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Communication

Evaluation of Two Chilean Native Macroalgae: "Pelillo" (*Gracilaria chilensis*) and "Lamilla" (*Ulva* sp.) for Thermal Insulation Application

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Abstract: Energy consumption in the residential sector and air pollution are relevant topics for the global population. One of the causes, especially in cold climate cities, is that buildings maintain a high energy consumption for heating and cooling, primarily using low-efficiency biomass combustion for heating, which releases a significant amount of particulate matter into the environment. In this context, thermal insulation materials play a crucial role in reducing the energy demand of buildings, requiring advancements in the sustainable development of such materials within the context of climate change. This study carried out an evaluation of two algae species found along the Chilean coasts, with the aim of characterizing them and creating a prototype of a sustainable material. Their physicochemical properties were analyzed, and the results demonstrate that the algae exhibit excellent thermal insulation properties, with an average thermal conductivity of 0.036 [W/mK]. This result is comparable to expanded polystyrene (EPS), a widely used material in the Chilean and global markets, which has an average thermal conductivity value of 0.038 [W/mK]. Additionally, the algae show a good thermal stability, and their morphology contributes to the development of a bulk material, as they possess a porous structure with air chambers between the fibers.

Keywords: energy efficiency; natural thermal insulation; low environmental impact material; sustainability

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1. Introduction

In various cities worldwide, high concentrations of particulate matter have been observed due to biomass combustion in the residential sector. Fine particles (PM2.5) have been attributed significant responsibility for serious respiratory illnesses in humans [1,2]. Moreover, buildings have been shown to account for over 35% of global energy consumption [3,4]. Hence, it is essential to analyze and enhance the energy efficiency of buildings, particularly during the design phase [5–7]. This juncture is crucial, as it allows for the specification of appropriate thermal insulation materials to reduce energy consumption in buildings, directly impacting the reduction of particulate matter emissions during the operational phase of constructions [8–11].

In Chile, as part of the strategies proposed by the Ministry of Housing and Urbanism (MINVU), there is an initiative to "enhance thermal insulation standards for homes", with the goal of reducing heating demand. While this strategy is widely applied and recognized globally, it has led to an increase in the demand for thermal insulation materials in the country. Simultaneously, there has been a rise in environmental impacts associated with projects, as companies continue to purchase synthetic and high energy content products [12,13]. In this context, the local market lacks environmentally friendly materials that can compete cost-effectively with traditional materials, especially expanded polystyrene, the most widely used material in the country's buildings [14].

For this reason, various research efforts have focused on developing new materials that can compete in the market and have demonstrated the potential to create and utilize new environmentally low-impact insulation materials with residual natural fibers or recycled products [15,16]. These materials also maintain thermal comfort conditions and reduce energy consumption during the building's operational phase [17,18]. For instance, in 2018, Cárdenas et al. developed a thermal insulation material using a natural polymer obtained from the Hydrangea Macrophylla plant, achieving an average thermal conductivity result of 0.042 [W/mK], comparable to traditional insulation materials [19]. In the same year, Rojas et al. created a prototype thermal insulation material from forest residues using the pulping method, achieving an average thermal conductivity of 0.040 [W/mK] [20]. By applying recycled paper cellulose in combination with wheat straw through a dry application method, average conductivity values of 0.041 [W/mK] were achieved, highlighting the potential of internal air chambers for all types of thermal insulation materials [21]. In 2020, Soto et al. evaluated an organic herbaceous fiber from the legume family called pisum sativum, determining an average conductivity value of 0.04 [W/mK] for a prototype fiber with a density close to 100 [kg/m^3] when the residue was applied dry [22].

Despite evidence of the development of thermal insulation materials from residual raw materials, most of these efforts have focused on agricultural and forest waste, leaving aside the assessment of the thermal potential that algae from Chilean coasts possess. It has been stated that algae can absorb ultraviolet radiation and carbon dioxide, and their long fibers can slow down the flow of heat through them [23]. However, there have been no specific or more in-depth studies of their physical properties (thermal performance) or a proposal for a thermal insulation material using these residual fibers [24]. Therefore, this study conducted a physicochemical evaluation and characterization of two Chilean algae species, Pelillo (*Gracilaria chilensis*) and Lamilla (*Ulva* sp.), with the aim of developing two thermal insulation materials to reduce thermal energy losses in buildings. Stretching across the extensive 4000 km of Chilean coastline, lies a rich diversity and abundance of algae. In the year 2014, a staggering total of over 28 million tons of algae were harvested, although specific data regarding the production levels of individual algae types remains unavailable [25]. This work aligns with and contributes to Sustainable Development Goal (SDG) 13 set forth by the United Nations General Assembly.

