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Multi criteria study of thermal insulation techniques based on natural insulators for exterior walls of buildings

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Abstract

The objective of this paper is to propose different solutions and techniques for local residential constructions in desert regions characterized by a hot and arid climate. These solutions aim to solve the problem of thermal discomfort of the occupants during winter and summer, and to minimize energy loads due to heating and cooling systems. This can lead to significant long-term annual energy savings. To achieve this goal, three conventional external thermal insulation (ETI) systems for opaque walls based on natural insulators (hemp fiber and sheep wool) under different techniques (under coating, under cladding, and a combination of the two insulators) were selected. The evaluation and study of these ETI systems was carried out using "TRNSYS" software. A technical-economic study was also carried out for all the systems tested, in order to determine the actual savings achieved. The results obtained show that the combined insulation system (hemp fiber and sheep wool) is the best performing solution among the proposed systems, with an average cost.

Keywords: Desert regions, Residential, Consumption, External insulation, Natural materials, Economic study

1. Introduction

Indeed, the current construction practices in Algeria do not consider the true significance of thermal insulation of the envelope [1-3] as an efficient solution. This minimizes the excessive consumption of the energy used. While it is becoming more and more common to promote solutions and techniques for the optimization of the building envelope [4-7], that is represents an important potential for energy savings [8, 9], in order to ensure a certain thermal comfort [10-12].

Numerous alternative solutions have been proposed to address these challenges and mitigate sustainability issues [13-15]. Tailoring these solutions to the specificities of each country and the nature of the building under study has resulted in several strategies to enhance thermal insulation and reduce energy consumption in buildings [16-20]. It is noteworthy that the high cost remains a significant obstacle to effectively implementing these solutions and achieving the objectives aimed at understanding the thermal behavior of the studied buildings. This situation creates a major contradiction between energy efficiency and the overall cost, contributing to an energy performance gap.

On the other hand, the utilization of natural insulation materials [15, 16] in building thermal insulation is gaining prominence due to their appeal, renewable and recyclable nature, environmental friendliness, increased sustainability, health benefits, and lower energy requirements for manufacturing compared to traditional materials. These materials, derived from natural resources such as cellulose, coconut, flax wool, hemp, recycled cotton, sheep's wool, wood wool, and expanded cork, are increasingly replacing traditional materials. Some of these alternatives boast comparable thermal properties and may offer enhanced thermal and moisture buffering capabilities.

In the existing literature, numerous studies have explored thermal insulation materials based on natural fibers. A notable example is the FITNESs: Sustainable Insulating Panels Made from Sheep's Wool and Hemp, conducted by Pennacchio et al. [21], in 2017. This study focuses on the fabrication of an experimental insulation panel using hemp and sheep's wool. Subsequently, tests were conducted on this experimental panel, including thermal conductivity, acoustic absorption coefficient, and heat transmission, in order to demonstrate the effectiveness of FITNESs panels as insulation products for buildings. The results of the experimental measurements show that FITNESs is a competitive product in terms of thermal conductivity, comparable to other products in the thermal insulation materials market, and it exhibits significant acoustic absorption performance. Another study was conducted by Zach et al. [22] in 2012, evaluating the performance and seeking alternative thermal insulators based on sheep's wool. The study was based on the development of experimental samples using sheep's wool, followed by testing the insulation and acoustic properties of these samples under various conditions. The experimentally obtained measurement results show that sheep's wool insulation has characteristics comparable to mineral wool and rock wool insulation and, in some applications, even outperforms them. Additionally, sheep's wool is characterized by high hygroscopicity, reaching up to 35%, and as a result, its high moisture absorption capacity prevents condensation, regulates humidity, and creates a pleasant indoor atmosphere. Gaujena et al. [23], in 2020, analyzed the hydrothermal properties of hemp based

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thermal insulation boards. The study is based on comprehensive measurements and the analysis of thermal conductivity, drying dynamics, and water absorption using experimental insulation samples made from fibers obtained from hemp stalks with dimensions of 300×300 mm. The results obtained show that the average thermal conductivity of the test samples ranged from 0,0544 to 0,0594 W/m. K. However, the values obtained were much higher than those of traditional thermal insulation materials, allowing for the use of local agricultural residues and providing materials for environmentally friendly building construction.

