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Characterization and Thermal Evaluation of a Novel Bio-Based Natural Insulation Material from *Posidonia oceanica* Waste: A Sustainable Solution for Building Insulation in Algeria

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Abstract: Natural bio-based insulation materials have been the most interesting products for good performance and low carbon emissions, becoming widely recognized for their sustainability in the context of climate change and the environmental impact of the building industry. The main objective of this study is to characterize a new bio-sourced insulation material composed of fibers and an adhesive based on cornstarch. This innovative material is developed from waste of the marine plant called *Posidonia oceanica* (PO), abundantly found along the Algerian coastline. The research aims to valorize this PO waste by using it as raw material to create this novel material. Four samples with different volumetric adhesive fractions (15%, 20%, 25%, and 30%) were prepared and tested. The collected fractions underwent a series of characterizations to evaluate their properties. The key characteristics studied include density, thermal conductivity, and specific heat. The results obtained for the thermal conductivity of the different composites range between 0.052 and 0.067 $W.m^{-1}.K^{-1}$. In addition, the findings for thermal diffusivity and specific heat are similar to those reported in the scientific literature. However, the capillary absorption of the material is slightly lower, which indicates that the developed bio-sourced material exhibits interesting thermal performance, justifying its suitability for use in building insulation in Algeria.

Keywords: bio-sourced insulation; *Posidonia oceanica* waste; sustainable construction materials; building insulation; environmental sustainability

1. Introduction

Buildings stand as the primary consumers of energy and account for the largest share of greenhouse gas emissions in Algeria accounting for 46% of the total national energy expenditure. Among these, residential buildings take up the largest share, amounting to 37%. This surge in energy demand can be primarily attributed to a substantial increase in both population and the number of housing units. Consequently, accurate predictions of energy consumption play a pivotal role in enabling effective planning, the formulation of long-term strategies, and the implementation of efficient initiatives aimed at reducing emissions, and the management of energy utilization within the construction industry [1,2].

The external envelope of buildings plays a crucial role as the primary barrier and protector against external climatic variations. Therefore, improving the energy performance of this envelope is essential [3]. The thermal insulation materials commonly used in the construction industry are primarily traditional plastics and inorganic insulators. However, these insulation materials are often criticized for their manufacturing processes, which are neither sustainable nor environmentally friendly. Researchers are increasingly interested in developing new insulation materials based on natural fibers due to their low cost and low environmental impact [4,5].

Many studies have focused on the development of thermal insulation materials derived from natural sources, both with and without binders [6,7]. These studies have conducted measurements and obtained promising results that are comparable to existing materials. Organic materials have renewable characteristics and exhibit exceptional hygrothermal properties, making them a viable contender for replacing traditional composites in the foreseeable future [8,9]. Cetiner et al. [10] examined the use of wood waste as an insulation material. The thermal conductivity values of wood waste at different densities are slightly higher than those of commonly used inorganic-based insulation materials. However, they are comparable to other natural insulation materials available in the market. Notably, these wood waste values offer an economic advantage due to their status as a low-cost by-product.

Addressing contemporary environmental challenges involves the exploration of innovative alternatives for managing waste generated by industrial and agricultural processes [11]. In response to this imperative, researchers have directed their efforts toward repurposing agricultural and industrial waste into insulation materials, mitigating the need for disposal or incineration [12–15]. This approach not only ameliorates the economic and environmental impact but also aligns with sustainable practices by utilizing natural and locally available waste resources, concurrently reducing dependency on oil and non-renewable sources.

Textile industry fabrics, a subject of sustained interest for thermal insulation producers in the construction sector over decades, have experienced a notable expansion in application. Particularly, recycled textile wastes have emerged as preferred materials for reinforcing buildings, owing to their commendable properties encompassing toxicity absorption, air purification, low thermal conductivity, high heat capacity, hygrometric comfort, vibration absorption, and minimal radioactive emissions. These materials exhibit a symbiotic affinity with human occupants and contribute to sound absorption coefficients, thereby enhancing environmental sustainability and aligning with principles of sustainable development [16].

Currently, there is a growing interest in utilizing agricultural residues or naturally occurring materials such as *Posidonia oceanica* (PO), also known as Neptune grass, which thrives abundantly in the Mediterranean Sea. During spring, this seagrass produces floating fruits known as 'olives of the sea'. PO, has been applied across various fields, including biotechnology, environmental decontamination, bioplastic and bio-composite preparation, and construction materials [17,18]. It has also been used as reinforcement for cement [19,20], adobe [21], lime [22], and gypsum [23] enhancing the thermal and mechanical properties of these materials. The combination of marine grass with cement yields more interesting results in terms of compatibility, particularly for outdoor applications compared to pine wood [24].

In addition, the incorporation of PO fiber into plaster has been very efficient to enhance both mechanical and thermophysical properties of the resulting mixture. In a comparative study conducted by Aldi Kuqo et al. [25], geopolymer panels incorporating wood fibers and Posidonia fibers were examined. The findings revealed that panels with Posidonia fibers exhibited superior resistance to fire, water, and bending when compared to those incorporating wood fibers. to study the impact of adding PO to the mechanical performance of cement. Allegue et al. [26] observed that composites reinforced with PO fibers displayed enhanced mechanical properties when compared to conventional cementitious materials. The marine waste from PO exhibited good insulating properties compared to other conventional natural fibers such as hemp and flax [27]. In comparison with conventional insulators, the plant demonstrated similar thermal performance. Hamdaoui et al. [28] obtained a thermal conductivity results ranged from 0.070 to 0.047 W.m^{-1}.K^{-1} as well as a thermal diffusivity between 3×10^{-7} and 10×10^{-7} m^2.s^{-1}.

