Valorization of Doum Palm Fibers and EPS Waste into Lightweight Bio-Composites for Energy-Efficient Buildings

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Abstract. The building sector accounts for a large share of global energy demand and CO_2 emissions, underscoring the urgent need for sustainable insulation solutions. This study develops lightweight bio-composite panels by combining Doum palm fibers (*Hyphaene thebaica*), a locally available by-product, with a recycled expanded polystyrene binder (EPSB) derived from post-consumer waste. Composite formulations with fiber contents of 40%, 50%, and 60% were fabricated and characterized for density, thermal conductivity, and thermal diffusivity using the transient Hot Disk technique. Increasing fiber content markedly reduced density while improving insulation performance. The DFE60 composite (60% fiber, 40% binder) exhibited the best properties, with a thermal conductivity of 0.1156 $W \cdot m^{-1} \cdot K^{-1}$ and a diffusivity of 0.1952 mm^2/s. To evaluate real-scale performance, a TRNSYS simulation was carried out for a typical building in Oujda, Morocco (semi-arid climate). Incorporating a 4 cm DFE60 layer into the envelope lowered annual energy demand by 37%, with cooling and heating loads reduced by 41% and 37%, respectively. These results highlight the potential of Doum palm fiber–EPS composites as a sustainable, low-cost alternative to conventional insulation, valorizing local biomass and plastic waste while enhancing energy efficiency in buildings.

1 Introduction

The building sector accounts for approximately 35% of global energy demand and nearly 40% of CO_2 emissions, underscoring its central role in greenhouse gas generation [1]. Enhancing the thermal efficiency of buildings is therefore essential, and the use of insulation materials remains one of the most effective strategies to lower energy requirements and associated emissions [2]. Conventional insulation materials such as mineral wool,

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polyurethane, expanded polystyrene, and fiberglass exhibit low thermal conductivity (0.02–0.05 $W \cdot m^{-1} \cdot K^{-1}$), yet their application is not without drawbacks. Glass wool and fiberglass, for instance, are linked to respiratory health issues and exhibit relatively low mechanical strength, which can complicate construction practices [3].

The development of environmentally friendly insulation materials offers a promising pathway to reduce reliance on non-renewable resources while mitigating health and environmental impacts throughout their lifecycle [4], [5]. In recent years, a wide range of bio-based fibers, including hemp, alfa, jute, and straw, have been studied for thermal insulation [6-7].However, the valorization of Doum palm fibers (*Hyphaene thebaica*) remains largely unexplored, despite their abundance in North Africa and potential as a renewable reinforcement [8].

At the same time, expanded polystyrene (EPS) waste has become a pressing environmental issue due to its persistence and global consumption trends. While recycling efforts exist, its use as a binder in natural-fiber composites has received limited attention, particularly for insulation applications.

This study addresses these gaps by developing lightweight thermal insulation composites that combine Doum palm fibers with a recycled EPS-based binder (EPSB). The composites were fabricated and systematically characterized for their thermophysical properties, with the objective of evaluating their potential as sustainable, locally sourced alternatives to conventional insulation materials.

2 Materials and sample preparation

2.1 Doum fibers

Doum palm fibers (*Hyphaene thebaica*), sourced from the local market in Oujda (Morocco), were employed in this study. The Doum palm, native to North Africa and illustrated in Figure 1, can grow up to 17 m in height and is characterized by a fibrous trunk, leaves composed of petioles and leaflets, and clusters of fruit. Doum fibers (DF) were extracted specifically from the petiole of the leaves. Each year, older leaves are pruned and often discarded, creating a stream of biomass waste. In this work, these pruned residues were repurposed as reinforcement for composite insulation materials, thereby promoting resource efficiency and waste mitigation [8-9].

Fig. 1 Doom palm trees.

