfortunately, this work has not addressed the effect of insulating with bio-based materials through a comprehensive parametric study, while the studies that have been carried out have dealt with examples of bio-based insulation separately. In this respect, this work presents a detailed parametric study of the effect of insulation with three bio-based materials and for three different insulation scenarios based on several insulation thicknesses ranging from 2 to 8 cm on the energy performance of a typical building. In addition, the effect of insulation on the thermal performance of the building envelope and its influence on indoor temperature are also addressed. The present work aims to find the bio-sourced thermal insulation best suited to the Mediterranean climate of Al-Hoceima, as well as its optimal thickness and the best possible insulation scenario. To this end, the study examined the insulating effect of three bio-based materials: hemp wool, wood fiber, and expanded cork, on the thermal and energy performance of a typical residential building in the city of Al-Hoceima. The study was carried out in the form of a transient energy simulation using TRNSYS software.

2. Case Study: Description of the Building and Climate Studied

To assess the effect of insulating a typical residential building with bio-sourced materials on heating and cooling energy requirements, as well as comfort inside, the present work includes a thermal study of a two-floor building in Al-Hoceima, Morocco.

Each floor is 2.7m high and has a surface area of 108 m^2. Figure 1 shows the different rooms that make up each floor. Our building faces due north.

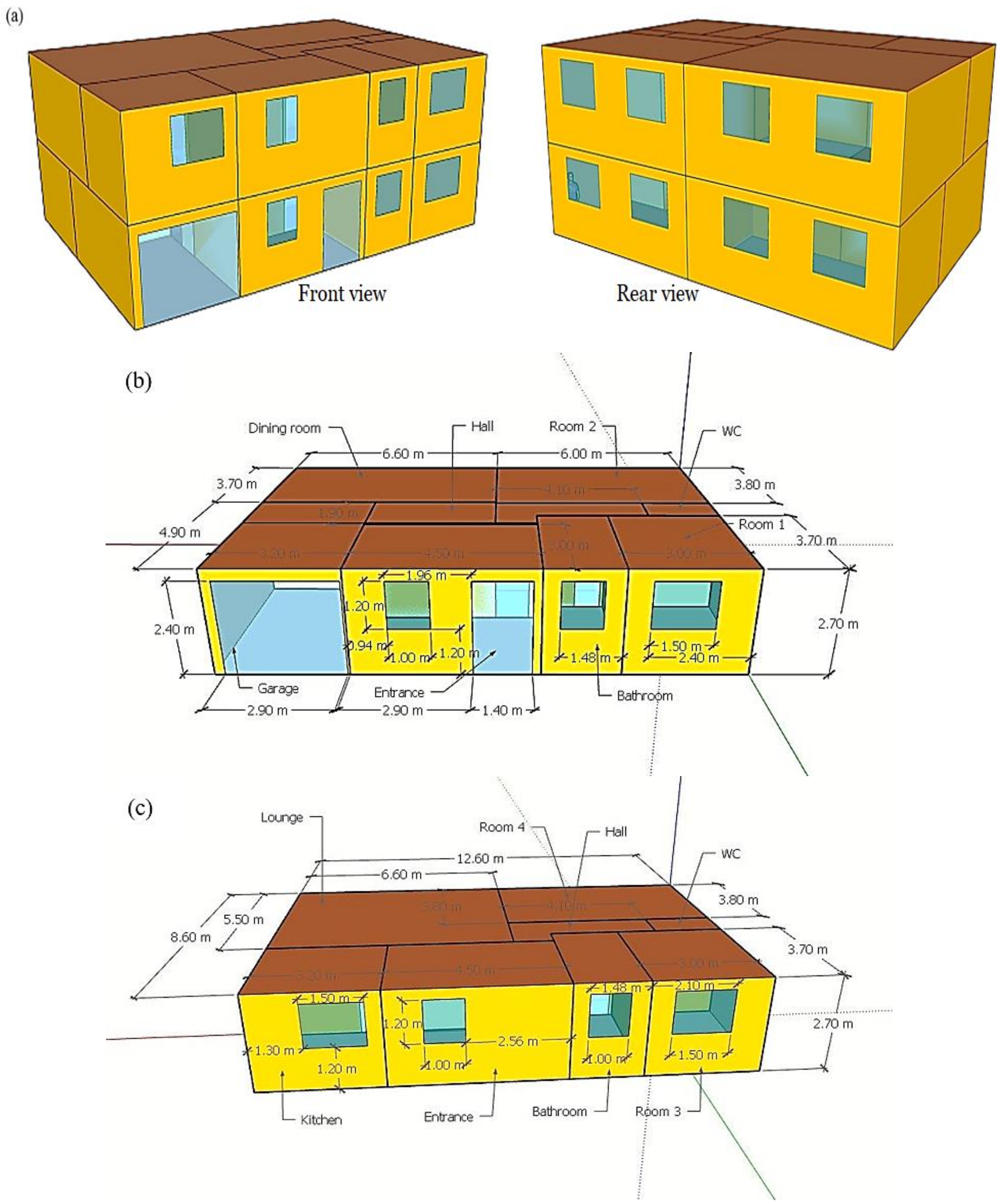


Fig. 1. (a) 3D plan of the building, (b) 3D plan of the ground floor, (c) 3D plan of the first floor

The building under study has two exterior façades. The main façade faces north, while the rear façade faces due south. The facades of each part of our building are shown in Table 1.