In the perspective of designing a 100% eco-friendly and sustainable building material, extensive research has been conducted to find natural binders offering good results in terms of thermal conductivity and material strength. Many researchers have sought to develop new adhesives for the design of eco-friendly materials. such as starch and guar gum [29]. The incorporation of binders in fiber-based materials enhances their mechanical properties [30]. Starch is used as a binder for materials by several researchers, including Elias Harb et al. [31], who demonstrate the possibility of developing starch and beet pulp-based materials as sustainable and load-bearing insulation for use in the construction sector. Indra Muizniece and Dagnija Blumberga [32] showed that by using minimal amounts of potato starch as a binder for conifer needles, the material's physical properties can be ensured without negatively affecting thermal properties when designing thermal insulation to achieve the best mechanical and hygrothermal characteristics of an agricultural material based on hemp and starch Alexandra Bourdote et al. [33] discovered that a hemp/starch ratio of 8 constitutes the optimal composition.

In the process of designing a food-based material utilizing hemp and starch, the researcher achieved a thermal conductivity of 0.05 W.m^{-1}.K^{-1}. This value is lower than the typical thermal conductivity values for hemp concrete. Additionally, the material demonstrates effective acoustic insulation properties [34].

The thermal conductivities for the insulation material, composed of date palm tree surface fibers with cornstarch resin as a binder, range between 0.0475 W.m^{-1}.K^{-1} and 0.0697 W.m^{-1}.K^{-1}. These values were obtained across densities spanning from 176 kg.m^{-3} to 260 kg.m^{-3} [35]. Table 1 provides a concise summary of the composition of plant fibers and binders used in insulation materials. Referring to this table, it is noticed that the fiber-starch composition yields more favorable thermal conductivity results, even with low percentages, in comparison to other binders.

Table 1. Synthesis of composition of plant fibers and binder in insulation materials.

Fibers	Binder	Percentage	Thermal Conductivity (W.m^{-1}.K^{-1})	References
PO	Cement	Po = 0–20%	0.0559–0.0778	[19]
PO and straw	Adobe	Po = 0.5–1.5–3%	0.63–0.83	[21]
Coniferous needles	Potato starch	C/S ½–1/1.5–1/1	0.0478–0.0524	[32]
Hemp	Wheat starch	H/S 0.14–0.16–0.19–0.21–0.24–0.27–0.31–0.38	0.05	[34]
Wine industry by-products	Potato starch	Starch/Aggregate 20%	0.075	[36]

This study explores the potential and the viability of a novel bio-sourced insulation material made from PO waste as a sustainable solution for building insulation in Algeria, where climate and economic factors converge to make energy-efficient construction an imperative. This material is derived from waste generated by the marine plant PO, which is abundant along the Algerian coastline, and a natural starch-based adhesive. The incorporation of PO waste into a composite material for building insulation, especially considering its unique properties and availability, distinguishes this work from previous studies. Furthermore, the combination of PO waste and cornstarch-based adhesive to create an insulation material has not been extensively explored in the existing literature, particularly with a focus on building insulation applications.

2. Materials and Methods

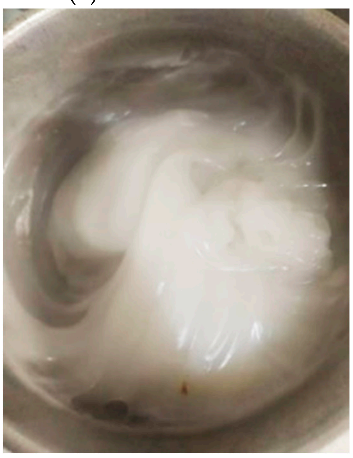
2.1. Sample Preparation

The following steps in sample preparation allowed us to obtain samples of PO reinforced with starch, with varying proportions of binder, for the thermal tests (Figure 1):

- The fibers used were waste from the PO plant, found on the coastal of the Tipaza province. The fibers were collected from the plant's dead leaves ensuring lengths ranging from 2 to 5 cm.
- The fibers were mechanically ground to achieve the desired size.
- The binder used was a natural starch-based adhesive. The volume fractions of binder used were 15%, 20%, 25%, and 30%. The selected range aimed to strike a balance between the need for mechanical strength and the desire to maintain low thermal conductivity [33]. The adhesive was prepared by mixing water and starch in a water-to-starch ratio of 0.15.
- Specimens with dimensions of $15 \times 10 \times 4$ cm^3 were used for thermal tests.
- After fabrication, the specimens were stored in a room at room temperature for 48 h. Then, they were stored for 28 days to allow for curing.