2.2 EPS waste

Expanded polystyrene (EPS) is a lightweight thermoplastic composed of approximately 98% air and 2% polystyrene, with thermal conductivity values ranging from 0.035 to 0.04 $W \cdot m^{-1} \cdot K^{-1}$ at densities between 15 and 35 kg/m^3 [10]. First developed in 1949, EPS is the oldest bead foam polymeric material and has become widely used in the construction sector due to its low cost, worldwide availability, and the unique advantage of being the only polymeric foam that does not require a blowing agent [11]. However, its large-scale production has also created significant waste management challenges. Global consumption reached nearly 7 million tons in 2019 and is projected to rise to 8.5 million tons by 2025, with Asia accounting for almost 70% of demand [12]. In this study, EPS waste was valorized as an organic binder. Post-consumer EPS was dissolved in a cellulose-based solvent to form a smooth, glue-like paste (EPSB), which served as the composite matrix. The dissolution process consisted of blending EPS with the solvent under mechanical stirring until a homogeneous mixture was obtained.

2.3 Specimen preparation

Composite samples were produced by combining chopped Doum palm fibers with the recycled EPS-based binder (EPSB). The fibers were cut into lengths of 0.5–2 cm and mixed with EPSB to ensure uniform dispersion. Three formulations were designed with EPSB-to-fiber mass ratios of 60:40, 50:50, and 40:60, corresponding to designations DFE40, DFE50, and DFE60, respectively. Each mixture was thoroughly blended, poured into cylindrical molds (8 cm diameter × 2 cm height), and subjected to compression to achieve uniform density and strong interfacial adhesion. The overall preparation process is illustrated in Fig. 2, while Table 1 summarizes the detailed composition of each batch, including fiber content, binder proportion, and solvent ratio.

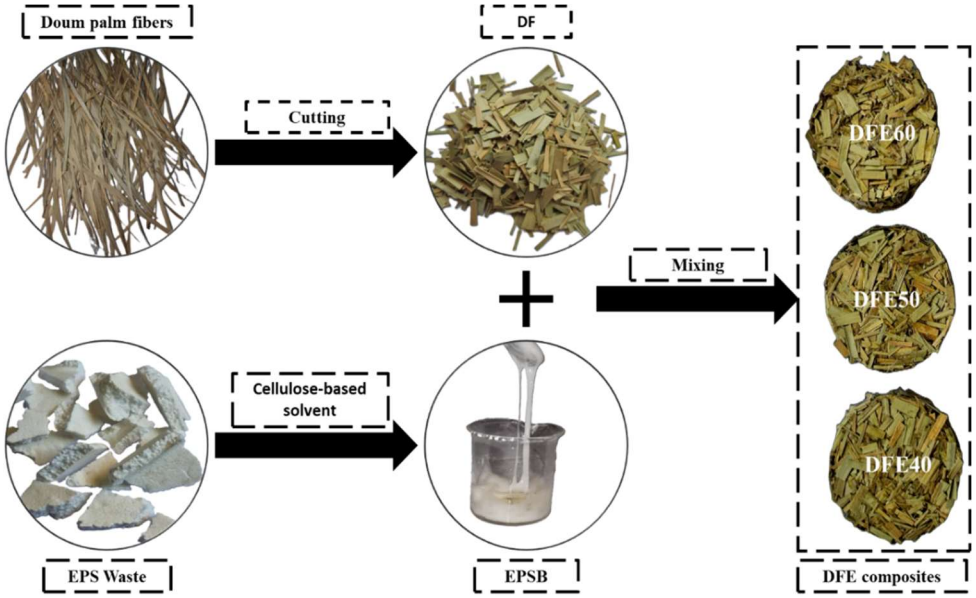

Fig.2 Samples preparation process.

Table 1. Formulation of DF–EPSB mixtures.