Table 1
Building facades

Floors	Room	Facades exposed to the outside
Floor on ground	Garage	North
	Entrance	
	Bathroom	
	Room 1	
	Dining room	South
	Room 2	
First floor	Kitchen	North
	Entrance	
	Bathroom	
	Room 3	
	Lounge	South
	Room 4	

Table 2 shows the composition of the walls, as well as the building materials and their thermo-physical properties. It should be noted that the Binayate Prescriptive Library was used for this purpose [19].

Table 2
Building components and their thermo-physical properties

Walls	Materials	Thickness (cm)	Density (Kg/m^3)	Thermal conductivity (W/m.K)	Heat capacity (kJ/kg.K)
Exterior Wall	Cement mortar	2	1900	1,30	1,00
	Brick (12 holes)	20	664	0,22	0,74
	Cement mortar	2	1900	1,30	1,00
Interior Wall	Cement mortar	2	1900	1,30	1,00
	Brick (8 holes)	10	918	0,19	0,74
	Cement mortar	2	1900	1,30	1,00
Roof and high floor	Floor tiles	2	2300	1,30	0,84
	Heavy concrete	7	2450	2,00	1,00
	Hollow slab	10	1513	1,04	1,00
	Gypsum plaster	1	1350	0,56	1,00
Floor on ground	Floor tiles	2	2300	1,30	0,84
	Cement mortar	5	1700	1,00	1,00
	Heavy concrete	20	2450	2,00	1,00

- Glazing: Single glazing (Transmission coefficient: U = 5,72W/m².K - Solar factor: g = 0,84)
- The window/wall ratio (WWR): 12 %

Table 3 illustrates the thermo-physical properties of the insulation materials used.

Table 3
Thermo-physical properties of insulation materials

Materials	Thermal conductivity (W/m.K)	Heat capacity (kJ/kg.K)	Density (Kg/m^3)
Wood fiber [20]	0,138	1,95	180
Hemp wool [21]	0,039	1,70	40
Expanded cork [22]	0,041	1,53	156

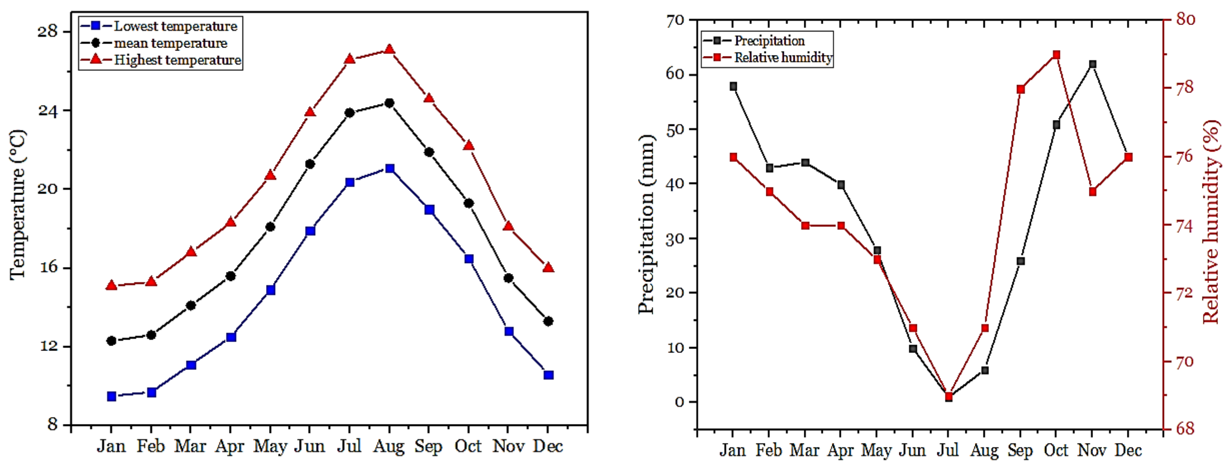
The internal gains due to occupants and equipment are detailed according to a schedule in Table 4.

Table 4
Occupancy and equipment planning

Element	Type of gain	Number of hours of daily use	Internal gains (W)
Room 1	Lighting	2h (every day)	12W
Room 3	Laptop	2h (every day)	40W
	1 person	in activity: 2h (every day)	83W
		Sleeping: 8h (every day)	72W
Room 2	Lighting	2h (all week)	12W
Room 4	Laptop	2h (all week)	40W
	2 persons	in activity: 2h (every day)	166W
		Sleeping: 8h (every day)	144W
Kitchen	Lighting	3h (every day)	12W
	Refrigerator	24h (every day)	300W
	Washing machine	2h (1 time/week)	2200W
	2 persons	4h (every day)	252W
Dining room	Lighting	3h (5 days/week)	36W
	Refrigerator	24h (every day)	300W
	TV	4h (5 days/week)	100W
	6 persons	5h (5 days/week)	498W
Lounge	Lighting	3h (2 days/week)	36W
	TV	4h (2 days/week)	100W
	6 persons	5h (2 days/week)	498W

In general, the region enjoys a Mediterranean climate, with mild, generally sunny summers and wet, relatively dry winters. Figure 2(a) shows that temperatures peak in August at 27.1°C, while the lowest temperature is recorded in January at 9.5°C. Over the year as a whole, winter rainfall is higher than summer rainfall (414 mm on average), according to Figure 2(b).

The meteorological data used in the simulation comes from the Typical Meteorological Year (TMY) file generated using METEONORM software for the city of Al-Hoceima.