(**a**) Fiber collection

(**b**) Fiber grinding



(**c**) Adhesive production

(**d**) Binder preparation

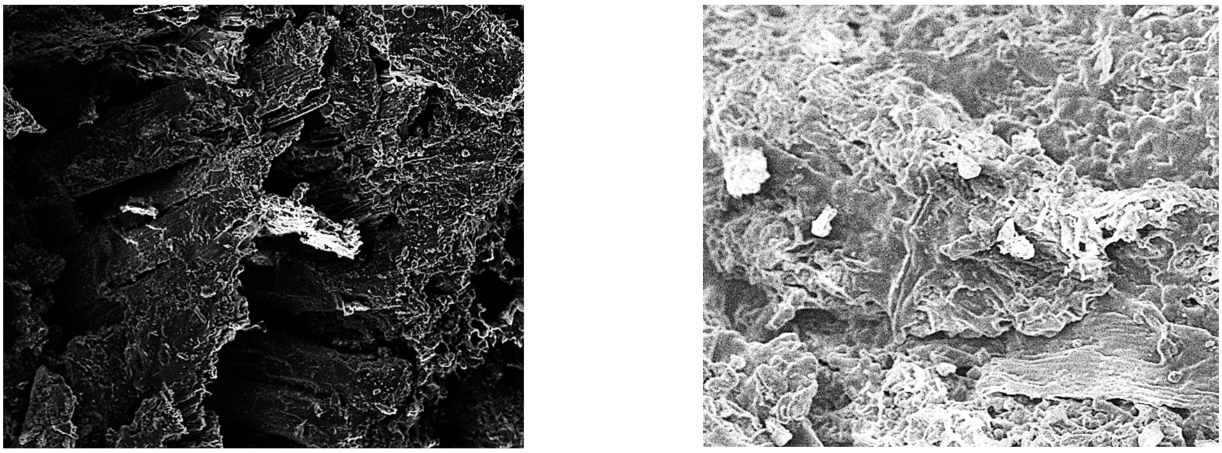
Figure 1. Preparation of starch binder.

2.2. Testing Methods

The fibers were placed in a mixer and agitated for 2 min to separate them (Figures 2 and 3). Then, the adhesive was added in specific quantities, and the mixture was kneaded. The final kneading was done to homogenize the fibers with the binder. Once homogeneous, the mixture was placed into the specimens.

(**a**) Starch binder (**b**) Fibers with adhesive

Figure 2. SEM images for *Posidonia oceanica* fibers reinforced paste (20% and 30%).



(**a**) Fibers (**b**) Fiber adhesion with binder

Figure 3. SEM images for *Posidonia oceanica* fibers reinforced paste (15%).

The scanning electron microscopy results are illustrated in Figure 2, where it can be observed that the fibers are dispersed throughout the material, while the adhesive ensures their adhesion. Due to the low percentage of adhesive used and the arrangement of fibers in the material, empty pores are present (Figure 3), which are considered as gaps that help trap heat.

The performance of an insulation material is related to its thermal conductivity and its heat capacity. An interesting material has low thermal conductivity and high heat capacity. To evaluate the thermal characteristics of the samples, thermal conductivity and specific heat were determined on three specimens with dimensions of $(10 \times 15 \times 4)$ cm^3 at the age of 28 days, using a CT-Meter machine (Figure 4), according to the standard NF EN 993-15 [37].

In order to investigate the capillary water absorption of the samples, specimens with dimensions of $(4 \times 4 \times 16)$ cm^3 have been selected. The procedure involves placing the sample vertically, with one face of the sample in contact with a water table maintained at a constant level and measuring the weight gains of the sample at defined time intervals. The lateral faces of the sample are previously rendered impermeable by coating them an epoxy layer, allowing the water to follow a unidirectional path and preventing evaporation through these same faces according to the standard NF EN 1305758 at the age of 28 days [38]. The average bulk density of three dried specimens, each measuring $(4 \times 4 \times 16)$ cm^3, was determined at 28 days. The weight of the samples was measured in air after they were dried, and their volume was calculated using the water displacement method.

Figure 4. Thermal conductivity tests.

The lateral faces of the sample are previously rendered impermeable by coating them an epoxy layer, allowing the water to follow a unidirectional path and preventing evaporation through these same faces according to the standard NF EN 1305758 at the age of 28 days [38]. The average bulk density of three dried specimens, each measuring $(4 \times 4 \times 16)$ cm^3, was determined at 28 days. The weight of the samples was measured in air after they were dried, and their volume was calculated using the water displacement method.

3. Results and Discussion

3.1. Thermal Conductivity

According to Figure 5, the thermal conductivity decreases from 0.0674 to 0.0528 W.m^{-1}.K^{-1} for a 15% concentration. The obtained results indicate that an increase in the proportion of adhesive leads to an increase in thermal conductivity. Furthermore, it was observed that a 15% proportion of adhesive yields the best results in terms of conductivity. This observation can be explained by the fact that a lower quantity of adhesive leaves voids after drying, resulting in the formation of a porous structure in the material (Figure 2). This structure helps slow down the heat transfer. The thermal conductivity of the material is considered acceptable compared to bio-composite panels made from hemp and cornstarch, which have a thermal conductivity ranging from 0.059 to 0.068 W.m^{-1}.K^{-1} [39]. Additionally, for plaster + gelatin + straw composites, Brahim Ismail et al. [40] found a thermal conductivity of 0.057–0.058 W.m^{-1}.K^{-1}. In comparison to flax, hemp, cork, and kenaf, the material exhibits similar thermal conductivity values [41].

3.2. Density

Figure 6 present the variation of the material density with the fraction volume of adhesive. As can be seen, the studied material exhibits a density ranging from 265 to 302 kg.m^{-3}. This density increases with the increase of the adhesive volume fraction due to the reduction of material porosity. As the adhesive volume fraction increases, there is a greater amount of adhesive available to infiltrate the interstitial spaces and coat the individual fibers. This enhanced bonding and penetration result in a denser and more closely packed fiber structure, as the fibers are effectively bound together and fill the voids, reducing the overall porosity. Consequently, the higher adhesive volume fraction leads to a denser composite material, ultimately increasing its overall density. A study conducted by Satta Panyakaew et al. revealed a density of 350 kg.m^{-3} for a thermal insulator made from coconut husks and bagasse [42]. Additionally, Aliaksandr Bakatovich et al. found a density of 200–250 kg.m^{-3} for a straw-based insulation (barley, oats, rice, rye, wheat) [43].

