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Research Article

Towards the use of natural thermal insulation on the exterior of vertical building walls in desert regions: A case study in the city of Bechar, Algeria

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ABSTRACT

The use of natural-based exterior thermal insulation systems constitutes a significant challenge for achieving energy efficiency of construction. The purpose of this article is to propose new exterior thermal insulation solutions based on natural materials such as wood wool, cellulose wadding, expanded cork, hemp fiber, and sheep's wool, in order to minimize energy consumption, address durability concerns, maintain thermal comfort, and promote the use of natural materials in thermal insulation system designs. The methodology followed consists of presenting a comparative numerical study of different exterior insulation techniques (ETI) using a dynamic thermal simulator for desert regions. The study evaluated ETI systems for vertical walls attached to a concrete block wall, including one EPS system with coating (wet process) and six systems with cladding (dry process). The results show that applying exterior insulation to walls using the two cladding systems based on hemp fiber and sheep wool resulted in a total reduction in building energy consumption of 42.21% and 42.81%, respectively. These results confirm the effectiveness of natural materials in improving the energy performance of buildings, particularly the system based on sheep wool.

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INTRODUCTION

In the context of constructions, natural convection [1] is an important process for air circulation inside a building, occurring when hot air rises and creates a low-pressure area near the ceiling, which leads to the suction of fresh air through building openings such as windows and doors. This natural air movement can help regulate the temperature and air quality inside a building without relying on heating or air conditioning systems. It should be noted that natural convection can also be influenced by the topology of the building, the position of windows, orientation, solar exposure, and the type of thermal insulation. This requires a well-designed building to make the most of natural convection. As a result, it should be considered as part of a comprehensive design strategy that takes into

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account all aspects of ventilation and air conditioning to ensure good indoor air quality, reduced energy costs, and optimal building performance. Researchers are therefore attracted to studying natural convection in all possible aspects, and we find some applications in which the latter is, such as: solar collector, heat exchanger, cooling of electronic devices, heating, ventilation and air conditioning (HVAC) systems [2-4].

In fact, the type of thermal insulation used on exterior walls can have a significant impact on air circulation inside a building (natural convection). However, poor thermal insulation can increase the heating load required to maintain a comfortable temperature inside the building. On the other hand, good thermal insulation of exterior walls can contribute to reducing drafts and improving natural convection in a building, as well as reducing energy costs and improving occupant comfort and overall energy efficiency of the building [5].

However, the use of energy in the building has continued to increase in recent years due to the rising demand of energy used for the heating and the air conditioning or still various human activities [6]. According to statistics from the International Energy Agency (IEA), buildings are responsible for 32% of total final energy consumption and represent more than 40% of primary energy consumption in most IEA countries [7]. Based on different authors [8, 9 and 10], the improvement of the thermal behavior of buildings depends on the parameters of optimization of the thermal quality of envelope as: the external insulation of vertical or horizontal walls, glazing orientation, the shading system, the use of building materials with high thermal and increasing the thickness of external walls or insulation.

The current construction practices in Algeria (collective habitats, individual, offices ... etc.), do not sufficiently consider the importance of thermal insulation of the building envelope to minimize excessive energy consumption required to maintain thermal comfort inside these buildings (poor thermal behavior), especially during the summer period that can last up to five months in the Saharan regions [11]. Therefore, improving the energy performance of residential buildings is crucial, given the rising cost of energy consumption. However, there is an increasing focus on promoting solutions and techniques for optimizing the building envelope, such as external thermal insulation (ETI) of vertical walls, to achieve significant energy savings [8]. ETI is an effective solution that can provide better thermal comfort regardless of the climatic conditions, while minimizing energy consumption, maintaining user comfort, and preserving habitable space.

There are currently three main techniques for applying (ETI) to walls: under coating, under cladding, and under veneer or siding. Various solutions or variants have been proposed allow for making a relevant choice ensuring reliable hygrothermal behavior and reducing durability issues. However, a question arises: what are the effects of introducing natural materials in ETI on the thermal behavior and energy consumption of local buildings? In order to answer this question, the main objective of this article is to study the improvement of thermal behavior and potential energy savings in local buildings by proposing ETI techniques for a vertical concrete block wall. To achieve this, we used different ETI techniques: a system with expanded polystyrene (EPS) under coating and six systems with natural materials under cladding, to achieve better energy and economic performance in the construction sector."

METHODOLOGY

The method followed involved examining a residential building using several External Thermal Insulation (ETI) systems for the vertical walls based on natural materials such as wood wool, cellulose wadding, expanded cork, hemp fiber, sheep's wool, and a single synthetic material: expanded polystyrene. Knowing that the numerical simulation was conducted using a dynamic thermal simulator called "TRNSYS." This simulator comprises several programs: the TRNSYS Simulation Studio, the simulation engine (TRNDll.dll) and its executable (TRNExe.exe), the building input data visual interface (TRNBuild.exe), and the Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe) [12].

The thermal behavior of the building under study was simulated using a transient modeling method called TYPE 56 with a time step of 1 hour. The building model in TYPE 56 is a non-geometric balance model that includes one air node per zone representing the thermal capacity of the zone's air volume and other closely connected capacities, such as furniture. Therefore, in addition to the zone volume, the node capacity is also considered as a separate input.

TRNBuild was used to enter the necessary information for simulating the building, including the description of the envelope (materials, layer thicknesses, and thermophysical parameters), windows, heating/cooling systems, ventilation, infiltration, gains and occupancy rate...etc.

Knowing that the assumptions adopted for the numerical simulation are:

- The initial temperature and humidity are set at 20°C and 50% respectively;
- Internal generation is null (unoccupied building);
- The effect of thermal bridges and shading is not considered;
- The heating and cooling needs of the building are determined based on a set point temperature of 20°C for heating and 26°C for cooling.

The determination of the ideal thermal conditions for the environment of the present study was carried out according to the ISO 7730 standard [13]. For this, we used a comfort temperature of 20°C to 25°C in winter and 23°C to 26°C in summer. Thus, the set point temperatures in our residential building were chosen as 20°C for heating and 26°C for cooling according to the ASHRAE society [14].

