

Performance Energy Analysis of Recycled Fiber (RFMs) Materials for Insulating Building Envelopes in Hot and Dry Climates

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Abstract

Reducing heating and cooling consumption by improving the thermal efficiency of building envelopes is crucial, especially in hot and dry climates like Algeria. This research aimed to develop sustainable, innovative thermal insulation systems using recycled fiber materials (RFMs) to enhance thermal comfort and mitigate environmental impact. This work incorporated recycled polystyrene, fiber wool, and cellulose into insulators, evaluating their thermal characteristics, energy efficiency, and indoor comfort levels using both experimental and numerical methods. Results indicate that RFMs offer viable alternatives to traditional insulators by effectively stabilizing interior temperatures and significantly reducing energy demand. Specifically, insulation utilizing recycled fiber wool achieved a 56% decrease in energy consumption, compared to 65% for cellulose and 50% for polystyrene, confirming their efficacy. While these thermal and energy-saving results align with scientific literature, the material's fire resistance and Lifecycle Cost Analysis (LCCA) showed limitations. Nevertheless, the superior insulation performance confirms the viability of recycled fiber composites for use in External Thermal Insulation Composite Systems (ETICS) in Algerian buildings. Key sustainability benefits include reduced landfill waste and low embodied energy.

Keywords: Thermal Insulation, Building, Recycled Materials, Energy Saving, Comfort.

1. Introduction

The thermal insulation of buildings is a fundamental requirement of sustainable construction, essential for assuring occupant comfort and positioning with economic and responsible development objectives. Adopting External Thermal Insulation (ETI), particularly in hot and dry climates like those prevalent in Algeria, constitutes a strategic approach to energy efficiency. Every insulating element helps mitigate excessive needs for heating and cooling, resulting in reduced energy consumption and, consequently, a significant decrease in greenhouse gas emissions

While thermal insulation is critical for mitigating the construction sector's heavy environmental impact by reducing energy demand for heating and cooling, the recyclability of end-of-life insulation materials (IMs) remains a considerable challenge [1].

Recycled textiles, such as denim, wool, and cotton, have gained attention as eco-friendly insulation materials. These materials offer excellent thermal

performance and are often treated to improve fire resistance and durability.

Ardente et al., 2018 Investigated the thermal performance of recycled textile insulation in residential buildings. The study found that recycled textile insulation could reduce heat loss by up to 30% compared to conventional materials, while also improving indoor air quality due to its breathability. [3]

Research by Zied et al. (2024): Examined the thermal insulation of natural materials. The results demonstrated that these systems provided comparable thermal resistance (R-values) to traditional insulation materials, making them a sustainable alternative. [4]

A study by benoudjafer et al. (2025) shows that straw has a better result, reducing energy consumption and maintaining comfort. Straw insulated plates reduced heating and cooling needs in the home. They increased by 25% and 16%, respectively. Their energy efficiency was higher than the performance of other materials even if the walls in the scenario have the same U-value

as Straw walls in current and future weather conditions.[5][6]

Research by Zhang et al. (2021): Developed a novel insulation material using recycled polyurethane foam. The material exhibited excellent thermal stability and reduced heat transfer, contributing to improved thermal comfort in buildings.[6]

Recent studies have explored various recycled materials as sustainable alternatives to conventional insulation:

A study by Pargana et al. (2020) investigated the thermal performance of insulation panels made from recycled textile waste. The results showed that these panels provided comparable thermal resistance (R-value) to conventional mineral wool, improving thermal comfort in buildings.[7]

Al-Homoud et al. (2021) explored PET foam insulation from recycled plastic bottles. Their findings indicated that PET-based insulation reduced heat transfer effectively, enhancing indoor thermal comfort while being environmentally sustainable.[8]

Berardi & Zaidi (2022) evaluated rice husk and straw composites as bio-based insulation. The study found that these materials improved thermal inertia, reducing temperature fluctuations and enhancing occupant comfort.[9]