(a) (b)

Fig. 2. (a) Temperature chart of Al-Hoceima city, (b) Precipitation and relative humidity

The temperature inside a naturally ventilated building depends on several variables, such as the temperature of the external environment, internal thermal loads, solar radiation loads, and the thermal inertia of the building [23]. The insulation of the building envelope is also one of the parameters on which it is possible to act to reduce heating and cooling energy demand and improve thermal comfort levels within the building. To this end, we propose to study insulation scenarios that will enable us to choose an appropriate insulation for our building envelope.

3. Simulation Tool: TRNSYS Software (version 18)

TRNSYS (Transient System Simulation) version 18 is a simulation tool used to carry out dynamic and transient thermal simulations for buildings. Simulation using this tool enables an exhaustive study of the thermal performance of the building, depending on several parameters and variables such as the meteorological and geographical data for the site under study, the architectural features of the building under study, and the occupancy and use schedules for equipment and lighting.

TRNSYS is a numerical simulation software package developed by the Scientific and Technical Center for Building (CSTB), which is used to study the thermal behavior of buildings, either by determining their energy requirements in terms of heating and cooling, or by assessing their thermal performance and estimating their state of comfort. Buildings are modeled in TRNSYS as multi-zone entities using type 56 in the TRNBUILD environment [24].

Our building is modeled as a multi-zone entity, so our building is divided into 16 thermal zones, each represented by an air node.

During our simulation, several conditions were taken into account, namely

i. The thermal simulation was carried out with a 1-hour time step.
ii. The infiltration rate is estimated at 0.6 vol/h.
iii. The solar absorption coefficient of the building walls is estimated at 0,6.
iv. Thermal bridges are not taken into account in our study.
v. The effect of shading is not taken into account.
vi. Set-point temperatures: heating is 20°C and cooling is 26°C according to Moroccan standard NM ISO 7730.
vii. Type 77 based on the Kusuda correlation is used to predict ground temperature [25].
viii. The convective exchange coefficients are calculated using the following correlation:

$$h = c(T_{surf} - T_{air})^n \tag{1}$$

where,
T_{surf} : The temperature of the surfaces of the building envelope.
T_{air} : The ambient air temperature.
c and n are parameters that depend on the type of surface.

The values for c and n are taken from the TRNSYS 18 manual. Table 5 summarizes the values of these constants for the different types of building surfaces and as a function of the difference between their temperatures and those of the air.

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

Type of surface	Condition	h_{inside}		$h_{outside}$	
		c (W.m^{-2}.K^{-n-1})	n	c (W.m^{-2}.K^{-n-1})	n
Walls	---	1,60	0,30	2,11	0,31
Floor on 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

Figure 3 shows a model of the building under study in the TRNSYS software simulation studio.

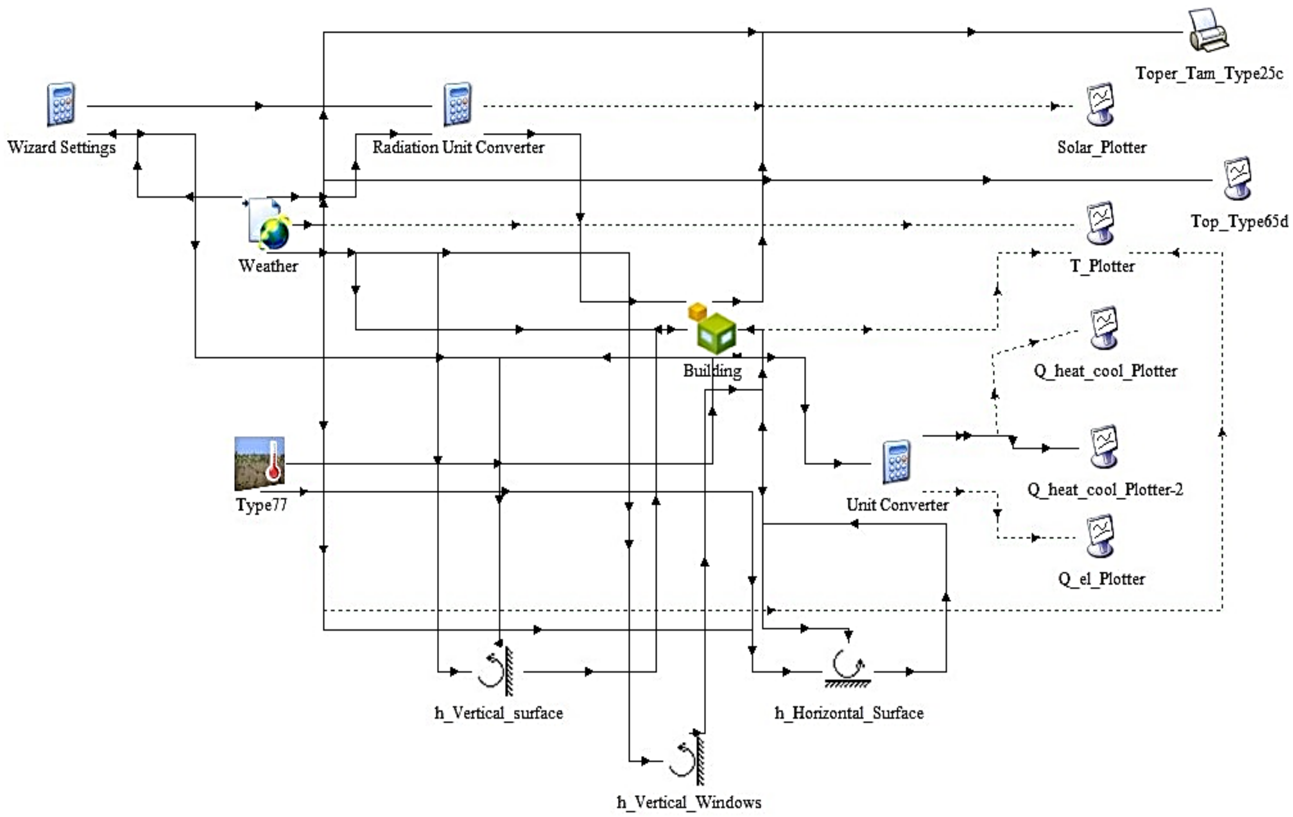


Fig. 3. Modelling of the building in the software "TRNSYS simulation Studio"