The heat balance at each node of the network is shown in Figure 1 [15].

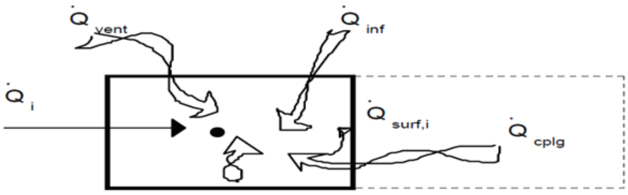


Figure 1. Heat balance on the zone air node – TRNSYS

It can be expressed as follows:

$$\dot{Q}i = \dot{Q}inf,i + \dot{Q}vent,i + \dot{Q}cplg,i + \dot{Q}surf,i \qquad (1)$$

$\dot{Q}_i$ is the global energy flow for node i,

$\dot{Q}_{inf,i}$ is the energy flow from air infiltration from outside to node i, given by:

$$\dot{Q}_{inf,i} = \dot{V}_{inf,i} \times \text{r} \times c_p \times (T_{out} - T_{in}) \qquad (2)$$

Where $\dot{V}_{inf,i}$, ρ, C_p, T_{out} and T_{in} are the air flow entering zone i through the opening, density of air, specific heat capacity of air, air temperature outside the zone and air temperature inside the zone respectively.

$\dot{Q}_{vent,i}$ is the energy flux induced by the ventilation of the room or rooms comprising node i via HVAC systems, given by:

$$\dot{Q}_{vent,i} = \dot{V}_{vent,i} \times \text{r} \times c_p \times (T_{vent,i} - T_{in}) \qquad (3)$$

Where $\dot{V}_{vent,i}$ and $T_{vent,i}$ are the airflow entering zone i through mechanical ventilation and temperature of the air entering zone i through mechanical ventilation respectively.

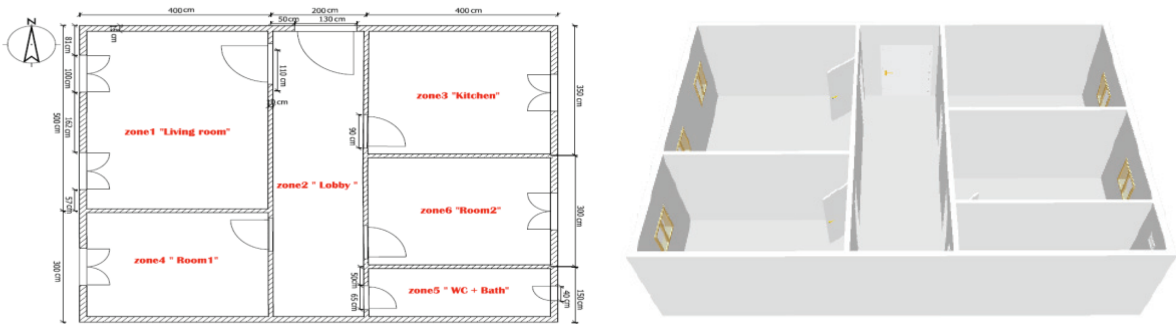
$\dot{Q}_{cplg,i}$ corresponds to the energy flows due to the air transfers of zone i or the boundary condition, given by:

$$\dot{Q}_{cplg,i} = \dot{V}_i \times \text{r} \times c_p \times (T_{zone,i} - T_{in}) \qquad (4)$$

Where $\dot{V}_i$ and $T_{zone,i}$ are the volume of comfort zone i and temperature of comfort zone i respectively.

$\dot{Q}_{surf,i}$ is the net energy flow from each surface delimiting node i towards it.

The terms $\dot{Q}_{inf,i}$ $\dot{Q}_{vent,i}$ $\dot{Q}_{cplg,i}$ correspond to the energy losses by ventilation and infiltration, applied to the study area.



(a) (b)

Figure 2. Architectural plans of the reference building. Author source (a): Plan view, (b): 3D view.

Table 1. Thermo-physical characteristics of materials used in ETI systems for vertical walls

	Thermo-physical characteristics (conductivity, specific heat and density)		
Materials	**λ (W/m. k)**	**Cp (J/kg. k)**	**D (kg/m³)**
Glue mortar [17]	0,900	1000	1600
Expanded polystyrene [18]	0,038	1404	35
Polyurethane coating [18]	0,40	1404	1650
Wire mesh [18]	52	468	7780
Wood wool [19]	0,042	1700	140
Timber frame [18]	0,15	1512	550
Air space [20]	0,025	1008	1,23
Wood cladding [18]	0,07	1512	250
cellulose wadding [19]	0,042	1900	70
Expanded cork [18]	0,044	1512	150
Rain-screen (Sd = 0,1) [19]	2,300	2300	130
Hemp fiber [17]	0,040	1550	45
Sheep wool [21]	0,035	1000	13

Table 2. Description of building materials for the reference building envelope, (from interior to exterior)

Envelope	Description	e (mm)	λ (W/m. k)	Cp (J/kg. k)	D (kg/m³)	Ep (cm)	U- value (W/m².k)
	Internal plaster coating [18]	20	0,35	936	1000		
External walls	Hollow concrete block [18]	150	1,10	1080	1300	19	2,986
	Exterior cement coating [18]	20	1,4	1080	2200		
Adjacent walls	Plaster coating [18]	20	0,35	936	1000		
	Hollow brick [18]	100	0,48	936	900	14	2,030
	Plaster coating [18]	20	0,35	936	1000		
	Tiling [18]	20	2,1	936	2200		
	Cement mortar [18]	20	1,4	1080	2200	35	2,594
Low floor in contact with the ground	Sand and gravel [18]	50	1,2	792	1800		
	Heavy concrete [18]	250	1,75	1080	2500		
	Cement mortar [18]	10	1,4	1080	2200		
	Cement coating [18]	20	1,4	1080	2200		
	Hollow slab block [18]	160	1,10	1080	1300		
Roof	Heavy concrete [18]	40	1,75	1080	2500	31	2,392
	Sand and gravel [18]	50	1,2	792	1800		
	Cement mortar [18]	20	1,4	1080	2200		
	Tiling [18]	20	2,1	936	2200		
Exterior carpentry	Thermal transmission coefficient U-value (W/m².k)			Solar factor g-value %			
Single glazed wooden window	5,8			0,855			
Wooden entrance door	1,8			0,589			

Finally, the term $\dot{Q}_{surf,i}$ regroups the heat transfers through the walls.