Composite designation	EPSB content	DF content
DFE40	60%	40%
DFE50	50%	50%
DFE60	40%	60%

3 Methods

3.1 Thermophysical characterization

The thermal conductivity and diffusivity of the composites were measured using a TPS 2200 Hot Disk apparatus in accordance with ISO 22007-2 [13]. A double-spiral Kapton sensor (Thermtest™ 8563, radius 9.8 mm) was placed between two identical flat samples, pressed together to minimize air gaps [14]. During each test, a constant electrical power (20–35 mW) was supplied to the probe, which simultaneously recorded the transient temperature response. The Hot Disk software analyzed the data to determine thermal transport properties with an accuracy better than 5%. Each measurement was conducted over 160 seconds, and density (ρ) was determined from the specimen mass-to-volume ratio. Specific heat capacity (c_p) was then calculated from the relation:

$$c_\rho = \frac{\lambda}{\alpha \times \rho}$$

where λ is thermal conductivity and α is thermal diffusivity.

3.2 Numerical model and simulation setup

3.2.1 Climatic data and building geometry

A transient building energy simulation was performed with TRNSYS 16 to assess the impact of the developed insulation under semi-arid conditions. The case study considered Oujda, Morocco (Latitude: 33.9° N, Longitude: 5.5° W, Altitude: 550 m), a region characterized by hot summers, cool winters, and pronounced diurnal temperature swings. The test building was modeled as a standalone office with an internal volume of 48 m³ (4 m × 4 m × 3 m) and a 2 m² north-facing window.

3.2.2 Building envelope composition and scenarios

The reference envelope composition, based on local construction practices, is summarized in Table 2. To evaluate the thermal benefit of the proposed insulation, two scenarios were simulated:

- *Scenario 1 (Reference Building):* Standard construction with no added insulation.
- *Scenario 2 (Insulated Building):* Same configuration, but with a 4 cm layer of the Doum palm fiber composite (DFE60) integrated externally into the wall, roof, and ground floor assemblies.

The thermophysical properties of the conventional materials and the DFE60 composite are reported in Tables 2 and 3, respectively.

Table 2. Building components and their thermophysical 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	1.3	1
	Brick (12 holes)	20	664	0.22	0.74
	Cement mortar	2	1900	1.3	1
Roof	Floor tiles	2	2300	1.3	0.84
	Heavy concrete	7	2450	2	1
	Hollow slab	10	1513	1.04	1
	Gypsum plaster	1	1350	0.56	1
Ground	Floor tiles	2	2300	1.3	0.84
	Cement mortar	5	1900	1.3	1
	Heavy concrete	20	2450	2	1

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Table 3. Thermophysical properties of the best performing composite (DFE60).

Density (kg/m^3)	Thermal conductivity (W/m.K)	Heat capacity (kJ/kg.K)
422	0.1159	1.417

4 Results and Discussion

4.1 Density

Fig. 3 shows the bulk density of the three composite formulations (DFE60, DFE50, and DFE40) as a function of EPSB content. Density values are strongly influenced by the relative proportion of Doum fibers, whose density is significantly lower than that of the EPSB binder. As the fiber fraction increases, the composites become progressively lighter. The DFE60 formulation (60% Doum, 40% EPSB) achieved the lowest density of approximately 422 kg/m³, while DFE40 (40% Doum, 60% EPSB) reached 560.7 kg/m³. This trend highlights the role of fibers in reducing overall weight, which is advantageous for lightweight construction and insulation applications. In contrast, higher binder fractions yielded denser composites, which could offer improved mechanical resistance and structural stability for semi-load-bearing applications. Comparable studies on hemp- and straw-based composites have reported densities in the range of 350–600 kg/m³, placing the present materials within a similar performance class [13–14].