A research team (Kinnane et al., 2023) analyzed cellulose insulation from recycled paper and cardboard. The material demonstrated excellent hygrothermal properties, contributing to stable indoor temperatures and comfort.[10]

Zhang et al. (2024) developed insulation from steel slag and recycled glass, showing superior thermal resistance and fire retardancy while maintaining comfort levels comparable to synthetic insulation.[11]

Recycled plastics, such as polyethylene terephthalate (PET) and polyurethane foam, are being repurposed into insulation boards and sprays. These materials are lightweight, moisture-resistant, and have low thermal conductivity. by Almeida et al. (2019): Evaluated the thermal performance of insulation boards made from recycled PET. The study concluded that these boards had a thermal conductivity of 0.033 W/mK, similar to conventional foam boards, and significantly reduced energy consumption in buildings.[12]

Study by Pomponi et al. (2023): Discussed the need for policy interventions and incentives to promote the use of recycled insulation materials in the construction industry. [13]

Research by Attia et al. (2023): Highlighted the potential of integrating recycled insulation materials with smart building technologies to optimize thermal comfort and energy efficiency. [14]

Materials such as fibers, petioles, and spikelets derived from date palm waste matter could be used as additives in composite construction materials. Among the advantages gained from adding these materials are features like, renewability, low cost, availability, absence of toxicity and polluting effects. In addition, these materials ensure good thermal performance for mechanical and thermal insulation. .[17],[18]

Recent advances in sustainable construction research have highlighted the potential of recycled and agro-waste materials as efficient thermal insulators, particularly suitable for hot arid climates such as those of southern Algeria.

According to Deng et al. (2023), recycled-straw insulating concrete demonstrates a viable balance between mechanical strength and thermal insulation, achieving a thermal conductivity of approximately 0.50 W/m·K while maintaining good structural integrity. Their optimization through experimental design confirmed that such composites can significantly enhance the energy efficiency of buildings without compromising durability.[19]

Similarly, Bouhabila and Bellel (2024) developed eco-bricks by incorporating date palm fibers into clay matrices. Their results indicated a marked reduction in thermal conductivity (down to 0.22 W/m·K) and an improvement in overall insulation performance. These findings emphasize the feasibility of utilizing local agricultural residues as cost-effective, eco-friendly solutions for sustainable building materials in arid and semi-arid regions [20].

Further reinforcing these results, Rachedi and Kriker (2025) examined plaster composites reinforced with date palm fibers in southern Algeria. Their experimental results yielded one of the lowest thermal conductivities reported (0.19 W/m·K) while maintaining acceptable density and heat capacity values. The authors concluded that such natural fiber composites provide a practical pathway toward passive

cooling strategies and energy-efficient housing in Saharan contexts.[21]

The primary purpose of this research is to evaluate the thermal and environmental performance of sustainable insulation materials derived from recycled resources for buildings located in hot arid regions of Algeria. The study aims to identify eco-efficient alternatives to conventional synthetic insulators, such as polystyrene, that can simultaneously enhance building energy efficiency, reduce carbon emissions, and promote circular economy practices in the construction sector.

Given the increasing energy demand for cooling in arid climates, the research focuses on determining how bio-based recycled materials, including cellulose, wood fibers, and other low-impact composites, can contribute to thermal comfort and energy savings while maintaining material durability and affordability under local climatic conditions.

The main objectives of the study are to analyze the thermal properties (thermal conductivity, specific heat capacity, and density) of selected recycled insulation materials suitable for hot arid climates. Second objective is to compare the energy performance of buildings insulated with recycled materials (e.g., cellulose, wood fibers) to those using conventional insulators (e.g., polystyrene) through simulation and empirical data.

2. Materials and Methods

This study adopts a quantitative and comparative approach, combining experimental characterization of recycled insulation materials with building energy simulation. The goal is to assess and compare the thermal efficiency and energy-saving potential of various recycled insulation materials when applied to buildings located in hot arid regions of Algeria, particularly in areas such as Béchar.