4. Results and Discussion

4.1 Energy Demand of the Reference Building

The monthly energy demand for heating and cooling the building is shown in Figure 4. It can be seen that the cooling loads are greater than the heating loads, which is explained by the nature of the Mediterranean climate, with hot summers requiring more cooling than heating loads during the winter.

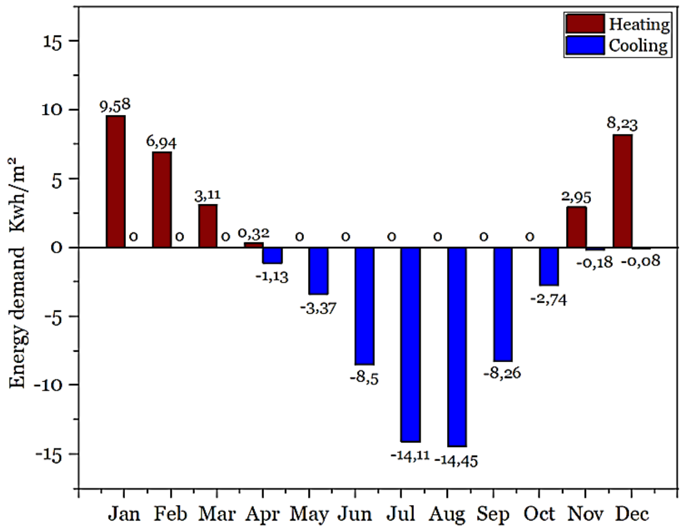


Fig. 4. The building's monthly heating and cooling energy demand

The building studied does not have any energy efficiency measures, including thermal insulation, which means that it does not comply with the specifications and standards of the Moroccan thermal construction regulations (RTCM) applied in 2015 (buildings constructed before 2015) [26]. As a result, the absence of monitoring data for this building to calibrate or validate our simulation model is a major obstacle. To this end, and as a check on our simulation model, a comparison of our results with the base case values required by the RTCM performance approach was carried out, and we note that our simulation values are of the same order of magnitude as those of the RTCM, as shown in Figure 5. It should be noted that similar validation work was carried out on the same building and using the same simulation model (TRNSYS software) [27].

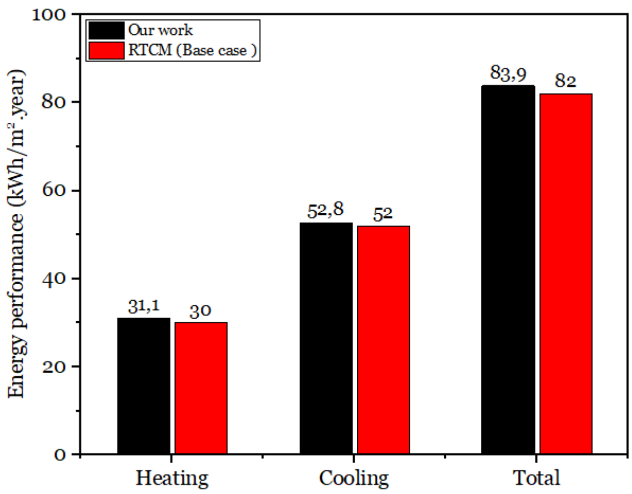
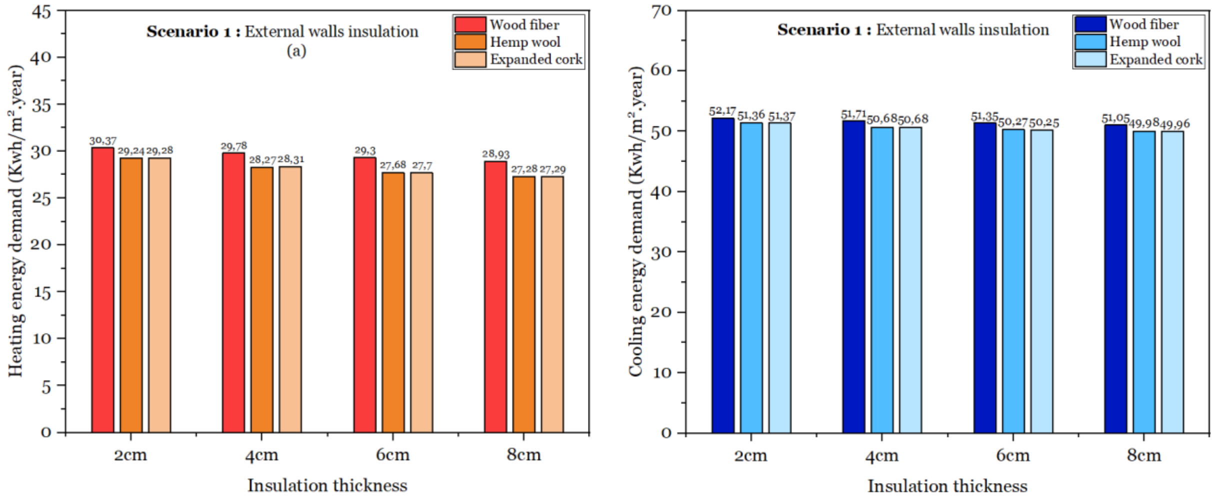