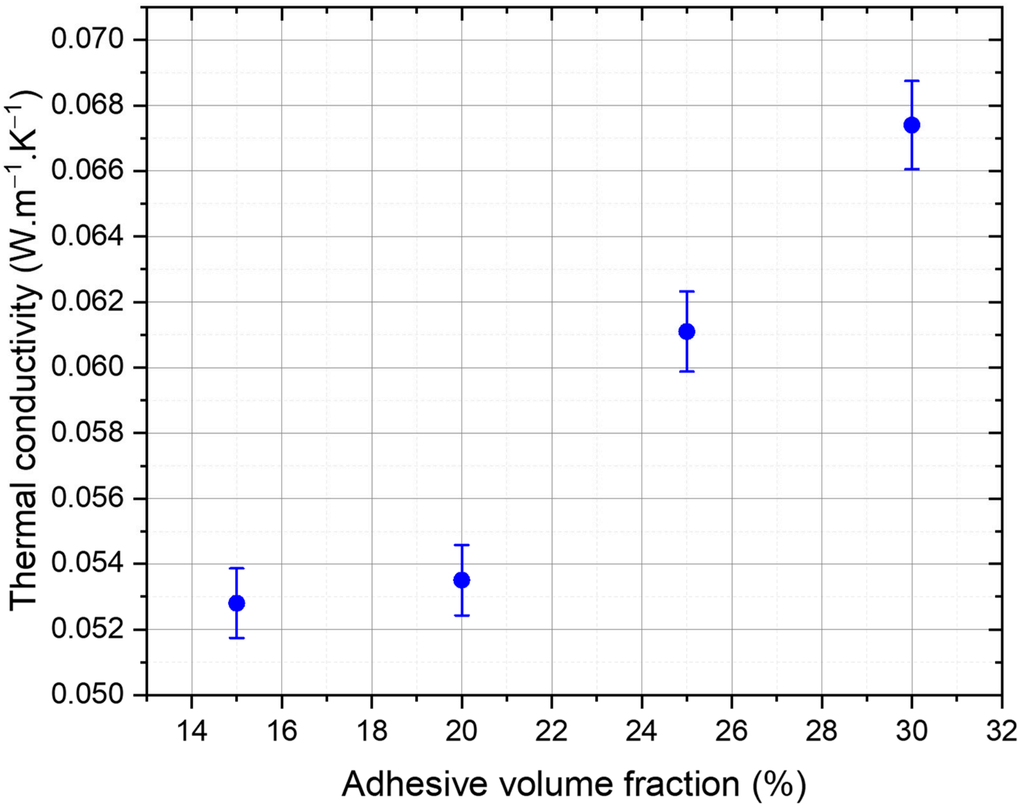


Figure 5. Thermal conductivity as a function of adhesive volume fraction.

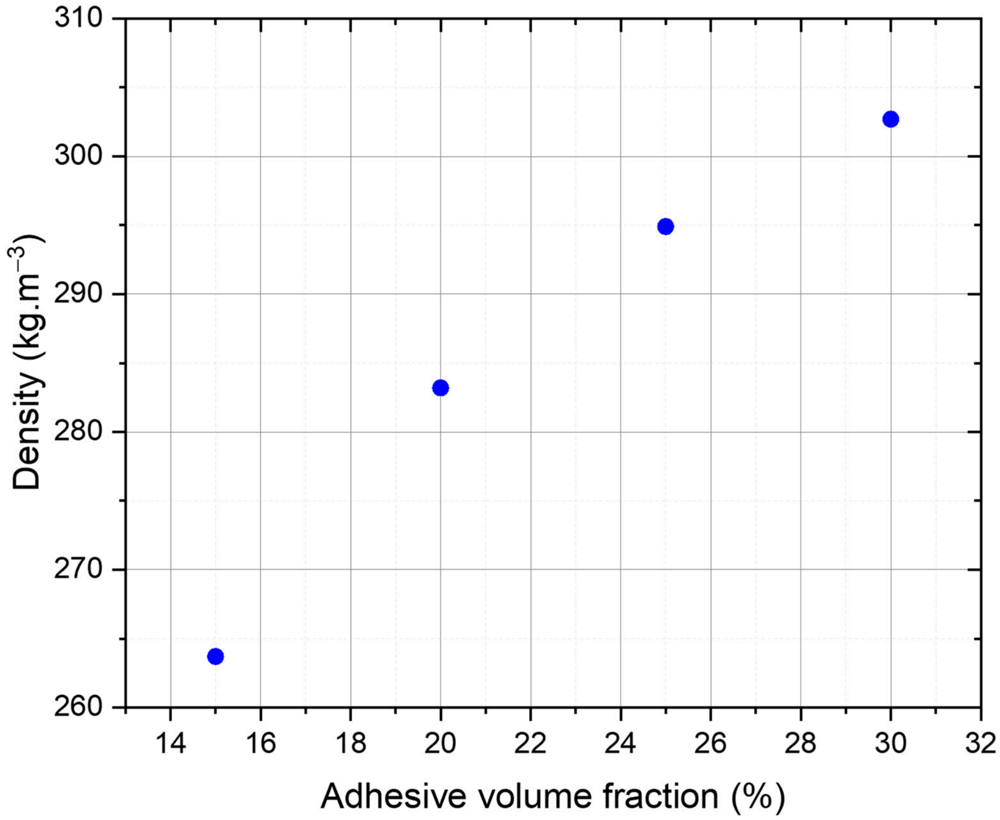


Figure 6. Density as a function of adhesive volume fraction.