The description of the reference building is presented in Figure 2. It is to be noted that the present built is located in the city of Bechar which is situated 1150 km southwest of the capital Algiers with an altitude of 773 m above sea level [16]. This building has a surface area of 80 m² and a volume of 240 m³. The description of its envelope and the thermo-physical characteristics of the building materials are given in Table 2. It is worth noting that the insulation materials used are listed in Table 1 and the various representations of the ETI systems are illustrated in Figures 3 to 10.

In the context of this numerical study, it should be noted that we have taken into account the factors related to the

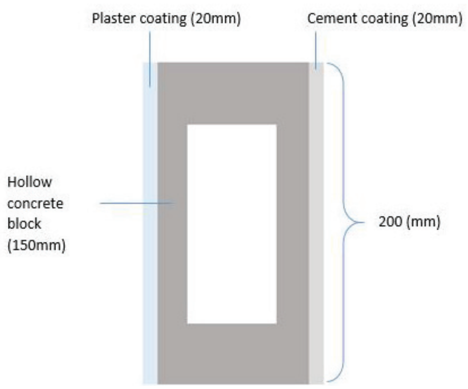


Figure 3. Reference wall (uninsulated). Author source Ep = 19 cm, U = 2.647 W/m². K.

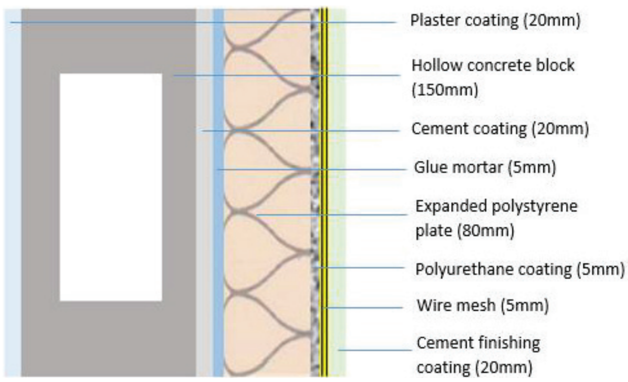


Figure 4. Wall insulated with expanded polystyrene. Author source Ep = 30.50 cm, U = 0.398 W/m². K.

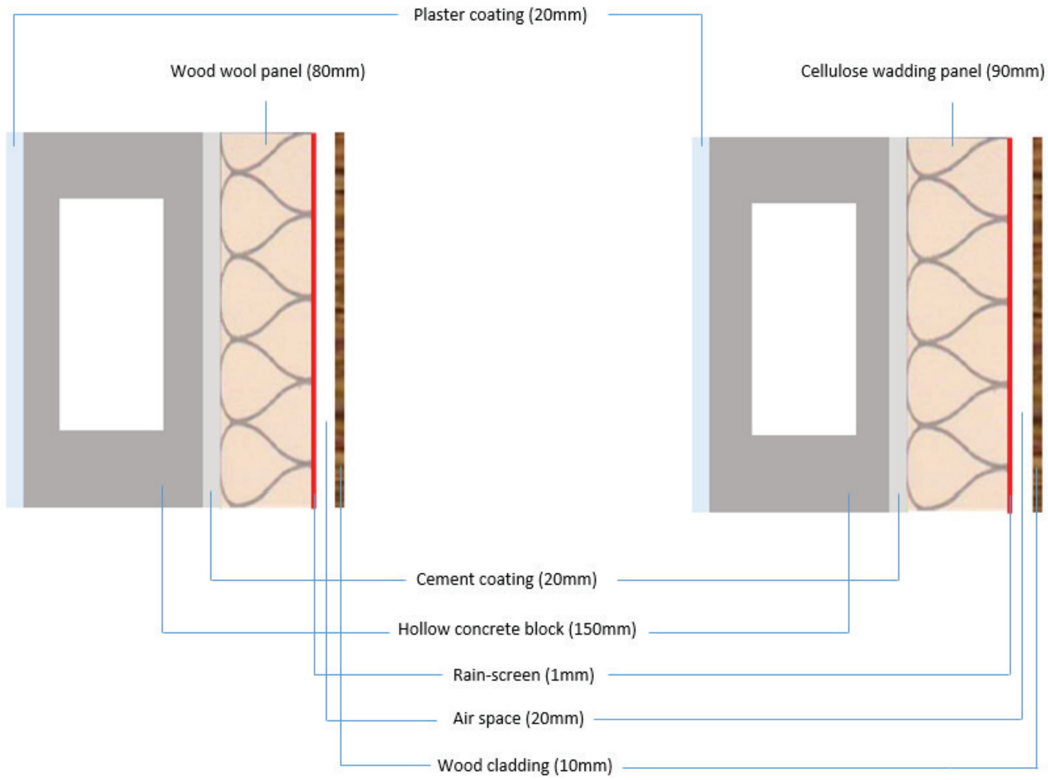


Figure 5. Wall insulated by wood wool. Author source
Ep = 30,10 cm, U = 0,310 W/m². K.

Figure 6. Wall insulated by cellulose wadding. Author source
Ep = 31,10 cm, U = 0,288 W/m². K.