This research is structured in three stages:

- Material selection and thermal characterization.
- Simulation of building energy performance using different insulation types.
- Comparative analysis and evaluation of environmental impact.

Material Selection and Characterization: The materials considered include:

- Recycled cellulose insulation (from paper waste)
- Wood fiber boards (from sawdust and recycled wood residues)
- Expanded polystyrene (EPS) as a reference conventional material

The physical and thermal properties — thermal conductivity (λ), specific heat capacity (C_p), and density (ρ) — were determined or retrieved from recent experimental studies

The research incorporates and models cutting-edge technological and architectural solutions, including:

- Adaptive façade systems: Using a several External Thermal Insulation (ETI) systems for the vertical walls based on natural and recycled materials with starch, with varying proportions of binder, for the thermal tests,
- Recycled Materials (RM): Embedded in walls and ceilings for passive thermal regulation, such as wood wool, cellulose wadding, expanded cork, hemp fiber, sheep's wool, and a single synthetic material: expanded polystyrene.

Analytical Model and Evaluation Metrics

The analytical model adopts a quantitative, scenario-based approach, with detailed building modeling and dynamic simulations across different configurations:

- Baseline scenario: Conventional design according to DTR 2005.
- Innovative scenario: Incorporating bio-based materials, natural ventilation, solar orientation, and advanced passive strategies.

Key performance indicators (KPIs) used to evaluate results include:

- Annual energy consumption (kWh/m².yr)
- Carbon emissions (kgCO₂e/m².yr)
- Thermal comfort indices (PMV/PPD as per ASHRAE 55)
- Cumulative Energy Demand (CED) over the building lifecycle.

Table 1. Thermal Conductivity, Specific Heat Capacity and Density of insulating materials) (Author, 2025)

Material Description	Conductivity (W/mK)	Sp. Heat Capacity (J/kgK)	Density (kg/m3)
Polyurethane Board	0.025	1400	30
Polystyrene	0.030	1380	25
Uf Foam	0.040	1400	10
Wood Wool Slab	0.100	1000	500
Cellular Phenolic – Mineral Fibre with Resin Binder	0.042	700	240
ineral Wool/Fibre – Fill	0.046	837	10
Cellulose Fill – IN13	0.039	1381	48
Plaster (Dense)	0.500	1000	1300

The table compares the thermal and physical properties of insulating materials based on their thermal conductivity, specific heat capacity, and density. Among them, polyurethane board exhibits the best insulating perfor

mance, with the lowest thermal conductivity (0.025 W/m·K) and low density (30 kg/m³), making it ideal for minimizing heat transfer in building envelopes. Polystyrene follows closely, offering slightly higher conductivity (0.030 W/m·K) but similar heat capacity and density, thus maintaining good insulation efficiency with excellent lightweight characteristics.

3. Results and Discussion

The higher density observed in alternative insulations is primarily attributed, such as sand polyurethane and Cellular Phenolic – Mineral Fibres. With Resin Binder, resulting in increased thermal conductivity. In contrast, the specific heat and thermal diffusivity values of polystyrene resemble those observed in the insulations studied by researchers.

The insulating materials for this work are: cellulose, polystyrene and fibers wood. We start with numerical study, then we completed with technical economic analysis. (Table 2).

Table 2. Evaluate of energy consumption (Q Cooling and Q Heating) and energy saving% of components of building in year (KWh/m2/years)) (Author, 2025)

	Initial building	WoodFibers	Cellulose	Polystyrene
Q Heting KWh/m2/years	260	100	80,35	110,6
Q Cooling KWh/m2/years	120	66,3	50,25	80,5
Total	380	166,3	130,6	191,1
Cep (KWh /m2)	380	166,3	130,6	191,1
Saving Energy (KWh /m2)	-	213,7	249,4	188,9
Saving Energy %	-	56,23	65,63	49,71

The results indicate a significant reduction in heating and cooling energy demands after the application of different insulation materials. The initial uninsulated building shows the highest total energy consumption, reaching 380 kWh/m²/year, composed of 260 kWh/m²/year for heating and 120 kWh/m²/year for cooling.