3.3. Heat Capacity

The variation of heat capacity of PO fibers with the volume fraction of adhesive is shown in Figure 7. For an adhesive volume fractions between 15 and 30%, an increase in specific heat is observed due to the high viscosity and molecular structure of cornstarch adhesive. The high viscosity of starch-based adhesives suggests a high molecular weight and complex molecular structure. The large and complex molecules may have a higher number of vibrational modes and degrees of freedom, contributing to increased heat capacity [44,45]. The heat capacity values of PO fibers range between 1492.8 J.kg^{-1}.K^{-1} and 1807.5 J.kg^{-1}.K^{-1}. Due to their relatively high Cp-values, these fibers could be regarded as a promising insulation material.

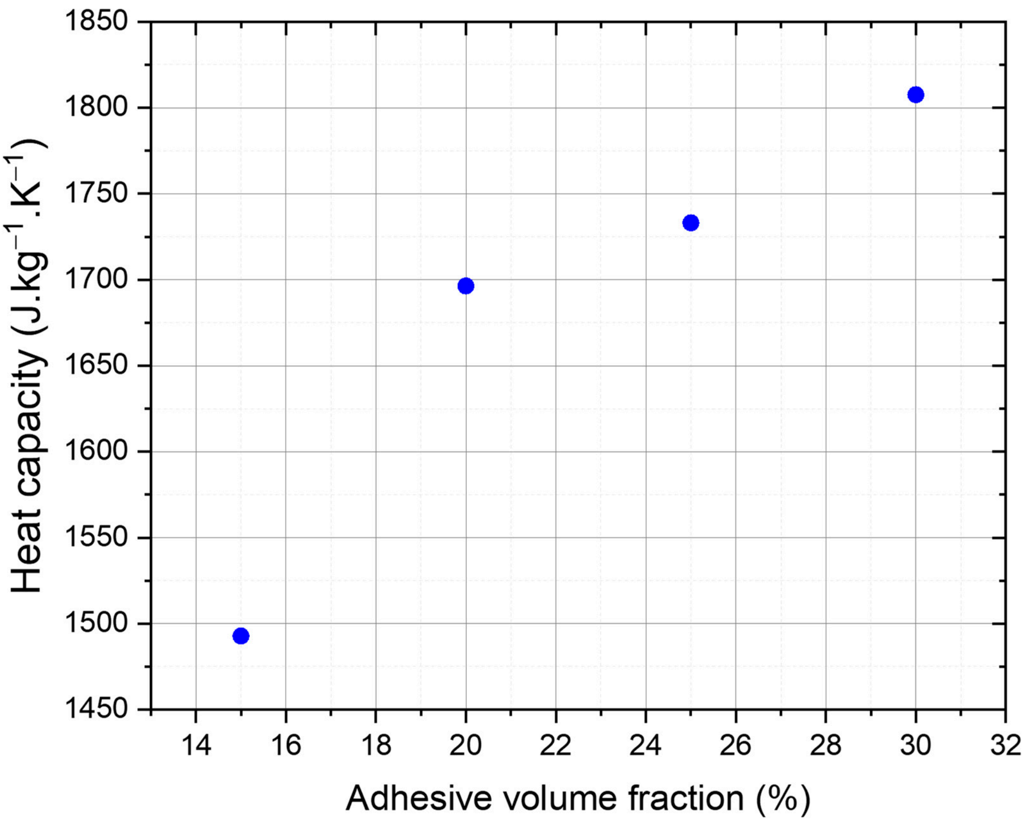


Figure 7. Heat capacity as a function of adhesive volume fraction.

Table 2 provides a comparison between Posidonia-based insulation and insulation from the literature. According to this table, researchers have chosen binder percentages ranging from 20% to 30% for fibers to achieve notable thermal properties [46–51]. In this study, binder percentages were selected within the range of 15% to 30% because, below 15%, the material lacks cohesion, while beyond 30%, a considerable increase in thermal conductivity is noted.

The material exhibits density and thermal properties similar to insulators crafted from bagasse and coconut fibers, utilizing binders containing Arabic gum. Furthermore, it closely parallels insulators made from Cork Pellets (developed) and Rice Husks with a Toluene Diisocyanate Polyurethane binder (20%) [46], along with Wood fibers/textile waste fibers employing a Sodium alginate binder [52]. This resemblance contributes to the observed low thermal conductivity in these insulation materials.

The higher density observed in alternative insulations is primarily attributed to the fiber or binder nature [46–51], such as sand and clay binders, resulting in increased thermal conductivity. In contrast, the specific heat and thermal diffusivity values of rice straw with sodium alginate and chitosan closely resemble those observed in the insulations studied by researchers.

Table 2. Comparison between Posidonia-based insulation and insulation from the literature.