The cumulative evidence from previous literature confirms the effectiveness of these natural materials in thermal and acoustic insulation for constructions, highlighting their superiority over traditional materials. Furthermore, natural-based insulation materials present a more environmentally friendly and less harmful aspect to health. In this context, the objective of this study is to propose a range of exterior thermal insulation techniques based on natural materials for building walls. The proposal encompasses three systems: a single system under coating based on hemp fiber and two systems under cladding based on (sheep's wool) and (sheep's wool + hemp fiber), respectively. Subsequently, a technical-economic study was conducted, estimating "heating" and "air conditioning" energy consumption in the tested building. This study includes investment costs for all proposed thermal insulation systems, total prices (gas + electricity) given in units of (Algerian Dinars/year), and savings achieved for each insulation system studied. The successful results encourage the continuation of this study and offer insights into achieving a balance between energy efficiency and the cost necessary for practical implementation of the proposed thermal insulation systems.

2. Methodology

In this study, the building studied was chosen according to the specificity and needs of the present study. It is a residential building located in an arid desert region. The description of the geometric characteristics for the reference building and the different facades to be insulated (East, South, and West) are presented in Table 1 and Figure 1 respectively. The building has a surface area of 80 m² and a volume of 256 m³, and the single-glazed windows have a U-value of 5,8 W/(m². K) and a solar factor (g) of 0,85. It should be noted that the reference building is located in the city of Bechar, which is 1150 km southwest of the capital Algiers at an altitude of 773 m [24].

Table 1 Geometrical characteristics

Zones	L (m)	W (m)	H (m)	S (m²)	V (m³)
B.room1	4,00	3,00	3,20	12,00	38,40
B.room2	4,00	3,00	3,20	12,00	38,40
L.room	5,00	4,00	3,20	20,00	64,00
Kitchen	4,00	3,50	3,20	14,00	44,80
Lobby	8,00	2,00	3,20	16,00	51,20
WC + Bath	4,00	1,50	3,20	6,00	19,20
		Total		80,00	256

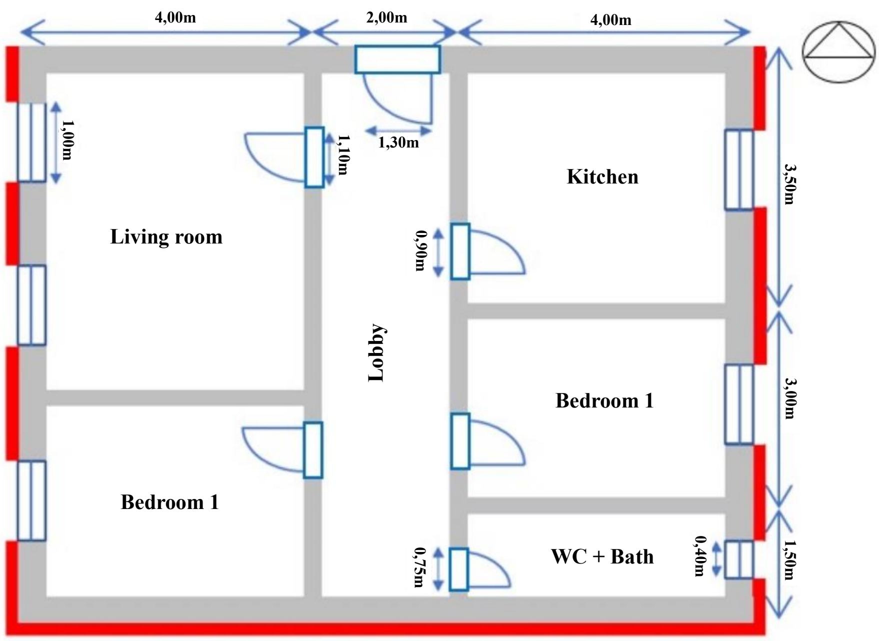

Figure 1 Plan view with the insulated facades in red (author source)