Among the insulated options, cellulose insulation achieves the best energy performance, reducing the

total consumption to 130.6 kWh/m²/year. This corresponds to an energy saving of 249.4 kWh/m²/year, or 65.63%, compared to the baseline. Wood fiber insulation also performs well, decreasing total energy use to 166.3 kWh/m²/year, representing a 56.23% energy saving.

In contrast, polystyrene insulation yields a moderate reduction, with a total energy demand of 191.1 kWh/m²/year, equivalent to 49.71% savings. While

polystyrene has a lower thermal conductivity, its performance is slightly less efficient in regulating both heating and cooling loads compared to bio-based materials.

Overall, the results demonstrate that natural insulating materials, particularly cellulose, provide superior thermal performance and greater energy savings, highlighting their suitability for sustainable building applications in hot arid regions such as Algeria.

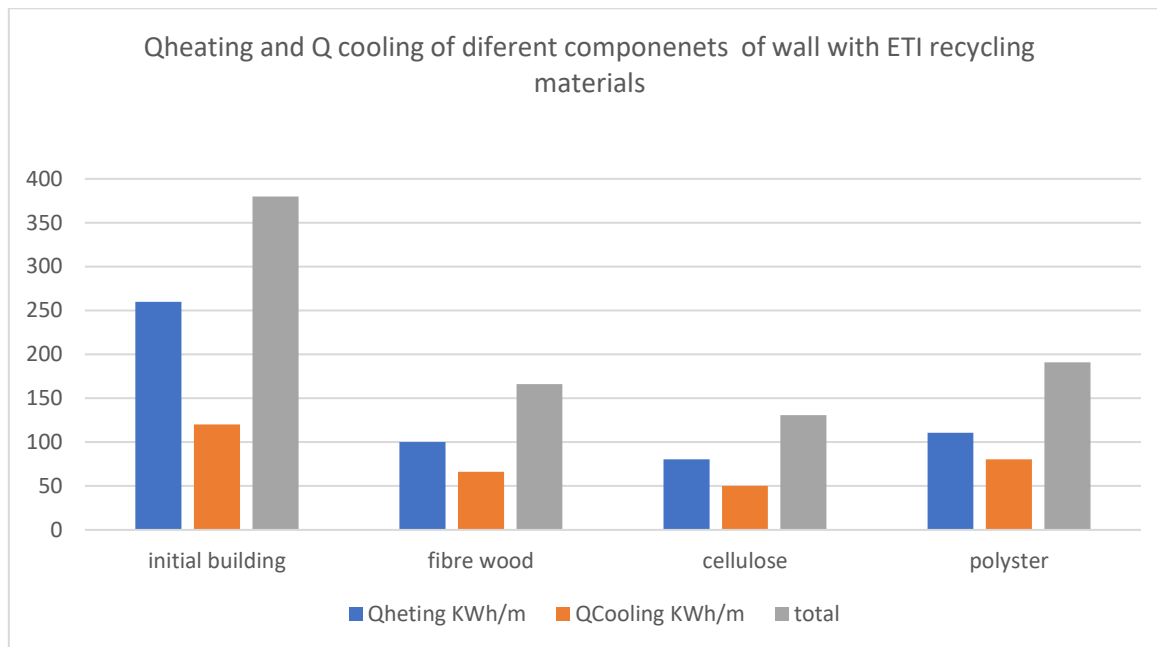


Fig. 1. Energy consumption (QCooling and QHeating) and energy saving% of components of building in year (KWh/m2/years) (Author, 2025)

The superior performance of cellulose insulation can be attributed to its low thermal conductivity, high specific heat capacity, and hygroscopic nature, which collectively enhance thermal stability within the building envelope. These properties allow cellulose to store and release heat gradually, reducing peak temperature fluctuations and improving indoor comfort — a crucial advantage in hot arid climates such as those found in Algeria.