Materials	Binder	Density ($kg.m^{-3}$)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Heat Capacity ($J.kg^{-1}.K^{-1}$)	Thermal Diffusivity ($m^2.s^{-1}$)	References
Cork Pellets (developed) and Rice Husks	Based on Toluene Diisocyanate Polyurethane (20%)	199–390	0.045–0.080	1329–1793	N/A *	[46]
Bagasse and Coconut Coconut Granules	Arabic Gum (33%)	245–276	0.015	1141	5.15×10^{-5}–9.14×10^{-5}	[47]
Date Palm Surface Fibers	Expanded Polystyrene (EPS)	970–930	0.053	1400	4.5×10^{-8}	[48]
Olive Fiber	Clay + Sand	958.91	0.428	1409	295×10^{-6}–387×10^{-6}	[49]
Typha	Starch	670.66–891.54	0.094–0.534	1590–1640	3.77×10^{-7}–9.0×10^{-8}	[50]
Wood Particles (palm oil), Ramie Fiber	Tapioca Starch (30%)	660–790	0.067–0.148	N/A	N/A	[51]
Wood fibers/textile waste fibers	Sodium alginate	308–333	0.078–0.089	1320–1402	193×10^{-7}–236×10^{-7}	[52]
Rice straw	Sodium alginate and chitosan	104–162	0.038–0.47	1428–1140	N/A	[53]
Posidonia-Based insulation	Corn starch	263–302	0.052–0.067	1493–1807	1.11×10^{-7}–1.23×10^{-7}	This study

* N/A: Not Assessed.

3.4. Capillary Absorption

Figure 8 illustrates the relationship between adhesive concentration and water absorption. It is evident that an elevation in the concentration of adhesive results in an increase in water absorption. This phenomenon can be attributed to the adhesive forming a denser and more impermeable layer on the material's surface as its concentration rises. This denser adhesive layer acts as a barrier, reducing the material's ability to absorb water. In addition, the water absorption coefficient increases as the material's density rises which suggests that denser materials are more effective at absorbing water. This relationship can be attributed to the compactness of the material's structure and its chemical composition. Denser materials typically have fewer empty spaces or pores, reducing their ability to repel water, and they may also feature chemical properties that promote interactions with water molecules. As a result, higher-density materials exhibit a greater capacity to absorb water per unit mass or surface area, which has important implications for material design.

Significantly, it was observed that the incorporation of 30% adhesive led to the most favorable results in terms of water absorption. It is interesting to note that the fibers tend to absorb water. These findings are consistent with the results obtained by Laurent Molez et al. [54] showing that the addition fibers to mortar causes a more or less pronounced increase in the capillary absorption kinetic coefficient. These results are also supported by Boukhalkhal et al. [55]. Jemi Merrin Mathews et al. [56] explained that the observed phenomenon is attributed to the cellulosic nature of the cardboard aggregates. This characteristic, coupled with the augmented presence of air voids in the composite material, ultimately leads to a notable increase in water absorption.

3.5. Thermal Diffusivity

Figure 9 illustrates the variation of the thermal diffusivity of PO fibers as function of adhesive volume fraction. A reduction in thermal diffusivity within the sample is observed when the volume fraction of adhesive is at 20%, 25%, and 30%. This decline is attributed to the decrease in fiber volume relative to that of the adhesive, resulting in a denser material.

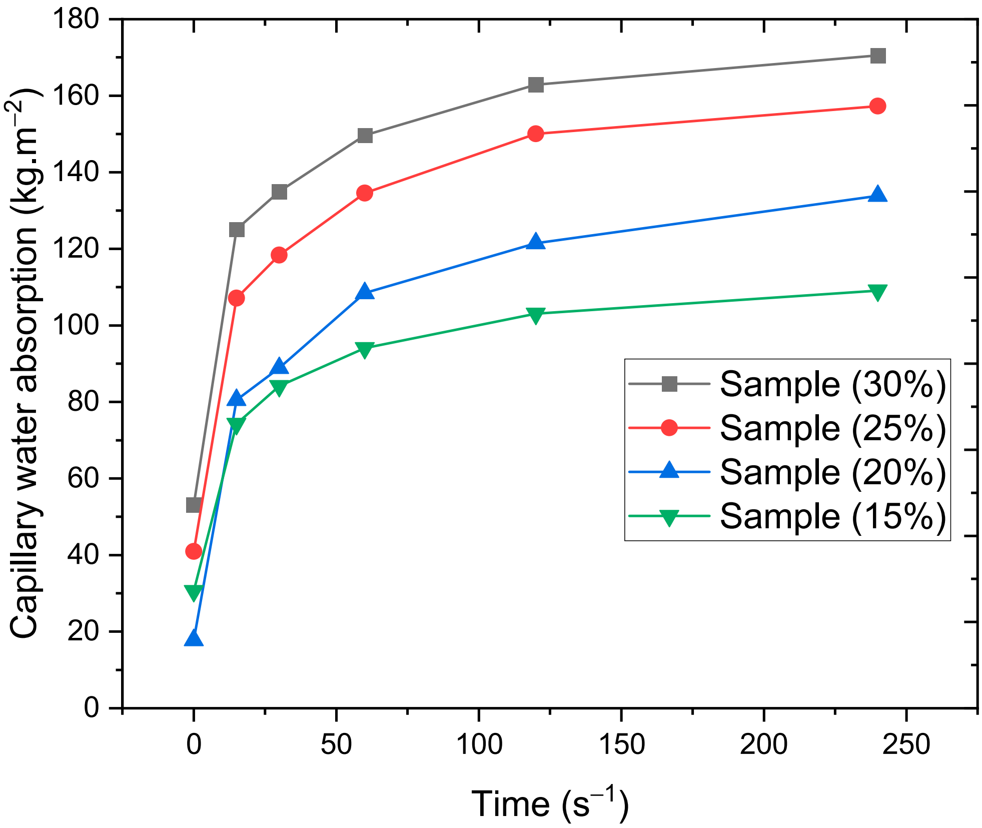


Figure 8. Relationship between adhesive concentration and water absorption.