The numerical simulation was carried out using the dynamic thermal simulator "TRNSYS." The method followed involves studying the aforementioned building with different External Thermal Insulation (ETI) techniques for the vertical walls, utilizing natural materials such as hemp fiber (SHF) and sheep wool (SSW). Figure 2 illustrate the physical characteristics of the insulated walls, including total thickness and coefficient of thermal transmission, as well as representations of insulation techniques.

The TRNSYS software is employed to calculate the thermal behavior of various areas within a building under dynamic conditions and simulate the behavior of the building envelope. It is also capable of determining heating and cooling consumption. The software incorporates a new library encompassing materials, elements, systems, equipment, etc., allowing the modeling of all desired elements in the envelope and its system. This typically includes:

- A geometric description of the building, involving the input of plans, specifying dimensions and orientations of rooms, walls, glazing, and openings. Corresponding location Data, such as latitude, longitude, and altitude, are also provided;
- A description of the building envelope, indicating the composition of walls, glazing, doors, etc., along with the physical properties (thermal and optical) of the materials constituting them;
- A description of equipment (heating, ventilation, domestic hot water, lighting, etc.), incorporating the parameters that define their operation;
- A description of external stresses (weather Data) and internal factors (ventilation scenarios/Data, occupancy, etc.).

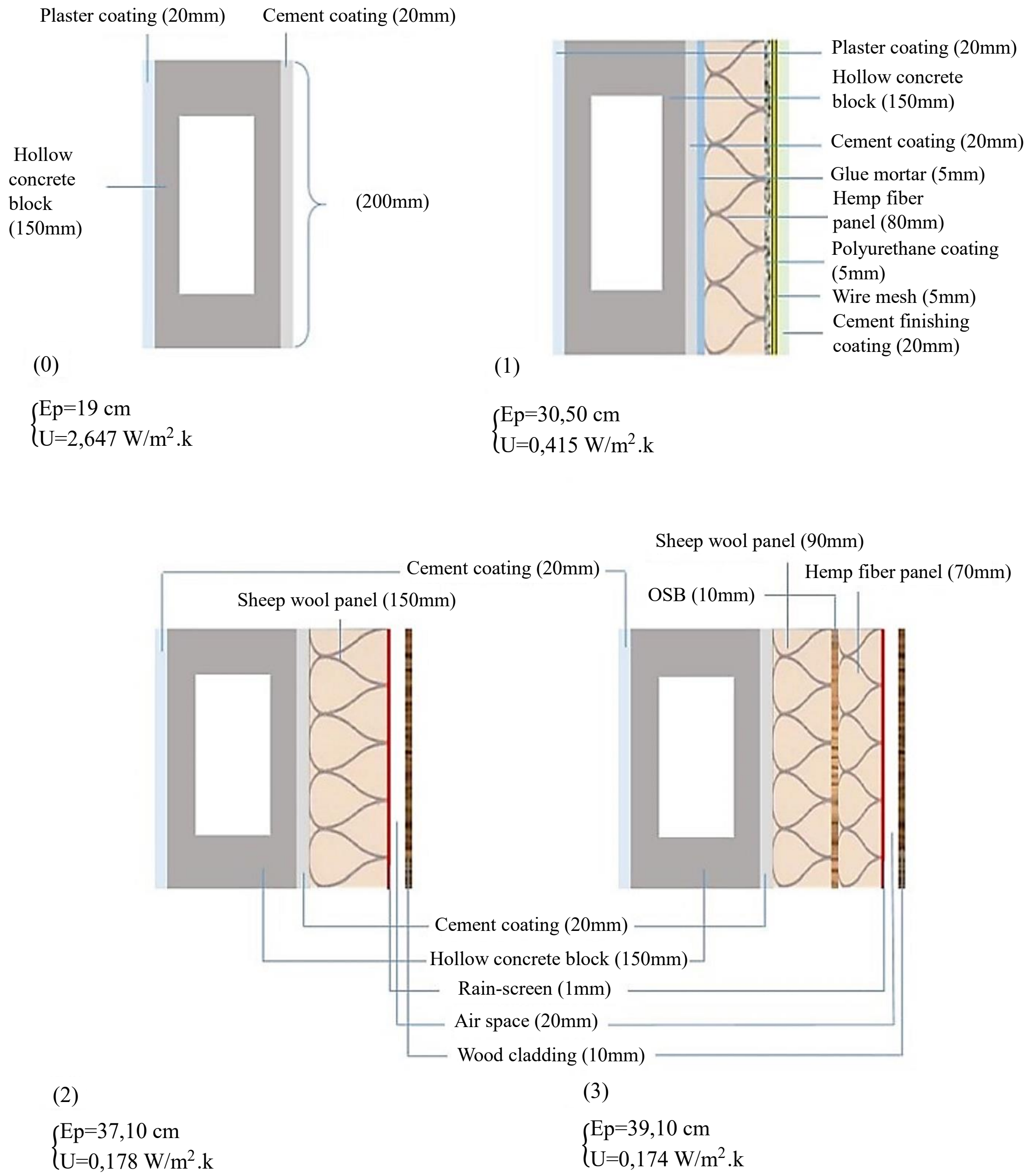