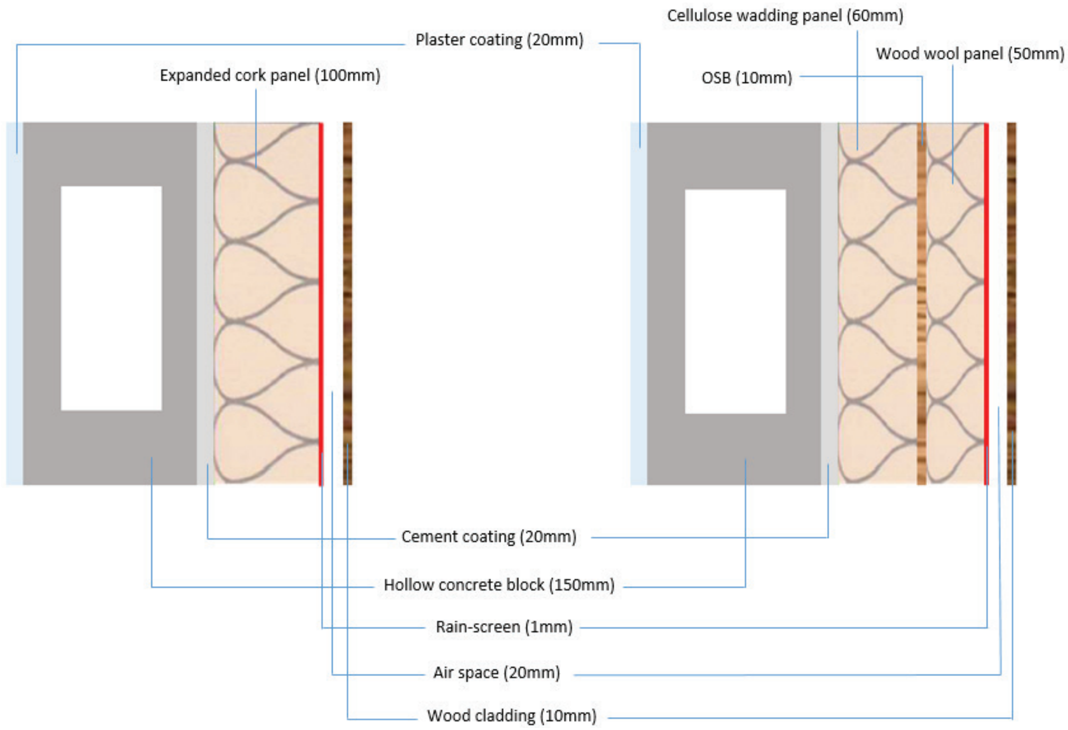


Figure 7. Wall insulated with expanded cork. Author source
Ep = 32,10 cm, U = 0,278 W/m². K.

Figure 8. Wall insulated by (cellulose wadding + wood wool). Author source
Ep = 34,10 cm, U = 0,249 W/m². K.

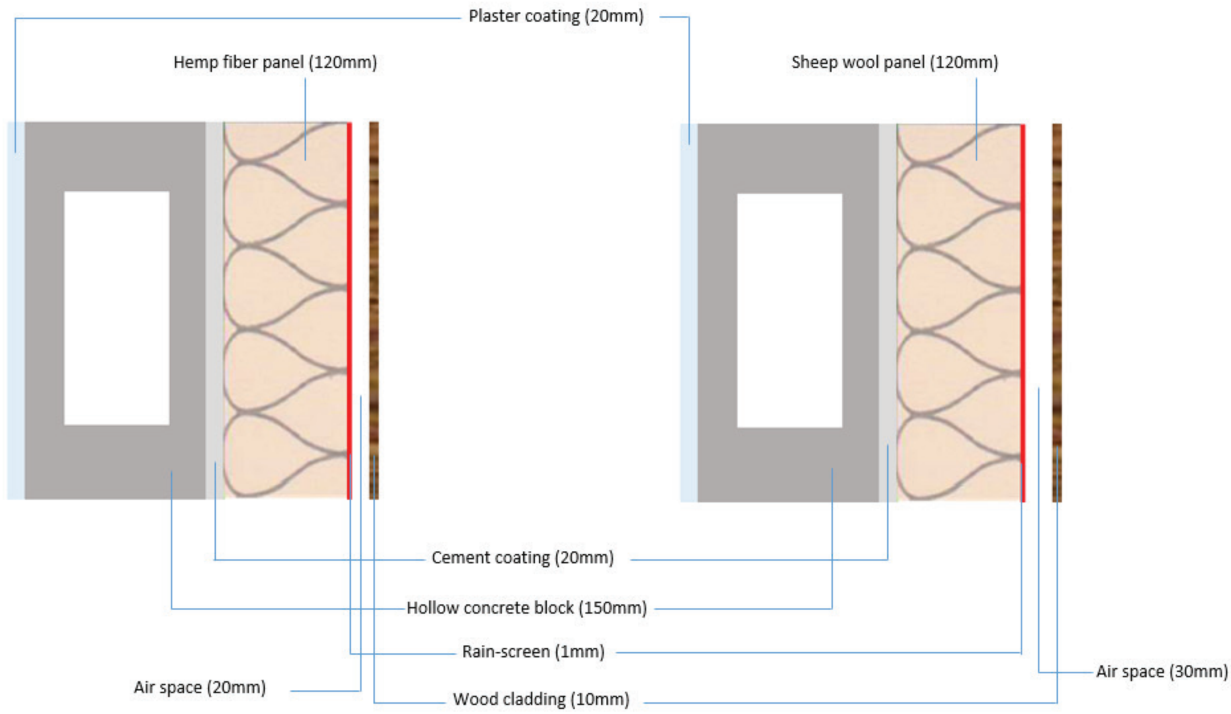


Figure 9. Wall insulated by hemp fiber. Author source Ep = 34,10 cm, U = 0,231 W/m². K.

Figure 10. Wall insulated by sheep wool. Author source Ep = 35,10 cm, U = 0,194 W/m². K.

exposure of the materials used to risks of fire and insect reproduction, as shown by sheep's wool of biological origin. Furthermore, this insulation (sheep's wool) was applied as a semi-rigid board, rather than in bulk, which also reduces the risk of fire. On the other hand, for the natural insulations used (cellulose wadding and sheep wool) have been protected against several hazards, including fire, insects, and mold, by using borax salt, a simple mineral substance extracted from certain borax-rich rocks, also it acts as a natural fungicide and insecticide, thus protecting against mold and insects. Additionally, it has fire-retardant properties [22], making it an excellent choice for fire protection.