Additionally, cellulose, being a recycled bio-based material derived from paper waste, exhibits high thermal inertia, which delays heat transfer through walls during the daytime and releases stored heat at night when temperatures drop. This passive thermal regulation significantly reduces the need for active cooling and heating, thus improving the building’s overall energy efficiency [19].

By comparison, wood fiber insulation also shows good performance due to its natural porosity and fiber structure, which trap air and limit conduction. However, its slightly higher density and moderate conductivity result in a somewhat lower energy-saving potential than cellulose.

In contrast, polystyrene, while offering low thermal conductivity, lacks the thermal mass and moisture-buffering capacity of natural materials. Its limited ability to manage indoor humidity and rapid heat transfer make it less effective in stabilizing interior thermal conditions, particularly in climates with high diurnal temperature variation [20], [21].

Consequently, the results confirm that bio-based recycled insulators like cellulose and wood fiber not only enhance thermal comfort but also contribute to sustainable construction practices, supporting the transition toward low-carbon and resource-efficient buildings in arid regions.

4. Conclusion

The use of thermal insulation made from recycled materials has a significant and measurable impact on improving the energy performance of buildings. Below is a detailed explanation, supported by results:

- **Reduction in Energy Demand**

Recycled insulation materials (e.g., cellulose, fibers wool, polystyrene) minimize heat transfer, reducing the need for mechanical heating and cooling. According to

the IEA (2022), buildings with high-performance insulation can reduce energy demand for heating and cooling by 30–50% compared to non-insulated structures IEA, 2022. A study by Papadopoulos (2020) in *Energy and Buildings* found that recycled cellulose insulation reduced annual heating energy demand by up to 40%, with a payback period under 5 years.[16]

Our results can reduce energy demand for heating and cooling by 50-60% compared to non-insulated structures.

- **Improved Thermal Comfort and Building Envelope Performance**

Recycled insulation materials often have comparable thermal conductivity (λ -values) to traditional materials: Cellulose ($\lambda = 0.038\text{--}0.042\text{ W/m}\cdot\text{K}$) and Recycled PET ($\lambda \approx 0.035\text{--}0.040\text{ W/m}\cdot\text{K}$)

This research demonstrates that recycled insulation materials, particularly cellulose and wood fiber, represent highly effective and sustainable alternatives to conventional synthetic insulators in hot arid regions such as southern Algeria. Through comparative analysis and energy simulation, it was shown that buildings insulated with cellulose achieve the highest reduction in total energy consumption, with savings up to 65% compared to uninsulated reference buildings.

The superior performance of cellulose is mainly attributed to its low thermal conductivity, high heat storage capacity, and moisture-buffering ability, which enhance both thermal inertia and indoor temperature stability. These properties are especially advantageous in climates characterized by large diurnal temperature variations, such as in Béchar. Similarly, wood fiber insulation provides excellent energy performance and environmental benefits due to its natural porosity and biodegradability.

In contrast, polystyrene, while possessing low conductivity, lacks thermal mass and hygroscopic properties, resulting in lower overall performance in hot arid conditions. Furthermore, synthetic insulators present higher embodied energy and carbon emissions, underscoring the environmental superiority of recycled and bio-based materials

Beyond thermal efficiency, the use of recycled materials contributes to circular economy principles, waste valorization, and carbon footprint reduction, aligning with sustainable development goals. The results suggest that recycled cellulose and wood fiber

insulation can be locally produced from Algerian waste resources, offering both economic and environmental advantages.

In conclusion, the study confirms that the integration of recycled insulation materials is not only feasible but also essential for the development of sustainable, energy-efficient, and climate-resilient buildings in Algeria's arid zones. Future work should focus on experimental validation under real climatic conditions, life-cycle optimization, and policy recommendations to promote the large-scale adoption of such eco-materials in North African construction practices.

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