Figure 2 Suggested external thermal insulation systems ETI (author source)

(0): Reference wall (uninsulated)
(1): Wall insulated by hemp fiber (SHF)
(2): Wall insulated by sheep wool (SSW)
(3): Wall insulated by sheep wool (SSW) + hemp fiber (SHF)
Ep: represents the total thickness of the exterior wall and thermal insulation system in (cm).
U: represents the thermal transmission coefficient of the exterior wall in each case of system (uninsulated and insulated), i.e., the quantity of heat passing through this wall in a permanent state, per unit of time, per unit of surface area and per unit of temperature difference between the environments on either side of the wall in (W/m². k).

3. Results and discussion

3.1 Comparative thermal analysis

The evolution curves of the external ambient air temperature, the indoor temperature of the reference zone (without an insulation system), and the indoor temperature of the study zone (living room) under different external insulation systems are presented as functions of time during both winter and summer periods (see Figures 3 and 4). These periods correspond to the coldest and hottest times of the year in 2022 (124 hours of January and July, respectively).

It's important to note that the phase shift, or the difference in indoor temperature between the reference system (uninsulated) and the various thermal insulation systems, was calculated for both the winter period (at time 50) and the summer period (at time 51) as follows:

For the winter period:

Phase shift = interior temperature of insulation systems - interior temperature of the reference system.

For the summer period:

Phase shift = reference system indoor temperature - insulation systems indoor temperature.