RESULTS AND DISCUSSION

This last section is devoted to presenting the results obtained by the various procedures described above. It is important to note that during the processing of numerical results, depending on the scenario studied and the type of material used (synthetic or natural), a comparison will frequently be made with the reference state, which includes all thermo-physical characteristics (thermal conductivity, thermal capacity and density), at ambient temperature. This knowledge is essential for determining the variation of the property studied with respect to the measurement temperature. To achieve this, throughout all presentations of the results obtained, the relative ratio and percentage deviation of the property studied will be calculated to determine the rate of dephasing recorded at a given temperature relative to the reference temperature. To accomplish this, we first present the evolution curves of the exterior and interior temperatures over time during the two respective winter and summer periods. These correspond to the coldest and hottest day of the year 2022 (January 7th and July 22nd), as shown in Figures 11(a) and 11(b). From these representations, we can clearly observe that there is a problem with comfort and a significant thermal loss.

The curves of the variation of the indoor temperature as a function of time for the different scenarios followed, during the two daily periods, "winter" and "summer" (24 hours), are shown in Figures 12(a) and 12(b) respectively. From these figures, we mainly notice that the indoor temperature, for all types of tested scenarios, varies over time and according to the studied period. For the two tested periods, the indoor temperature for the different scenarios is clearly higher than that recorded at the reference temperature, with a maximum dephasing reaching values lower than 3.10°C. We observe that natural-based systems show better results for both studied periods (winter and summer). Therefore, the effect of natural-based systems is more effective than the synthetic-based system (expanded polystyrene) with a thermal lag of 0.19°C.

In contrast, the evolution of the thermal resistance of different insulation according to their thickness is shown

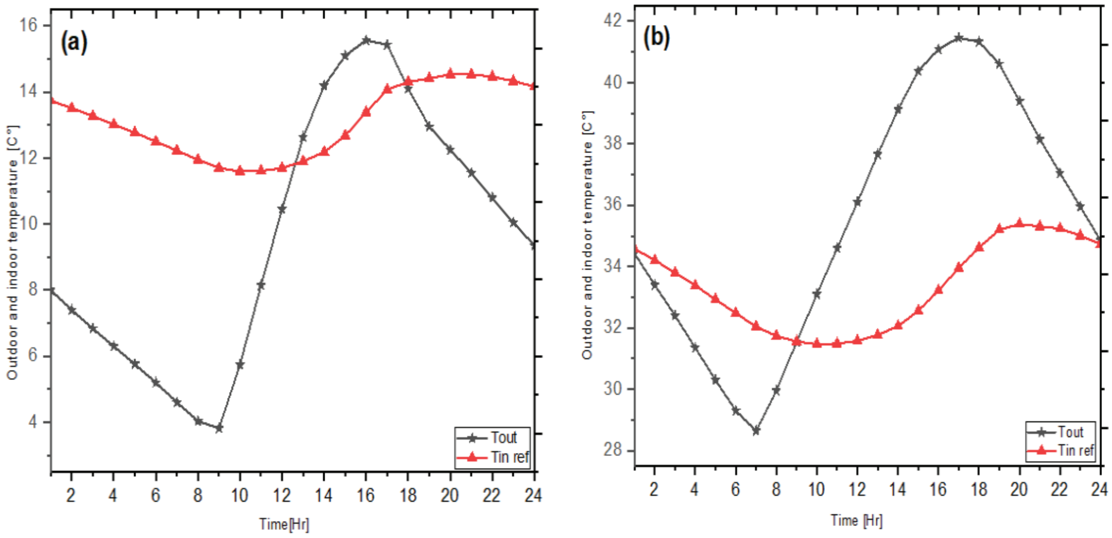


Figure 11. Evolution of the outdoor and indoor temperature as a function of time in the northern zone "living room". (a): Winter period, (b): Summer period.

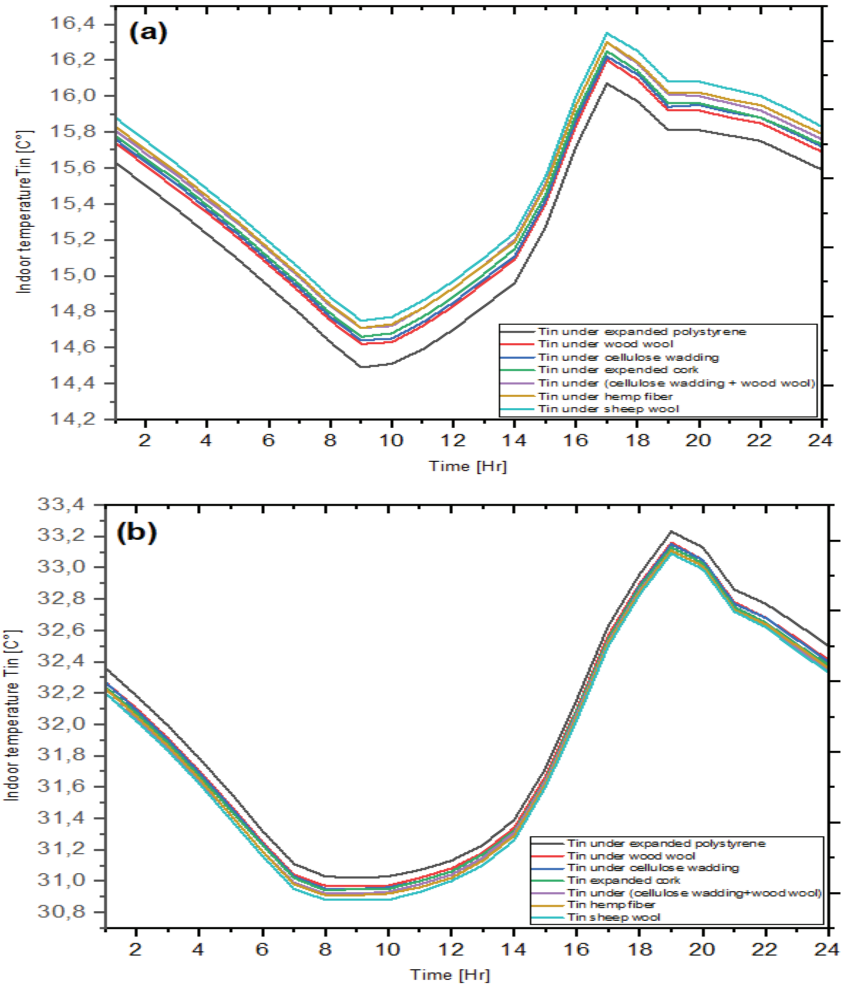


Figure 12. Evolution of the indoor temperature as a function of time for the different scenarios of the northern zone "living room". (a): Winter period, (b): Summer period.

in Figure 13. We can observe essentially that the increase in thermal resistance is mainly correlated with an increase in thickness for each type of insulation.