Fig. 5. Comparison of the building's energy performance with the requirements of the RTCM (base case)

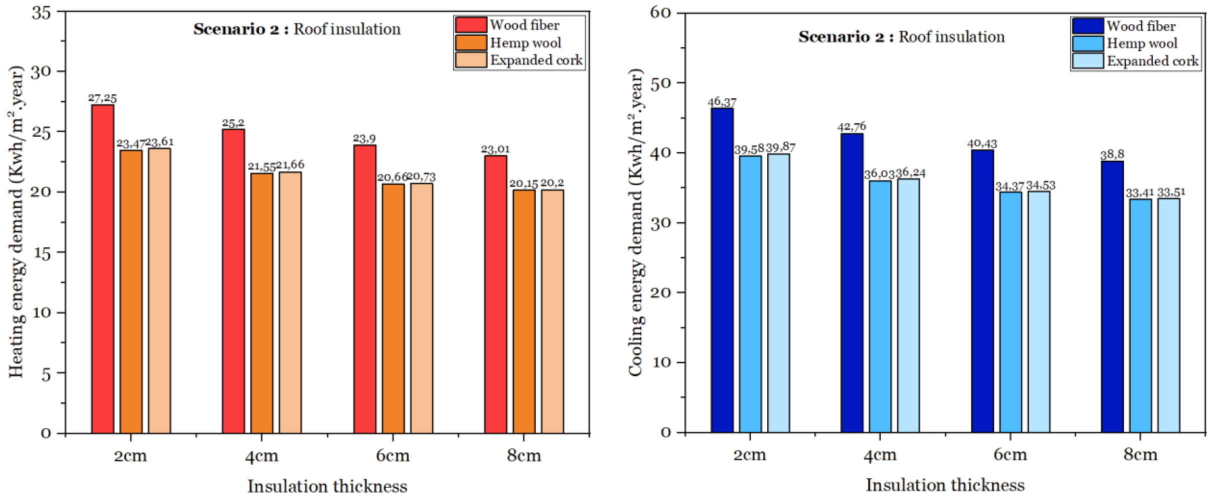
4.2 Effect of Insulation on Heating and Cooling Energy Demand

To study the effect of insulation on the energy performance of the building, the heating and cooling energy requirements were calculated. Figure 6, Figure 7, and Figure 8 show the heating and cooling energy requirements according to the three insulation scenarios and with the three insulations already considered for thicknesses ranging from 2 cm to 8 cm (with a 2 cm increment).



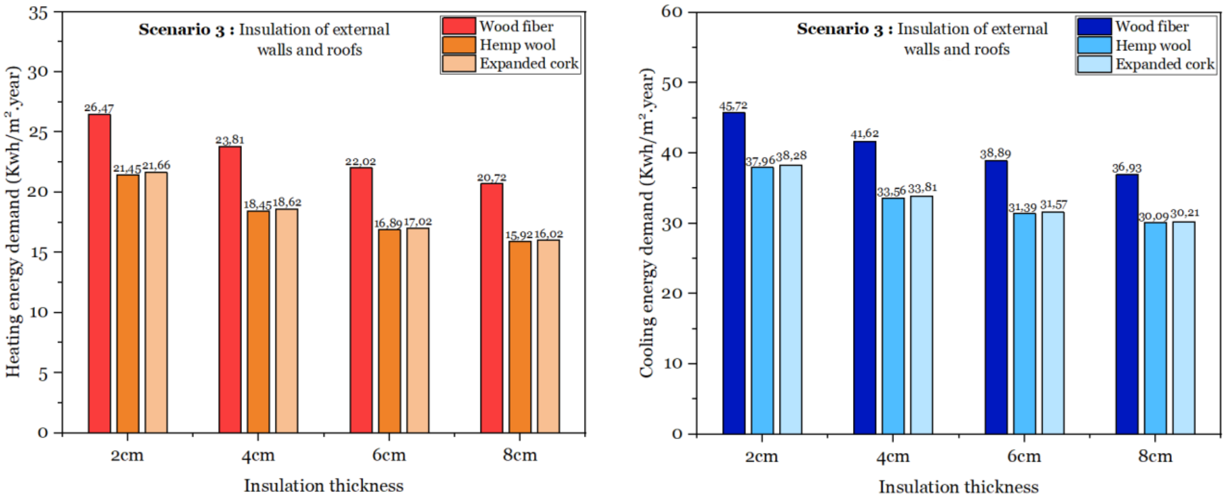
(a) (b)

Fig. 6. Energy demand for the external wall insulation scenario: (a) for heating, (b) for cooling



(a) (b)

Fig. 7. Energy demand for the roof insulation scenario: (a) for heating, (b) for cooling



(a) (b)

Fig. 8. Energy demand for the external walls and roofs insulation scenario: (a) for heating, (b) for cooling

Firstly, and according to the results in Figure 6 and Figure 7, it was found that roof insulation is more energy efficient than external wall insulation, with a maximum difference of around 7Kwh/m^2.year for heating and around 16.5Kwh/m^2.year for cooling, which is fully in line with the work already carried out by Boursas and Labidine [8]. The combination of external wall and roof insulation saves up to 33.4%, 48.8%, and 48.5% of heating energy for wood fiber, hemp wool, and expanded cork insulation, respectively. In terms of cooling load, it contributes to the following reductions: 30%, 43%, and 42.8% respectively (Figure 8).