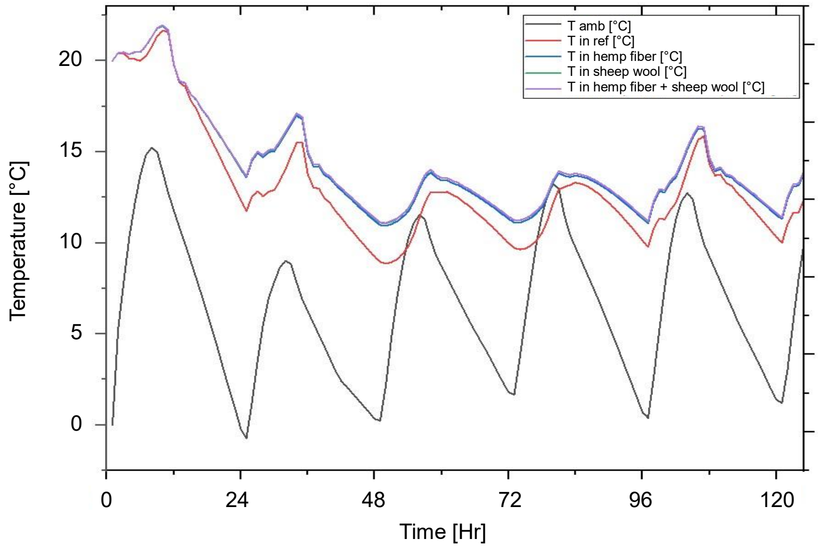

Figure 3 Evolution of the ambient and interior temperature of each ETI technique as a function of time in the northern "living room" zone during the winter period

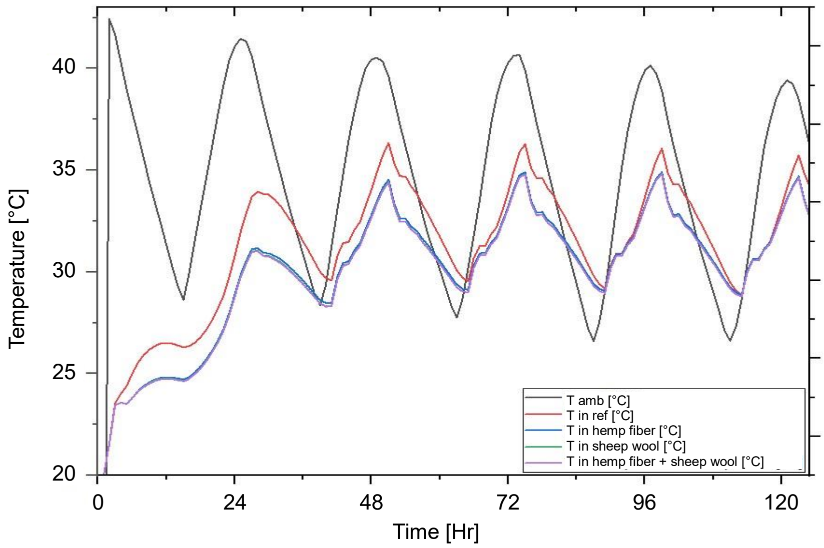

Figure 4 Evolution of the ambient and interior temperature of each ETI technique as a function of time in the northern "living room" zone during the summer period

From these figures, we observe that the indoor temperature, for all types of systems tested, varies with time and the studied period. During the winter period, the indoor temperature for the different ETI systems is significantly higher than that recorded at the reference temperature, with a maximum phase shift of 2,17°C occurring at hour 50. In contrast, during the summer period, the indoor temperature of the study area under the ETI systems is lower than that recorded at the reference temperature, with a maximum phase shift reaching values below 1,90°C at hour 51.

This variation in internal temperature between the different studied thermal insulation systems and the reference case during the winter and summer periods can be explained by the thickness of each system and the performance of the insulator used. Similar results have been reported by various authors [25-27], demonstrating that as the thermal insulation thickness increases, the heat transfer through it decreases, resulting in higher thermal resistance.

The values of the annual heating and air conditioning requirements of the reference building, along with the Eco Index for each improvement system, are summarized in Table 2. Subsequently, the percentage reduction in energy consumption through the external walls of the studied apartment, according to each proposed technique, is shown in Figure 5.