According to various authors [23-25], the thicker the thermal insulation, the lower the heat transfer through it, and therefore the higher the thermal resistance because R

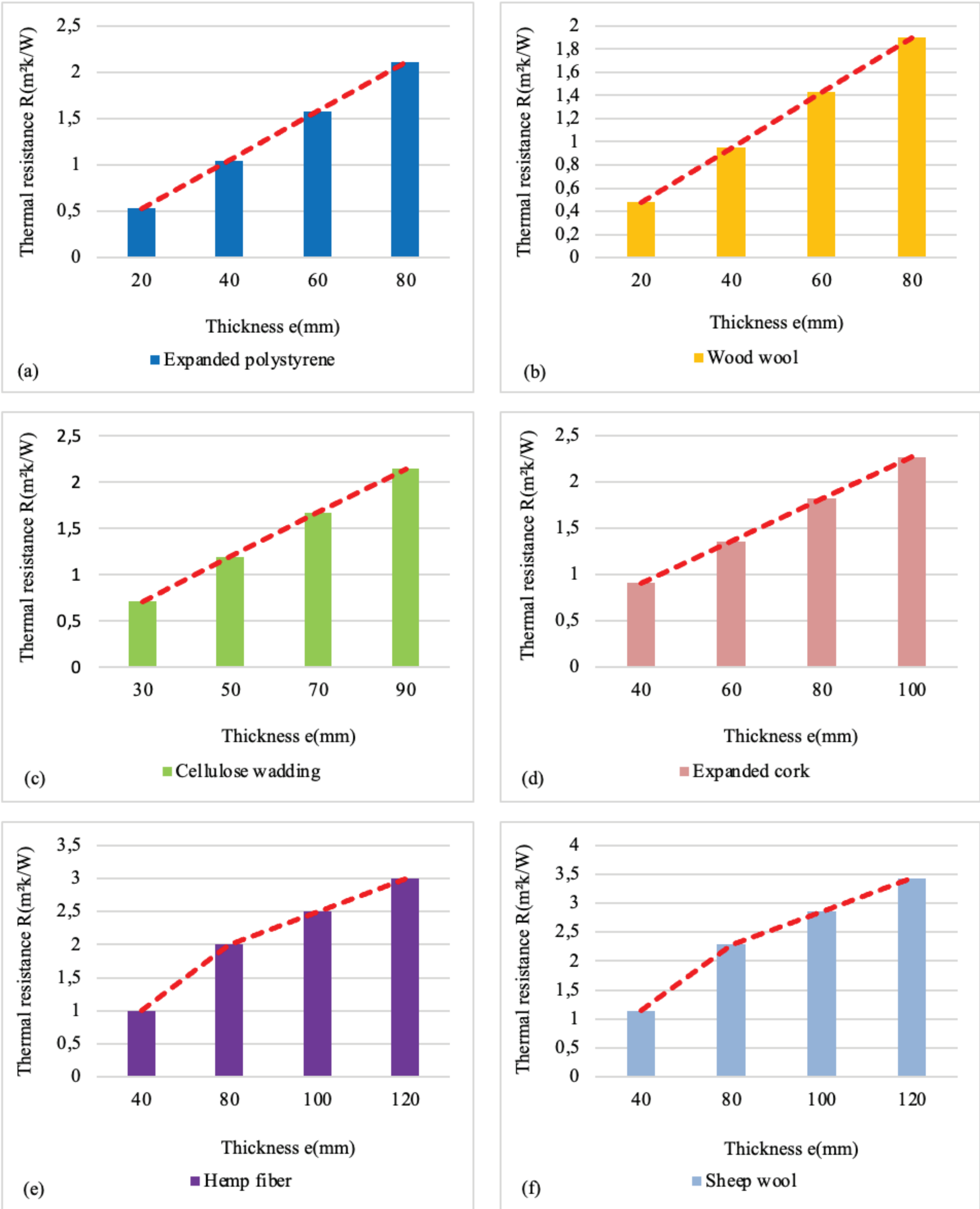


Figure13. Evolution of the thermal resistance of insulators according to their thickness. (a): Expanded polystyrene, (b): Wood wool, (c): Cellulose wadding (d): Expanded cork, (e): Hemp fiber, (f): Sheep wool.

= 1/U (m^2. k/W). On the other hand, the thermal conductivity does not depend on the thickness of the insulation, which rather affects its thermal resistance [25]. Based on Lakatos & al's research., the thermal conductivity of expanded materials was found to be dependent on thickness [23]. They proved that the thermal conductivity does not depend on the thickness of the samples, Unlike the values of thermal resistance, which increase compared to the data calculated from the measurement. Another study conducted on sheep wool [26] indicated that thermal resistance increases with the increase in sample thickness from 40 to 80 mm at different average temperatures. In our study, we can conclude that the minimum resistance was recorded by wood wool R=1.90 m^2. k/W with a thickness of 8 cm, and the maximum thermal resistance was recorded for sheep wool R=3.43 m^2. k/W with a thickness of 12 cm, which clearly shows a dependent relationship between thermal resistance and thickness for this type of insulation.

In order to better analyze the results obtained, we have grouped together the variation in thermal conductivity as a function of density for the different categories of insulation tested and presented them in Figure 14. From these histograms, we can observe a proportional relationship between the thermal conductivity of the insulations studied and their densities. Specifically, we observed an inverse relationship for "expanded polystyrene" and a direct relationship for the following insulations: "sheep's wool, hemp fiber, cellulose wadding, wood wool, and expanded cork."