In terms of heating requirements, the results in Figure 6, Figure 7, and Figure 8 show that for external wall insulation, 8cm of wood fiber insulation saves up to 6.8% of heating energy, while 8cm of expanded cork and hemp wool insulation achieves reductions of around 12.2% and 12.3% respectively. In addition, for roof insulation, energy savings of around 26%, 35%, and 35.2% were achieved by applying 8 cm of wood fiber, expanded cork, and hemp wool insulation respectively. Finally, a combination of external wall and roof insulation reduced the building's heating demand by 33.4%, 48.5%, and 48.8% by incorporating an 8 cm layer of wood fiber, expanded cork, and hemp wool respectively.

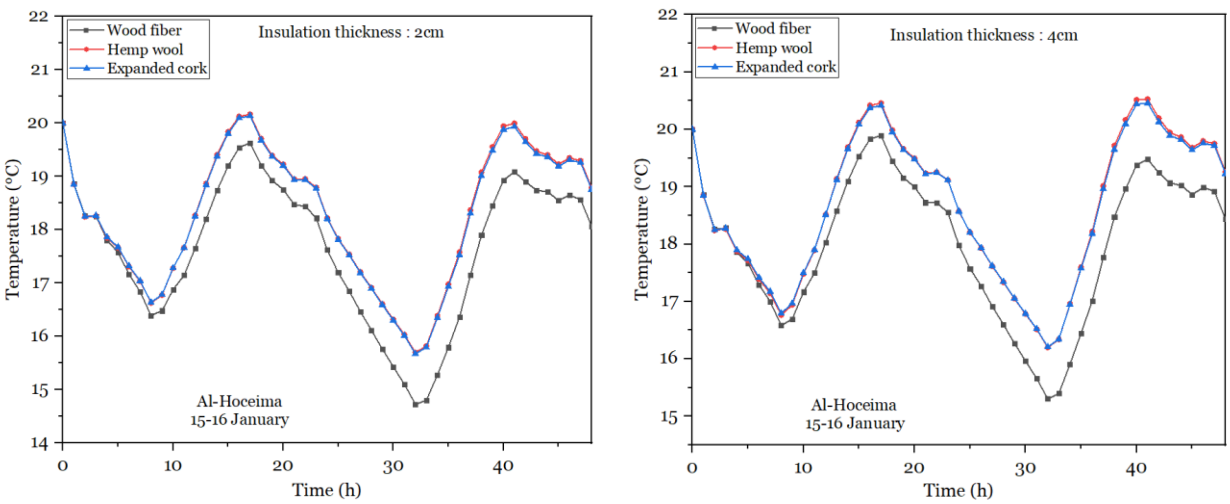
In terms of cooling requirements, the results in Figure 6, Figure 7, and Figure 8 show that for external wall insulation, 8cm of wood fiber insulation saves up to 3.3% of heating energy, while 8cm of expanded cork and hemp wool insulation achieves reductions of around 5.3% and 5.4% respectively. In addition, for roof insulation, energy savings of around 26.5%, 36.5%, and 36.7% were achieved by applying 8 cm of wood fiber, expanded cork, and hemp wool insulation respectively. Finally, a combination of external wall and roof insulation reduced the building's heating demand by 30%, 42.8%, and 43% by incorporating an 8 cm layer of wood fiber, expanded cork, and hemp wool respectively.

Comparing the results in Figure 6, Figure 7, and Figure 8, it can be concluded that hemp wool and expanded cork represent the optimal choice over wood fiber insulation in terms of insulating capacity since hemp wool and expanded cork provide remarkable reductions in the heating and cooling loads of the building compared to wood fiber. Consequently, the use of 2 cm of hemp wool and expanded cork insulation is roughly equivalent to 6 cm of wood fiber insulation for the three insulation scenarios examined. In addition, the external wall and roof insulation scenario is more energy efficient than the roof insulation scenario alone, with an average difference of 7.5 kWh/m^2.year in terms of total energy, which is fully in line with the results of the work carried out by Guechchati *et al.,* [7] However, from an economic point of view, the best choice is to insulate the roof since the combined insulation of the external walls and the roof requires 312m^2 of insulation while insulating the roof requires only 108m^2. Hence, the optimal choice and that insulate the roofs with 8cm of hemp wool or, as a second choice, expanded cork for the same insulation scenario and the same thickness.

4.3 Effect of Insulation on Indoor Temperature

From a thermal point of view, we are assessing the influence of insulation on indoor temperature. For reasons of visibility, the graphs in Figure 9 and Figure 10 show the variation in indoor temperature in room 4 for the roof insulation scenario and for two typical days (48h) in winter (January) and summer (July).

For two typical days in January, Figure 9 shows the variation in temperature inside chamber 4 for different insulation thicknesses. A careful reading of the four graphs in Figure 9 shows that the indoor temperatures for the building insulated with hemp wool and then expanded cork are the highest, followed by the temperature for wood fiber. For an insulation thickness of 2 cm, the temperatures recorded for hemp wool and expanded cork are 20.17°C and 20.14°C respectively, compared with 19.63°C for wood fiber. For a thickness of 8 cm, the temperature inside chamber 4 is 20.94°C, 20.87°C, and 20.17°C respectively for hemp wool, expanded cork, and wood fiber. These results show that the thermal comfort obtained with 2 cm of hemp wool insulation is equivalent to that obtained with 8 cm of wood fiber insulation. These significant temperature differences are due to the different insulating properties and low thermal conductivity of hemp wool compared with expanded cork and wood fiber. In other words, there is only a small temperature difference between hemp wool and expanded cork for the four insulation thicknesses.