Table 2 Annual heating and air conditioning requirements of the reference building and the Eco Index for each improvement insulation system

		Vertical Wall Insulation Systems (ETI)		
		Under coating	**Under cladding**	
Consumption	**Reference building**	**Hemp fiber (80 mm)**	**Sheep wool (150 mm)**	**Sheep wool (90 mm) + Hemp fiber (70 mm)**
Heating [kWh]	7046	5262	5089	5083
Air conditioning [kWh]	6795	5304	5159	5154
(Heat +Air cond) [kWh]	13841	10566	10248	10237
(Heat +Air cond) [kWh/m².year]	173,01	132,08	128,10	127,96
Eco [kWh/m².year]	-	40,93	44,91	45,05
Reduction %	0,00	23,66	25,96	26,04

From this table, we can deduce that:

- The heating and cooling consumption for generating warmth and cold in our study site, especially in the reference case, highlights the necessity to explore efficient techniques for enhancing the thermal performance of local residences;
- The application of external thermal insulation under a hemp fiber-based coating for vertical walls led to a 23,66% reduction in energy consumption compared to the reference state, resulting in an energy saving of approximately 40,93 KWh/m² per year. Conversely, the technique under cladding based on sheep wool achieved a reduction of up to 25,96%, with a saving of 44,91 KWh/m² per year, highlighting the distinction between the two techniques (considering the type and thickness of the insulators);
- The third technique, combining the two previous insulators (hemp fiber and sheep wool), emerged as the optimal solution, outperforming the first two techniques with a 26,04% reduction and a saving of 45,05 KWh/m² per year in terms of energy savings.

These results enable us to identify the most effective selections for thermal optimization systems, establishing a reliable system in terms of energy consumption and savings.

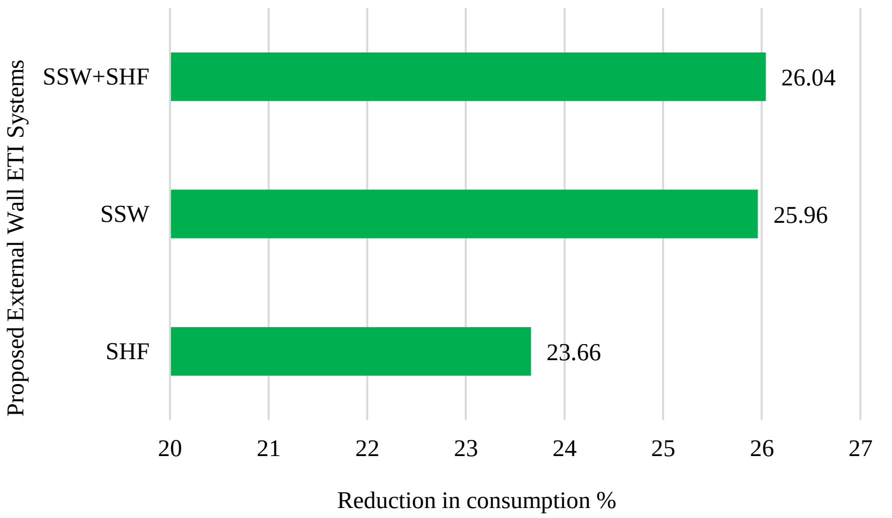

Figure 5 Percentage reduction in energy consumption

3.2 Technical and economic study

All the results obtained for the different ETI systems, including investment costs, gas and electricity consumption (based on current gas and electricity tariffs), and the achieved savings, are summarized in Table 3. This economic evaluation allows us to distinguish the economic weight of ETI systems by considering their diversity, identifying the lowest and highest systems in terms of costs and energy savings. The potential gas and electricity savings through insulation systems in the selected region, such as the city of Bechar with its dry and hot climate, are also discussed.