The use of expanded polystyrene resulted in an increase in density and a lower thermal conductivity value. This phenomenon can be explained by the reduced volume of air within the material, which reduces heat transfer by convection and subsequently lowers the thermal conductivity values. Similar results have been reported by various authors [27,28], who have attributed this correlation to the structure of the insulating material and the testing methodology employed. However, for natural-based thermal

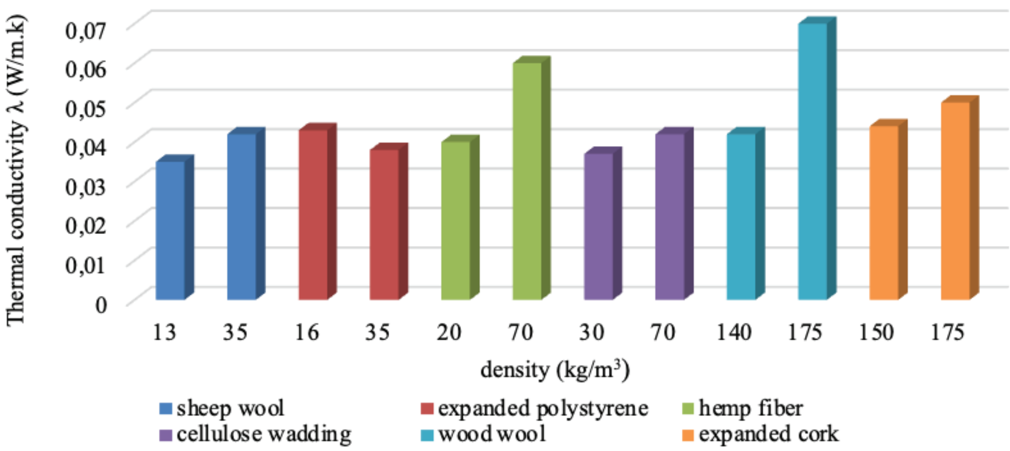


Figure 14. Evolution of the thermal conductivity of insulators as a function of their density.

Table 3. Annual heating and cooling requirements of the reference building and the Eco index for each improvement scenario

		Wall insulation systems (ETI)						
		Under coating by:	Under cladding by :					
Scenario type	**Reference building**	**Expanded polystyrene**	**Wood wool**	**Cellulose wadding**	**Expanded cork**	**Cellulose wadding + Wood wool**	**Hemp fiber**	**Sheep wool**
Heating [kWh]	8040	4074	3923	3889	3869	3821	3794	3733
Cooling [kWh]	8621	6019	5920	5897	5885	5851	5835	5796
Total (Heat+Cool) [kWh]	16661	10093	9843	9786	9754	9672	9629	9529
Total (Heat+Cool) [kWh/m^2.year]	208,26	126,16	123,04	122,33	121,93	120,90	120,36	119,11
Ieco [kWh/m^2. Year]	-	82,10	85,22	85,93	86,33	87,36	87,90	89,15
Reduction %	-	39,42	40,92	41,26	41,45	41,95	42,21	42,81

Table 4. Cost of each insulation material and the ETI technique applied

Technique	**Under coating**	**Under cladding**					
Insulation materials	**Expanded polystyrene (80 mm)**	**Wood wool (80 mm)**	**Cellulose wadding (90 mm)**	**Expanded cork (100 mm)**	**Cellulose wadding (60 mm) + Wood wool (50 mm)**	**Hemp fiber (120 mm)**	**Sheep wool (120 mm)**
Overall cost of insulating materials [DZD/m²]	1120,50	2100	2454	3930	2949	2304	2772
Overall cost for each ETI technique [DZD/m²]	3473,30	4194,33	4548,33	6024,33	5289,27	4221,87	4866,33

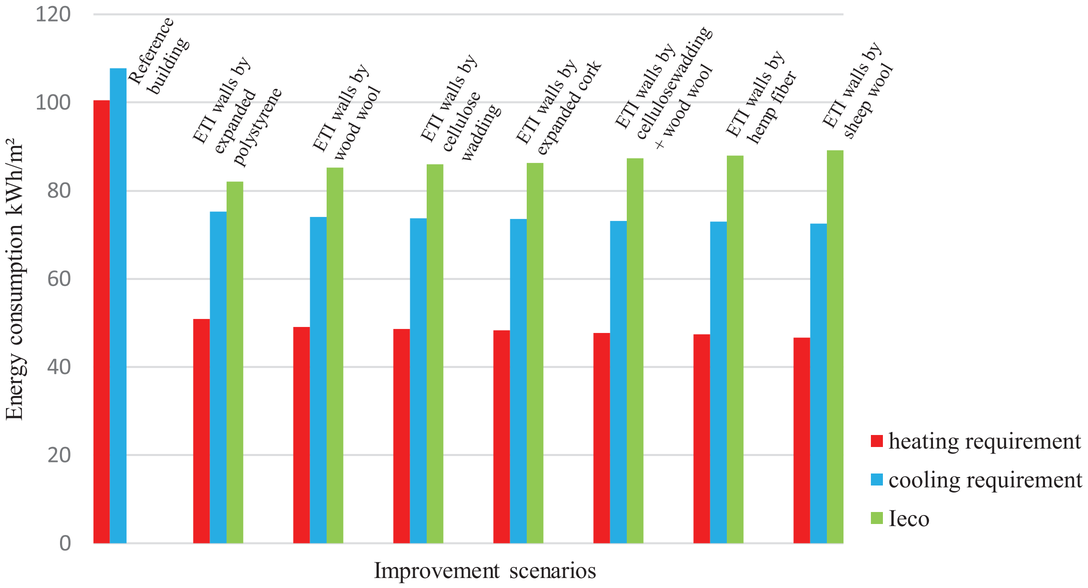


Figure 15. Annual energy requirements in kWh/m². Year and eco index for each improvement scenario.

insulation systems, higher density values correspond to higher thermal conductivity values. This trend has also been observed in several studies [29-33] that utilized natural fibers such as hemp, sheep's wool, bamboo, rice straw, and jute fiber.

It should be noted that this finding of proportionality between thermal conductivity and density for natural-based insulating materials can also be derived inversely. This was highlighted in the study conducted by Kosinski et al. [34], which focused on thermal insulation materials like hemp fibers. The study found an inverse proportionality between thermal conductivity and density. Specifically, the variation showed that there is an optimal density point at which thermal conductivity is minimized.