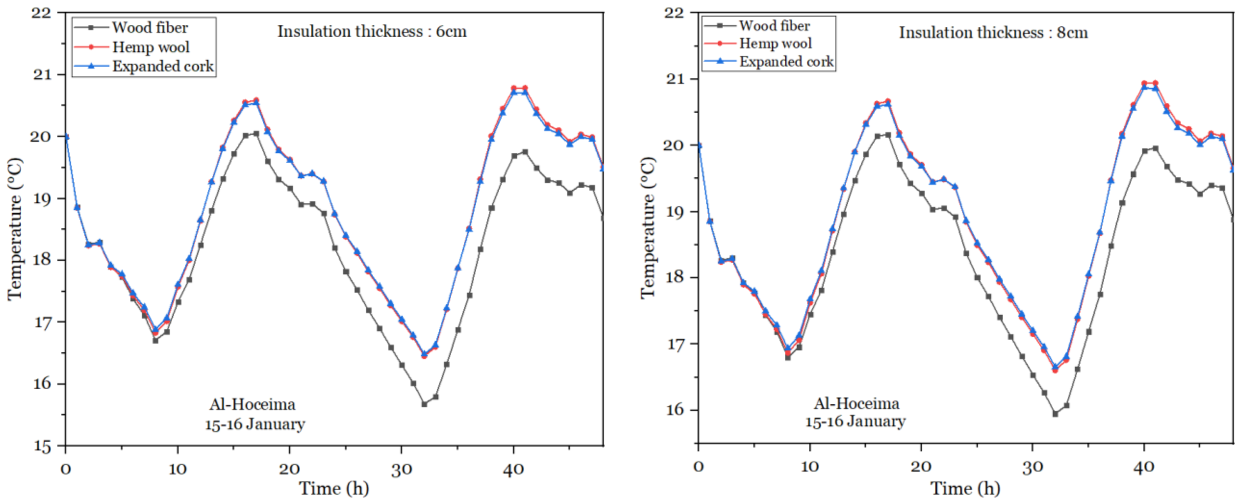
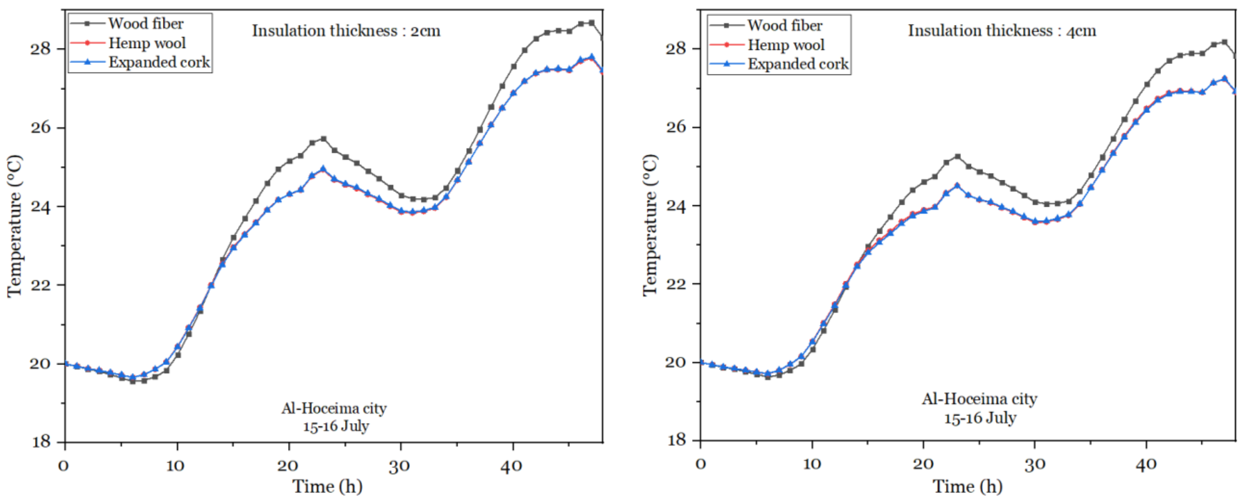


Fig. 9. Indoor temperatures as a function of different insulation thicknesses for two typical days in January

Similarly, for the two typical days in July, the thermal study involved the same three insulations with the same insulation thicknesses. The results in Figure 10 show that the maximum temperature inside chamber 4 is recorded for insulation using wood fiber, followed by expanded cork and then hemp wool. For an insulation thickness of 2cm, the temperatures recorded are 28.69°C for wood fiber, 27.81°C for expanded cork, and 27.78°C for hemp wool. For an insulation thickness of 8cm, the values are 27.56°C for wood fiber and around 26.80°C for expanded cork and hemp wool. Insulation with hemp wool and expanded cork is therefore recommended for good levels of thermal comfort in summer.