2. Materials and Methods

2.1. Materials

The algae were gathered from the coastal shores of Quinchao Island, part of the Chiloé archipelago, Chile. These collections were conducted on beaches designated for material harvesting, specifically in the Putique sector. Figure 1 illustrates the algae within the harvesting area.

Subsequently, the algae were air-dried on both sides at ambient temperature within the same beach vicinity. Any surplus sand was eliminated before the samples were transported to the laboratory for measurement and testing purposes. The algae were manually defibrated and stored in airtight containers for the duration of the measurement and testing process in order to protect their integrity during this process.

Figure 1. Pelillo and Lamilla in extraction meadow.

2.2. Moisture

The moisture content was determined using a BOECO moisture analyzer, model BMA H50, featuring a power output of 400 [W]. This instrument operates via a halogen light within a temperature range of 10–40 °C, yielding precise results with an accuracy of 0.001%. The equipment employs a gradual heating process with designated time intervals, during which alterations in sample mass are recorded until the device detects a consistent mass.

2.3. Density

This characteristic was assessed by establishing a correlation between the mass of algae that could be accommodated (without compression) within a cylindrical polyvinyl chloride sample of volume 393.55 [cm^3]. These cylindrical specimens form the foundation for measuring the thermal conductivity of the samples.

2.4. Thermal Conductivity

This measurement was conducted using the Decagon "KD2 Pro" instrument, which is based on the "Transient Line Heat Source" technique and adheres to the specifications outlined in the IEEE 442-1981 standard and ASTM D5334-08 [26,27]. This method has been applied in previous studies due to its ability to swiftly yield results with minimal error, given that the measurement principle aligns with fibers of this kind, which generate internal air chambers [28].

To delve deeper into the thermal characteristics of the algae, triplicate measurements were executed at various density levels of the samples. Specifically, Pelillo was assessed within the range of 60–80 [kg/m^3], while Lamilla was investigated within the range of 50–70 [kg/m^3].

2.5. Thermal Stability

The algae were first prepared by drying in an oven at a consistent temperature of 40 °C, followed by subsequent crushing until achieving homogeneous samples. The measurements were carried out using a TGA/DSC STA6000 instrument from Perkin Elmer, Waltham, Massachusetts, United States. The selected purge gas and carrier gas was nitrogen (N2) at a flow rate of 40 mL/min. The temperature program employed was as follows: an initial heating phase from 25 °C to 120 °C at a heating rate of 50 °C/min; followed by a 3 min hold at 120 °C; subsequent heating from 120 °C to 950 °C at a rate of 100 °C/min; then cooling from 950 °C to 450 °C at a rate of 100 °C/min, involving a gas switch to oxygen at a flow rate of 40 mL/min; further heating from 450 °C to 800 °C at 100 °C/min; and, lastly, a 3 min isothermal period at 800 °C.

2.6. Surface Analysis (Morphology)

The morphological examination of the samples was conducted using scanning electron microscopy (SEM) with a VP-SEM SU 3500 microscope from Hitachi, Tokio, Japan. The microscopy utilized specific magnification settings of 40×, 100×, 200×, and 500×, employing a backscattered electron (BSE) detector at 10 KeV, with a working distance (WD) of approximately 12 mm and a pressure of 30 Pa.

3. Results and Discussion

3.1. Moisture

Under typical conditions, algae possess the capability to rapidly absorb and expel moisture. Therefore, careful measurement and control of their moisture content is imperative to avoid impacting their thermal efficiency [29]. Additionally, all lightweight building elements, whether wood or steel, use vapor and moisture barriers that control the passage of moisture from the interior to the exterior or from the exterior to the interior [30,31]. In this way, algae, as insulation material or otherwise, are protected, and their decomposition is prevented. In this context, Chilean standards address this aspect, and it is also considered that in the summer or hotter season, any remaining moisture in the materials is released into the environment [14,32].