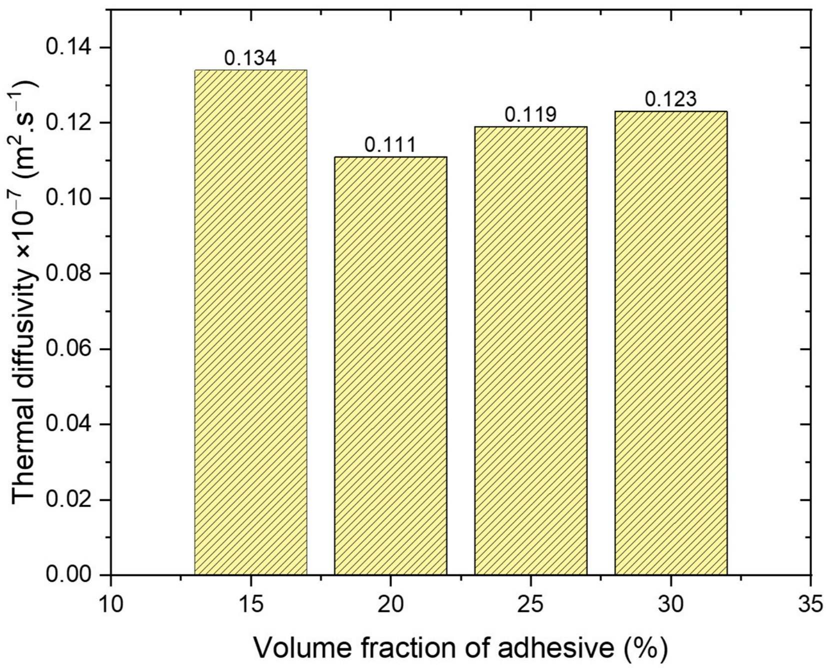


Figure 9. Thermal diffusivity as function of adhesive volume fraction.

The thermal diffusivity results align closely with the values found in wood-based insulation [10]. The incorporation of hemp fibers into clay reduced thermal diffusivity by up to 27%. An effective insulation material must combine low thermal conductivity with the ability to retard heat transmission [57]. Equation (1) was used to calculate the thermal diffusivity.

$$\alpha = \frac{\lambda}{\rho \times C_p} \quad (1)$$

where: α is the thermal diffusivity, λ is the thermal conductivity, ρ is density, and C_p is the heat capacity.

Figure 10 presents the thermal diffusivity values for different insulation materials. When comparing PO fibers with insulation materials commonly used in industrial applications, acceptable values of thermal diffusivity are observed relative to their density making it a promising option for applications where both insulation efficiency and material weight are important considerations.

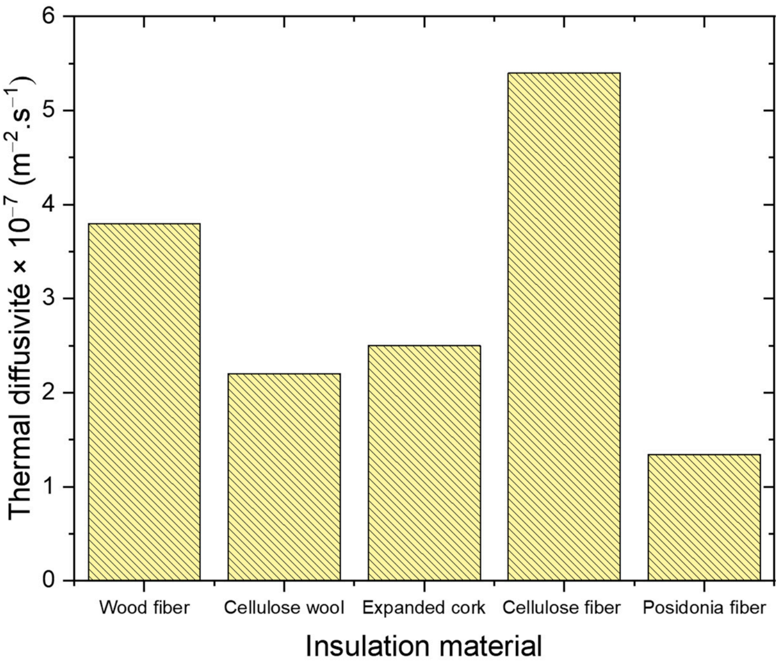


Figure 10. Thermal diffusivity of various insulation materials.

3.6. Heating Energy Consumption

Thermal insulation has advantages over other building materials in terms of better thermal comfort, less energy use and heat loss, cheaper heating expenses, and a favorable effect on the environment and climate due to lower energy consumption [58]. To assess the effectiveness of the thermal insulation, a dynamic simulation using the software TRNSYS 17 (A transient system simulation program, University of Wisconsin, Solar Energy Laboratory, Madinson, WI, USA, 2010) was conducted to evaluate the energy requirements of a single room in the region of Medea (Algeria). TRNSYS can derive the thermal behaviour of every building component that is classified by a Type. Each Type works with input data and transforms them in output values, which are used in the other simulations.

Figure 11 illustrates the monthly variations of the heating energy use for the prototypical room without and with PO insulation. Without seagrass insulation, the dynamic simulation offers limited heating energy use reduction, especially during the coldest winter months. However, following the reinforcement of the exterior envelope with a 10 cm thick PO insulation, the dynamic simulation achieves extra savings, including during the months of January, February, and December, and the heating energy needs decreased by 200 kWh during the most adverse months. This implies about 10% reduction in heating energy consumption. The analysis results clearly indicate that the performance of PO insulation has effectively contributed to increased energy efficiency, resulting in both economic benefits and a reduced environmental impact associated with heating resource consumption.