Table 3 Investment cost and savings of the proposed ETI systems

		Wall ETI Systems		
		Under coating		Under cladding
	Reference building	**Hemp fiber (80 mm)**	**Sheep wool (150 mm)**	**Sheep wool (90 mm) + Hemp fiber (70 mm)**
Investment cost (DZD/m²)	-	3888,80	5859,33	5640,87
Investment cost (DZD) for the three external walls (S =77m²)	-	299437,60	451168,41	434346,99
Gas consumption (for Heating) [KWh/year]	7046	5262	5089	5083
Electricity consumption (for Cooling) [KWh/year]	6795	5304	5159	5154
Gas price per tranche/Year (0,384 DZD/kWh)	2705,66	2020,61	1954,18	1951,87
Electricity price per tranche/Year (5,340 DZD/kWh)	36285,3	28323,36	27549,06	27522,36
Total Price (Gas + Electricity) (DZD per tranche/year)	38991,26	30343,97	29503,24	29474,23
Savings achieved (DZD/year)	-	8647,29	9488,02	9517,03

Note: DZD: Algerian Dinar

To better analyze the results obtained, we have grouped the values of the economy and their gaps in Figures 6 and 7, respectively. According to these representations, annual savings values range from 8647,29 DZD for the system under hemp fiber coating to 9,488.02 and 9517,03 DZD, respectively, for the two systems under sheep wool cladding and hemp fiber + sheep wool cladding. However, the values of the achieved savings appear relatively low compared to the amounts invested for the different systems illustrated. This is mainly due to several factors, including the amount of energy consumed, the cost of supply by type of energy (electricity or gas) and subscription (business or household), and the future performance of the building.

The variability in investment costs between different ETI systems can be explained mainly by the type of ETI technique (under coating or under cladding), where ETI under cladding is more expensive than ETI under coating, including labor [28].

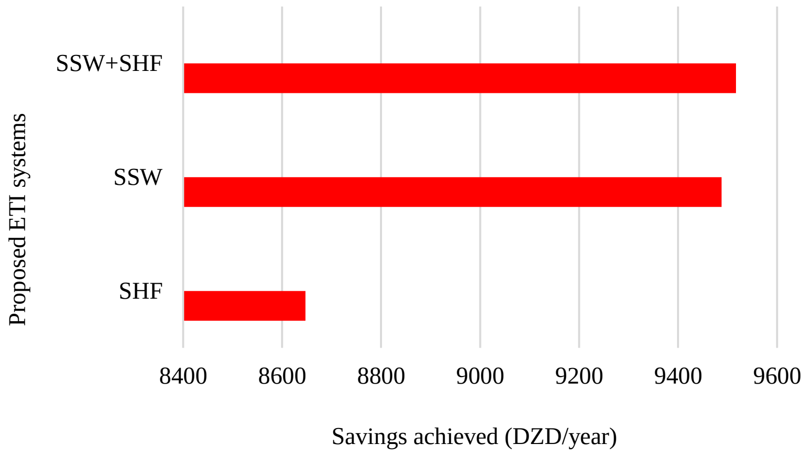

Figure 6 Savings from the proposed ETI systems

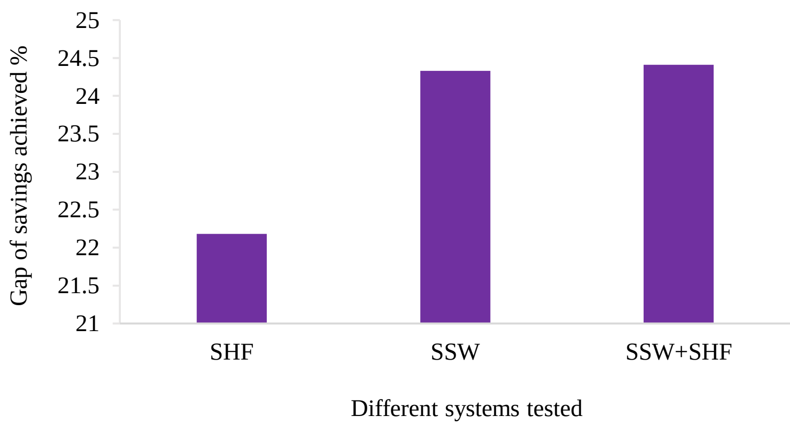

Figure 7 Evolution of the savings gap according to the proposed ETI systems

From the above, we can conclude that the cost of natural gas, particularly, and the cost of energy in general, significantly affect the annual savings for the different thermal insulation systems tested. The low energy cost, for example, natural gas cost at 0,384 DZD/KWh, results in relatively low annual savings.