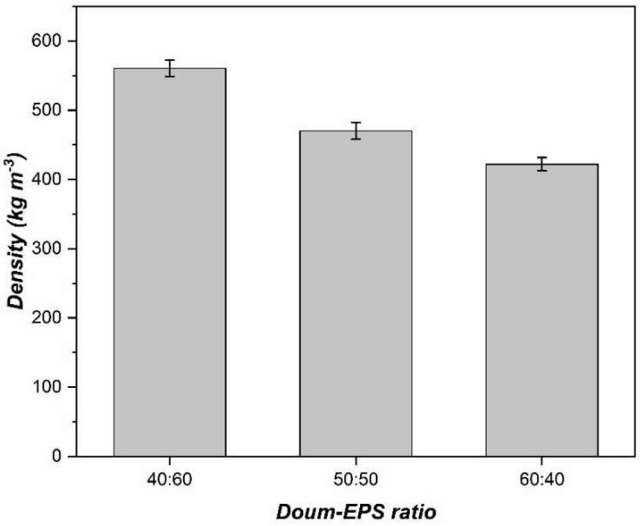

Fig. 3 Variation in Bulk Density of DFE-Based Composites.

4.2 Thermal properties

The thermal conductivity (λ) and diffusivity (α) of the composites, presented in Fig. 4, decreased consistently with increasing fiber fraction, mirroring the behavior observed in bulk density. This reduction arises from the low thermal conductivity of Doum fibers relative to the EPSB matrix, as well as the higher porosity associated with the fibrous phase. The DFE60 composite (60% Doum) exhibited the most favorable values, with $\lambda = 0.1156$ W·m⁻¹·K⁻¹ and $\alpha = 0.1952$ mm²/s. By comparison, DFE40 recorded $\lambda = 0.1515$ W·m⁻¹·K⁻¹ and $\alpha = 0.2696$ mm²/s, while DFE50 reported intermediate values ($\lambda = 0.1299$ W·m⁻¹·K⁻¹, $\alpha = 0.2203$ mm²/s).

These results confirm the positive effect of Doum fibers on thermal insulation, positioning the composites within the range of other bio-based insulators such as straw–lime and hemp–gypsum panels (0.11–0.16 W·m⁻¹·K⁻¹) [15-16]. The low diffusivity of DFE60 further indicates a high capacity to delay heat transfer, which is particularly beneficial in climates with large diurnal temperature fluctuations.

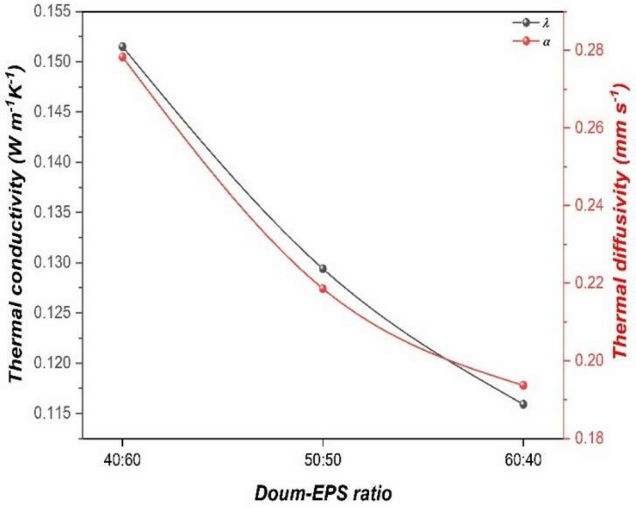

Fig. 4 Thermal conductivity and diffusivity of the studied composites.

4.3 Energy simulation results

4.3.1 Indoor temperature

The incorporation of Doum palm fiber insulation led to a marked improvement in indoor thermal stability. As shown in Fig. 5, the diurnal indoor temperature variation was significantly reduced in the insulated building compared to the reference case. While the reference building closely followed the outdoor temperature profile, producing pronounced peaks and troughs, the insulated model maintained a more stable indoor environment within the comfort-oriented range. This improvement is attributed to the increased thermal resistance and enhanced thermal inertia of the bio-composite layer, which delayed and attenuated the transmission of outdoor temperature fluctuations. Such behavior is particularly advantageous in semi-arid climates, where large daily temperature swings can otherwise compromise indoor comfort.