Table 1 provides precise data on fiber measurements, highlighting that Pelillo samples maintained an average moisture content of 12.02%, whereas Lamilla exhibited an average moisture content of 14.91%. These findings can be attributed to the natural open porosity of the fibers and the underlying chemical structure of the fundamental polysaccharide [33,34]. Notably, Lamilla's considerably more porous structure contributes to its elevated moisture content. It is worth noting that these percentages are relatively higher compared to other fibers, such as those composed of lignocellulose, which typically register around 6% moisture content [20]. They remain comparable to conventional insulation materials. Hence, these results bode well for the thermal conductivity potential of algae and their potential utility as thermal insulation materials in building applications [35,36].

Table 1. Moisture content of the samples [%].

Sample	S1	S2	S3	AVG	SD
Pelillo	11.80	11.92	12.33	12.02	0.28
Lamilla	15.68	12.96	16.10	14.91	1.70

3.2. Density

The density of the Pelillo samples fell within the range of 60–80 [kg/m^3], whereas for Lamilla, the density spanned 50–70 [kg/m^3]. These findings align closely with the densities observed in conventional thermal insulation materials, such as glass wool, mineral wool, polyurethane foams, and expanded polystyrene, which typically vary from 10–90 [kg/m^3] [12,37,38]. In contrast, the density results for both types of algae are lower than those of other lignocellulosic fiber materials, which typically range from 105–130 [kg/m^3] [13]. Table 2 provides a comparison of density data among different materials.

Table 2. Materials' density.

Material	Density [kg/m^3]
Pelillo	60–80
Lamilla	50–70
Expanded polystyrene	10–30
Mineral wool	40–90
Glass wool	10–47
Wheat straw	105–115

3.3. Thermal Conductivity

The thermal conductivity measurements are depicted in Figure 2, with the identical procedure applied to each sample of both fibers. It is evident that Pelillo achieved an average thermal conductivity of 0.036 ± 0.003 [W/mK], while Lamilla yielded a value of 0.036 ± 0.004 [W/mK].

Figure 2. Thermal conductivity measurement of samples.

Upon comparing these results with data from other materials, it is apparent that the algae exhibit thermal conductivities akin to conventional materials and surpass those of wheat straw, corn husk, and hybrid composites. The latter materials present thermal conductivity values of 0.046, 0.047, and 0.072 [W/mK], respectively, while expanded polystyrene falls within the range of 0.036 to 0.043 [W/mK] [12,21].

In both types of fibers, optimal outcomes for this characteristic are achieved at minimal densities: 60 [kg/m^3] for Pelillo and 50 [kg/m^3] for Lamilla, as illustrated in Figure 3. This behavior contradicts findings from the work of Gnip I. et al. in 2012, wherein expanded polystyrene and other materials exhibited an improved thermal conductivity as density increased [12]. Conversely, in the case of algae fibers, the trend is inverted due to the fact that as sample density rises, the internal air chambers within the material diminish. This quality stands as a fundamental characteristic of thermal insulating materials [8,16,39].

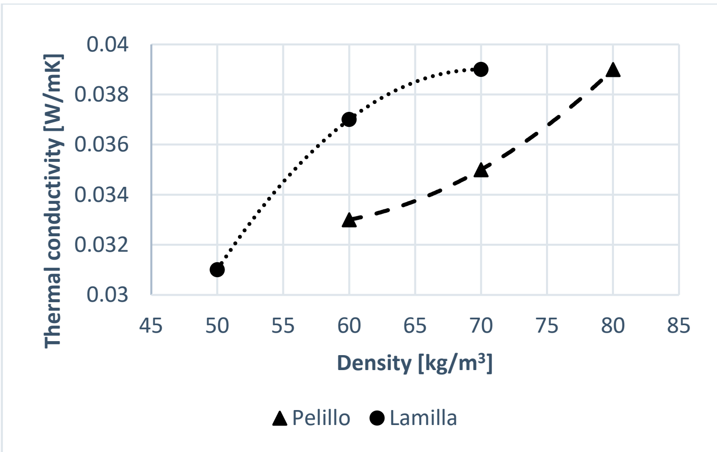

Figure 3. Thermal conductivity and density ratio.