Another similar study has shown that the cost of energy has an impact on the payback period, which, in turn, influences the realized savings. Increasing the price of electricity, for instance, decreases the return time and increases the realized energy savings [15].

It should be noted that the initial investment costs of these insulation systems may seem large and high. However, insulation is necessary to save on the cost of energy consumption. Installing such ETI systems allows for a reduction in the energy bill (electricity and natural gas) in the long term, providing an energy-efficient, comfortable, and healthy building.

4. Conclusion

In this study, we have presented a range of technical solutions aimed at improving the thermal performance of residential buildings in the city of Bechar, characterized by a hot and arid climate. The objective is to provide thermal comfort to individuals while reducing annual energy overconsumption. The study focused on the exterior walls of a reference building, representing the predominant construction model in the region. Three conventional External Thermal Insulation (ETI) systems for the walls, based on natural materials, were proposed: one system under coating with hemp fiber and two systems under cladding, one with sheep's wool and the other with a combination of hemp fiber and sheep's wool. Subsequently, a numerical simulation using TRNSYS software was conducted to validate these improvement techniques and evaluate various results such as energy consumption for heating and air conditioning and indoor temperature values for different study cases. Following that, an economic study estimated the costs of implementing these systems and the yearly savings achieved. Based on these solutions, the following conclusions can be drawn:

- The composition of the external envelope of the reference building, particularly the vertical walls, indicates the cause of poor thermal behavior in local buildings (high thermal transmission U = 2,647 W/m². k), affecting the thermal comfort of individuals and contributing to excessive energy consumption (173,01 kWh/m² per year) and therefore the high bills paid by occupants annually;
- The difference between the reference indoor temperature (without insulation) and that of thermal insulation techniques during both winter and summer periods is almost 2,17 and 1,90°C, respectively, highlighting the reliability of the proposed systems in improving thermal comfort, especially in regions with extreme climates like the town of Bechar;
- Applying these insulation systems to walls can reduce energy consumption by up to 23,66% for the system under coating based on hemp fiber, 25,96% for the system under sheep's wool cladding, and 26,04% for the system under hemp fiber and sheep's wool cladding;
- The annual savings achieved for the three studied techniques are estimated at 8647,29 DZD/year for the system under coating based on hemp fiber and 9488,02 to 9517,03 DZD/year for the two systems under cladding based on sheep's wool and hemp fiber and sheep's wool, respectively;
- The best insulation technique for reducing energy consumption and providing higher annual savings, considering an average application cost, is represented by the under cladding insulation system based on natural insulators common to sheep's wool and hemp fiber.

However, the findings from the different systems studied open the way to several perspectives:

- Discovering other natural thermal insulators with lower thermal conductivity than hemp fiber and sheep wool and at a lower cost;
- Undertaking further similar studies and research, this time on a multi-story building, to assess excessive energy consumption each year and demonstrate the importance of using external thermal insulation on walls to provide appropriate thermal comfort for individuals during winter and summer periods;
- Raising local awareness of the need to apply thermal insulation to buildings to conserve energy, reduce greenhouse gas emissions, increase the lifespan of residential buildings, and make significant annual profits;
- Encouraging the use of thermal insulators of natural origin for their health benefits, environmental friendliness, and renewability, unlike traditional insulation such as expanded polystyrene;
- Determining the optimum percentage of sheep's wool and hemp fiber for the under-cladding system by proposing different thicknesses for the two previous thermal insulators.

5. Acknowledgments

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