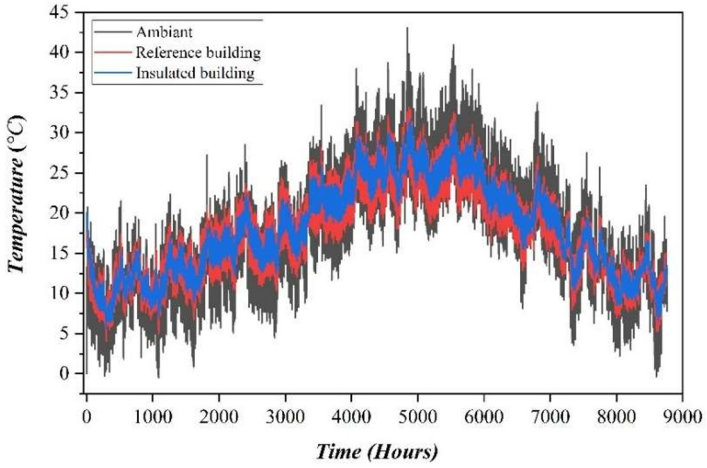

Fig. 5 Annual variation of ambient and indoor temperatures for the reference and insulated building.

4.3.2 Cooling and heating energy consumption

The impact of the bio-composite on building energy demand is illustrated in Fig. 6. Total annual energy consumption decreased from approximately 310 kWh/m²·year in the reference building to 190 kWh/m²·year in the insulated case, corresponding to a 37% reduction. Cooling loads were reduced by 41%, while heating loads decreased by 37%. The greater reduction in cooling demand reflects the composite's effectiveness in limiting heat gains during hot summers, which dominate the semi-arid climate of Oujda. These savings are a direct result of the enhanced thermal resistance and high heat storage capacity of the Doum palm fiber insulation, which mitigates heat transfer through the envelope. Comparable studies on hemp-based insulation have reported annual energy savings in the range of 25–40% [17-18], placing the present results within the upper range of reported performance.

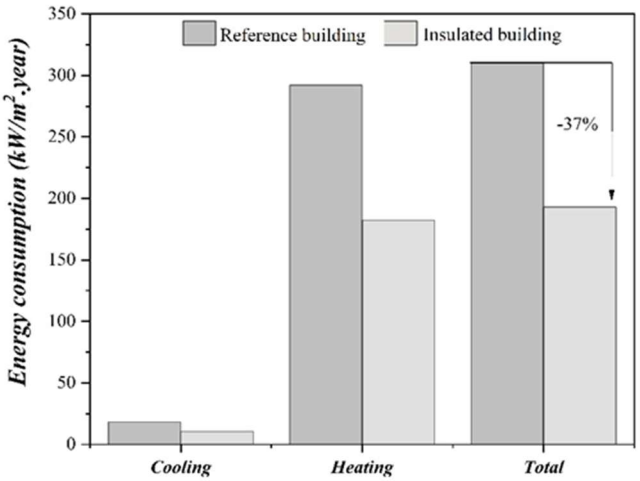

Fig. 6 Annual Heating, Cooling, and Total Energy Demand (Reference vs. Insulated Building).

Overall, the simulation demonstrates that integrating Doum palm fiber composites into the building envelope can simultaneously enhance indoor comfort and reduce energy demand, reinforcing their potential as sustainable insulation materials for semi-arid and similar climatic regions.

5 Conclusion

This study demonstrated the successful valorization of Doum palm fibers and recycled EPS waste into lightweight insulation composites with promising thermophysical performance. Experimental results showed that increasing fiber content reduced density and improved insulation capacity, with the DFE60 formulation achieving the lowest thermal conductivity (0.1156 $W \cdot m^{-1} \cdot K^{-1}$) and diffusivity (0.1952 mm^2/s). Building energy simulations confirmed these findings, indicating that integrating a 4 cm DFE60 layer into the envelope of a model building in Oujda reduced annual energy demand by 37% and markedly improved indoor thermal stability. By coupling waste valorization with enhanced energy efficiency, these composites represent a viable alternative to conventional insulation. Future research should address mechanical properties, durability under real climatic conditions, and life-cycle impacts to support large-scale application in sustainable construction.

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