The values of the annual heating and cooling requirements of the reference building in addition to the Eco Index for each improvement scenario are summarized in Table 3 and illustrated in Figure 15. It is to be noted that the Eco index represents the difference between the heating and cooling needs of the reference building and the scenario tested.

Based on the achieved percentage of energy savings (for heating and cooling), it is necessary to conduct an economic comparison to confirm the economic viability of the presented insulation materials mentioned above. In this regard, we provide an economic comparison in Table 4 and Figure 16, considering the overall cost of each insulation material and the applied ETI technique. These results clearly demonstrate the positive impact of utilizing such insulation materials in enhancing the energy performance of the analyzed building, in order to better analyze the results obtained for the various thermal insulation materials tested.

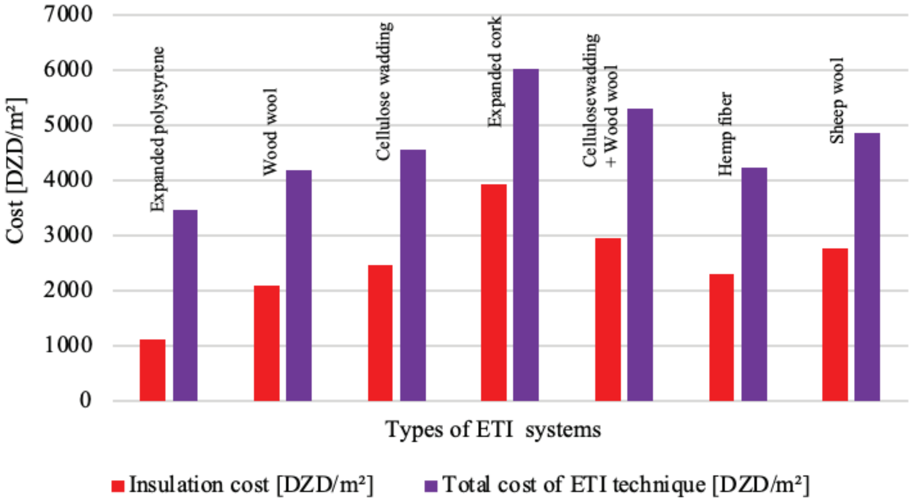


Figure 16. Ultimate cost of insulation materials and the various ETI techniques used.

CONCLUSION

In this paper, we have proposed external thermal insulation techniques for vertical walls of local buildings in hot and arid areas. We present a system using under coating (wet process) with expanded polystyrene (EPS) and six systems under cladding (dry process) using insulating materials of natural origin, in order to improve the energy performance, comfort and possible energy savings in residential buildings in Bechar. To accomplish this, we conducted a numerical simulation using TRNSYS software which yielded the following syntheses:

- The ETI techniques for vertical walls, presents a very important reduction in energy consumption (improved thermal behavior of envelope);
- Natural based materials offer better thermal insulation efficiency than synthetic materials, provided that the thickness of the insulator is taken into account;
- The most effective ETI technique among those proposed in terms of energy savings is the ETI system using sheep wool cladding, which reduces energy consumption by 42.81% with an average investment cost around 4866,33 DZD/m² from the economical view.

The reasons why the system of insulation under cladding based on sheep's wool outperforms all the other proposed systems, can be explained as follows:

- The thickness and nature of the thermal insulator and the overall composition of the insulation system. In particular, a 12cm-thick panel of sheep wool was used, making it the thickest insulation material studied and improving the efficiency of the system
- Sheep's wool has good physical and thermal properties compared to the other insulation materials studied, particularly its thermal conductivity coefficient (λ = 0.035 W/m. k), which is the lowest among all the materials proposed (expanded polystyrene, wood wool, cellulose wadding, expanded cork and hemp fiber).

It should also be noted that the system of insulation under cladding is characterized by the presence of an additional insulating layer represented by air, which is a good insulator due to its low coefficient of thermal conductivity (λ = 0.025 W/m. k), contrary to the system under coating. In the case of the system under cladding based on sheep wool the thickness of the air layer was increased by 1 cm compared to other insulation systems under cladding, which allowed the system in its total composition to have a heat transmission coefficient lower than that of other systems (U = 0.194 W/m². k) and therefore, it was selected as the best system of thermal insulation and energy saving.

However, the findings from the different systems studied paved the way for several future research directions:

- Developing a thermal insulation system for the roof based on natural materials and studying its hygrothermal and energetic behavior;
- Studying the coupling of external thermal insulation of the vertical walls and the roof with the aim of passing from a high energy performance building (from 91 to 151 kWh/m². Year) to an economical building (< 50 kWh/m². Year);
- Comparing the thermo-physical properties of sheep wool with the properties of mineral wool and glass wool, which are widely used as natural thermal insulators of inorganic origin.

NOMENCLATURE

IEA	International Energy Agency
EPS	Expended Polystyrene
ETI	External Thermal Insulation
OSB	Oriented Standard Boards
TRNSYS	Transient System Simulation program

ISO	International Organization for Standardization
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
HVAC	Heating, ventilation and air conditioning systems
DZD	Algerian dinar
e	thickness of material, mm
R	thermal resistance, m^2. k/W
C_p	specific heat capacity, J/kg. k
D	density of the material, kg/m^3
T_{out}	outdoor temperature, °C
T_{in}	indoor temperature, °C
$T_{zone,i}$	temperature of comfort zone i, °C
$T_{vent,i}$	temperature of the air entering zone i through mechanical ventilation, °C
$\dot{V}_{inf,i}$	air flow entering zone i through the opening, m^3/s
$\dot{V}_{vent,i}$	airflow entering zone i through mechanical ventilation, m^3/s
$\dot{V}i$	volume of comfort zone i, m^3
Ep	total wall thickness, cm
U	thermal transmission coefficient, W/m^2. k
g	solar factor, %
Ieco	economic index, Wh/m^2. year

Greek symbols

λ	thermal conductivity, W/m. k
r	density of air, kg/m^3

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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