3.4. Thermal Stability

The thermogravimetric analysis of the Pelillo samples is depicted in Figure 4. In the initial 5 min of the test, we observe a temperature rise to approximately 100 °C, resulting in a 21.81% mass loss. This mass loss is attributed to the moisture content of the algae. The most significant mass loss occurs between the 5th and 14th min, within the temperature range of 120 to 700 °C, accounting for 46.24% of the mass. This loss is associated with volatile solids. Upon cooling, in an oxygen-rich environment, a portion of the organic matter, identified as fixed carbon (11.23% of the sample), is consumed. Consequently, it is indicated that this algae exhibits thermal stability up to approximately 120 °C. Therefore, when processing the fiber for its use as a thermal insulating material, it is advisable not to exceed this temperature to avoid compromising the material's structural integrity.

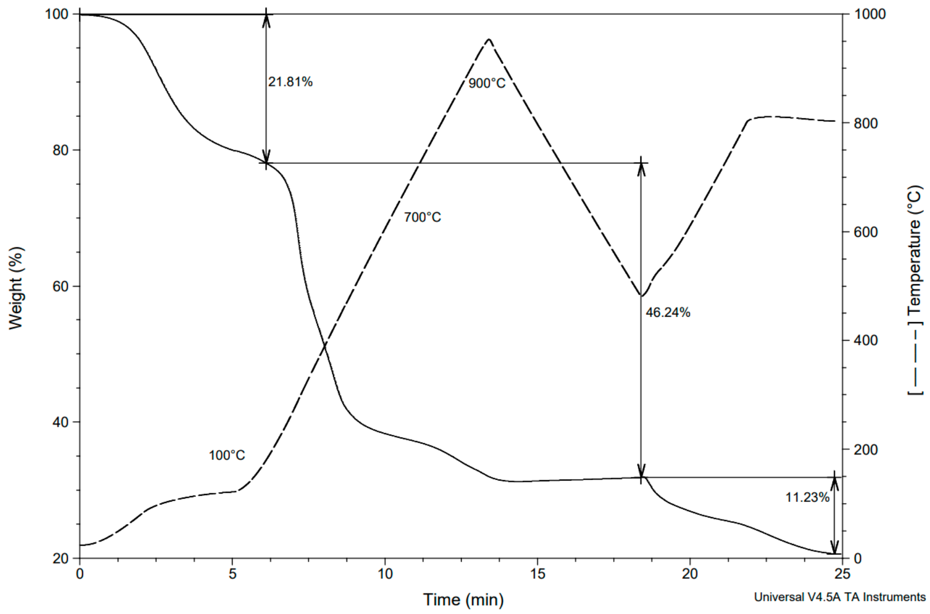

Figure 4. TGA samples from Pelillo.

The thermogravimetric analysis of the Lamilla samples is presented in Figure 5. In the initial 4 min of the test, we observe a temperature rise to approximately 100 °C, resulting in an 8.22% mass loss, which is attributed to the moisture content of the seaweed. Subsequently, between the 6th and 14th min, within the temperature range of 200 to 700 °C, there is a mass loss of 45.28%, primarily associated with volatile solids. During the cooling phase, in an oxygen-rich environment, a portion of the organic matter, identified as fixed carbon (2.42% of the sample), is consumed. Consequently, it is indicated that this algae exhibits thermal stability around 200 °C. Therefore, when processing the fiber for its use as a thermal insulating material, it is advisable not to exceed this temperature to prevent structural damage to the material.