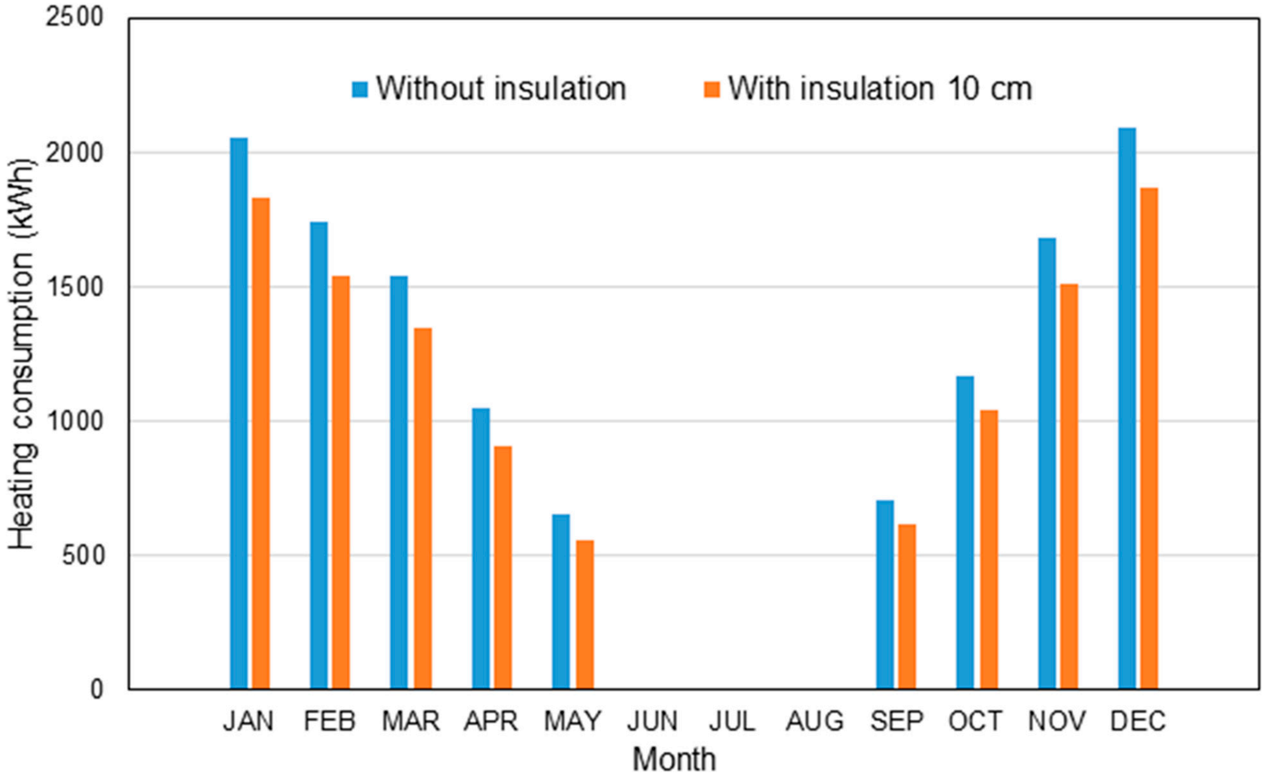


Figure 11. Comparison of monthly home heating consumption without and with PO insulation.

4. Conclusions

The objective of this study was to design a new thermal insulation material suitable for buildings, using local bio-sourced materials. To achieve this goal, the waste fibers from PO, available in the Algerian coastal region, were developed along with a natural binder derived from cornstarch. In addition, a series of experiments were conducted to evaluate the thermal performance of the bio-based composite material, and the following findings have been established:

- The measured thermal conductivity of the PO fiber is found to be ranged from 0.0528 to 0.0674 W.m^{-1}.K^{-1}, with a diffusivity between 1.11 × 10^{-7} and 1.23 × 10^{-7} m^2.s^{-1}. The obtained values make the material a promising candidate to compete with other industrial insulators.
- The obtained values of heat capacity of PO fibers vary from 1807 J.kg^{-1}.K^{-1} to 1492 J.kg^{-1}.K^{-1}. These fibers could be considered an interesting insulation material because of their relatively high Cp-values.
- Increasing the adhesive volume fraction in PO fibers effectively increases the mass of the material without significantly changing its volume. This results in a denser material, which can have advantages in terms of structural stability and thermal performance, although it may slightly reduce the material's insulation properties.
- Increasing the concentration of adhesive on a material's surface effectively reduces its water absorption capacity by enhancing bonding, reducing porosity, increasing hydrophobicity, and improving water resistance.

In addition, a simulation conducted using TRNSYS software for a single room in the region of Medea (Algeria) demonstrated that the reinforcement of the exterior envelope using a 10 cm thick insulation, heating energy requirements decreased by 200 kWh during the coldest months, resulting in an impressive 10% reduction in heating energy consumption. This improvement not only signifies potential cost savings but also indicates a more energy-efficient and environmentally friendly building.

Nevertheless, it should be noted that the bio-sourced material exhibits limited water absorption performance due to the use of this marine plant. Nevertheless, it can still be employed in buildings in Algeria due to the availability of the raw material, its low cost, and its energy-efficient manufacturing process. By exploiting this material, it is possible to reduce the energy consumption of buildings while providing appreciable thermal comfort.

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Conflicts of Interest: The authors declare no conflict of interest.

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