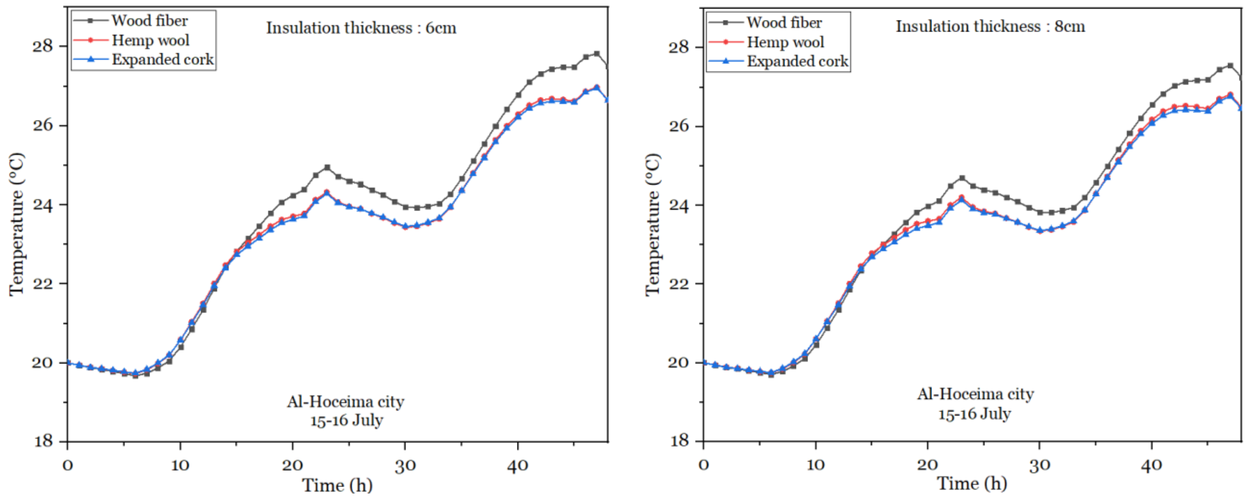


Fig. 10. Indoor temperatures as a function of different insulation thicknesses for two typical days in July

4.4 Economic and Environmental Impact of Using Insulation
4.4.1 Economic impact

Table 6 provides a summary of the energy savings achieved after applying 8cm of the three insulating materials mentioned above. Monthly energy consumption represents the average annual consumption over one year. The savings made on the building's energy requirements also have a direct impact on its electricity bill. To calculate the cost of the building's electricity consumption, Table 7 gives the price of a kilowatt-hour in Morocco according to the bracket system.

The results show that the greatest reduction in electricity bills is achieved by hemp wool insulation, with a contribution of 36.1%, followed by expanded cork and wood fiber insulation with reductions of 35.9% and 26.3% respectively. This can be explained by the fact that applying insulation using hemp wool saves the most energy, followed by expanded cork and wood fiber insulation.

Table 6
Savings on energy bills and electricity prices

Scenarios	Annual energy consumption (KWh/m^2.year)	Annual energy consumption (KWh)	Average monthly energy consumption (KWh)	Average monthly cost of electricity consumption (MAD)	Average monthly savings (MAD)
Without insulation	83,9	18122,4	1510,2	2409,9	-
Wood fibre insulation	61,81	13350,9	1112,5	1775,3	26,3%
Hemp wool insulation	53,56	11568,9	964	1538,3	36,1%
Expanded cork insulation	53,71	11601,3	966,7	1542,6	35,9%

Table 7
The price of a kilowatt-hour (kWh) in Morocco [28]

Consumption	0 - 100 kWh	101 - 150 kWh	151 - 200 kWh	201 - 300 kWh	301 - 500 kWh	> 500 kWh
Price per kWh in MAD	0.9010	1.0732	1.0732	1.1676	1.3817	1.5958
With : 1 MAD = 0,1 USD						

4.4.2 Environmental impact

In this section, we attempt to assess the environmental impact of applying insulation to the wall layer or building envelope. To measure or quantify this impact, we take into account that the building is an energy-intensive entity and that each kWh of electricity produced causes the emission of an equivalent quantity of carbon dioxide CO_2 of 0.743 kg [29]. Calculations of the equivalent quantity of CO_2 show that the building without insulation contributes to the emission of 13464.9 Kg/year, whereas the application of 8cm of insulation to the roof reduces these emissions by 4869.2 Kg/year in the case of hemp wool, 4845.2 Kg/year in the case of expanded cork and 3545.2 Kg/year in the case of wood fiber (Table 8).

Table 8
Reduction of CO_2 emissions

Scenarios	Annual energy consumption (KWh/m^2.year)	Annual energy consumption (KWh)	Annual CO_2 emissions equivalent (Kg)	Annual reduction CO_2 emissions (Kg)
Without insulation	83,9	18122,4	13464,9	-
Wood fibre insulation	61,81	13350,9	9919,7	3545,2
Hemp wool insulation	53,56	11568,9	8595,7	4869,2
Expanded cork insulation	53,71	11601,3	8619,7	4845,2

5. Conclusion

The present work represents a study aimed at evaluating the thermal and energy performance of the envelope of a typical residential building located in Al-Hoceima, Morocco. The study aims to minimize energy demand and improve the level of thermal comfort inside the building by acting on its envelope through the application of insulation using three bio-sourced materials: wood fiber, hemp wool, and expanded cork. Three insulation scenarios were examined, with insulation thicknesses ranging from 2cm to 8cm (in 2cm increments). The study was carried out as a series of energy simulations using TRNSYS simulation software, using the type 56 multi-zone model. The results of the simulations showed that the most appropriate insulation for the Mediterranean climate of Al-Hoceima is to insulate the roof with 8cm of hemp wool. Insulating with 8cm of hemp wool reduces the heating load by 35.2% and the cooling load by 36.7%. Thermal comfort levels have also been improved, with the maximum indoor temperature reaching 26.80°C in July and 20.94°C in January.

Finally, this work can be completed, firstly by integrating passive strategies in combination with bio-sourced insulation, and then by a more detailed technical-economic, and environmental study to propose more effective solutions and measures in energy, environmental and economic terms.

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