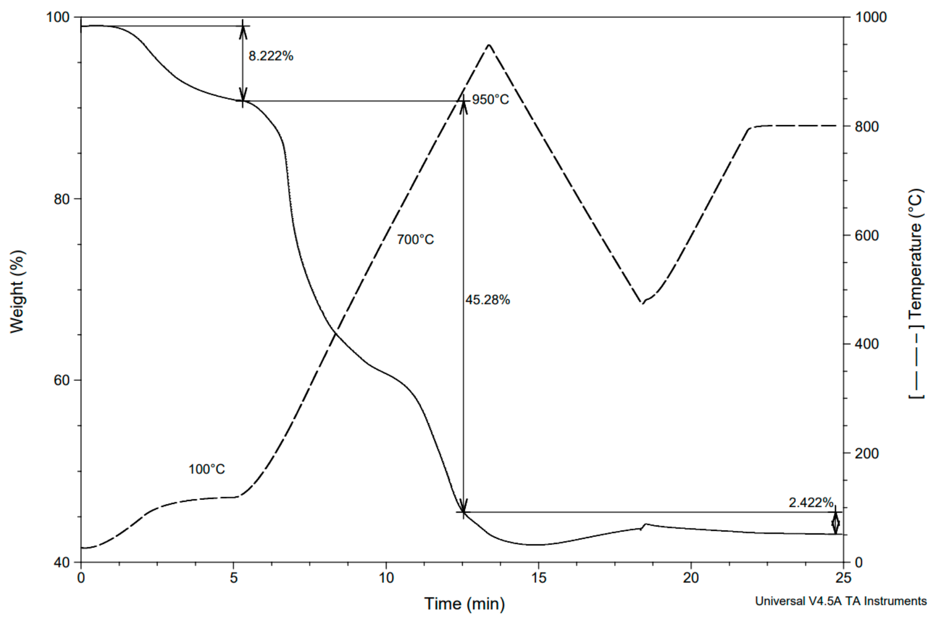

Figure 5. TGA samples from Lamilla.

It is worth noting that the thermal stability of this algae is comparable to that of other traditional fibers and insulating materials, which typically have a thermal stability of around 150 °C [10,40].

3.5. Surface Analysis (Morphology)

Figure 6 presents the morphological analysis of the samples, with a particular focus on the longitudinal section of Pelillo. Within this section, we can observe cellular structures with porosity levels ranging between 400 and 500 microns. It is worth noting that this level of porosity is relatively lower than what is typically found in conventional insulating materials, which tend to have a more open porosity [41]. Additionally, a significant presence of crystallized salts is evident, and the primary elements in the chemical composition have been identified. What is particularly interesting is that the chemical composition of macroalgae appears to give rise to this lightweight cellular structure, facilitating carbon and oxygen storage, often referred to as "Carbon and Oxygen Integrated Thermal and Acoustic Storage" [42,43]. Specifically, in the case of the Pelillo alga analyzed in this study, carbon (C) is the predominant element, constituting 49.1% of the total mass analyzed, followed by oxygen (O) at 24.6%.

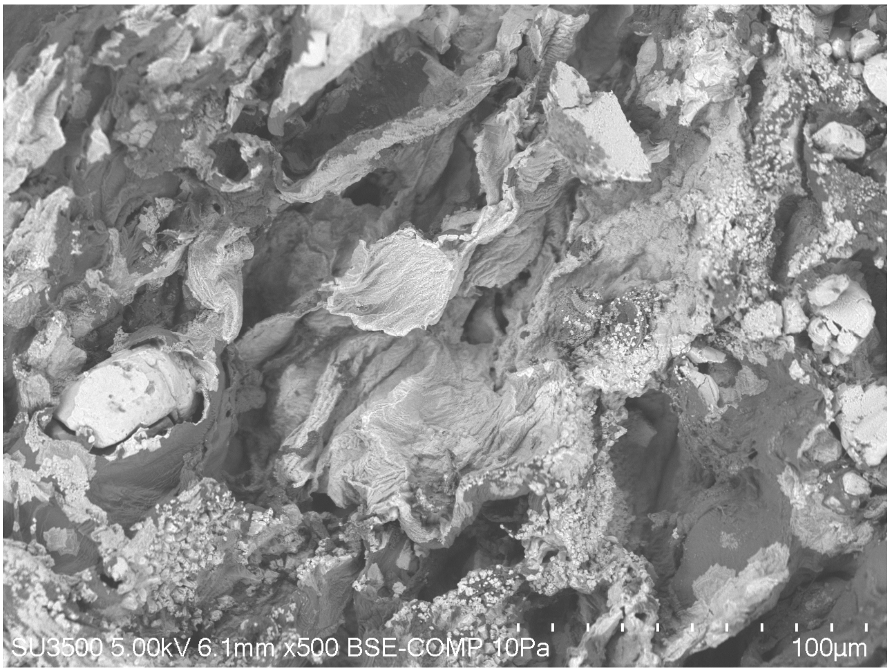

Figure 6. SEM samples of Pelillo.

Figure 7 presents the analysis of Lamilla, which reveals a uniform surface with small pores of 50 to 100 microns, similar to data reported in previous work [44]. It is important to note that neither longitudinal nor cross sections were performed, as Lamilla lacks a tubular morphology that would provide it with a specific direction or orientation. In terms of chemical composition, this native alga has similar properties to those previously reported, where carbon (C) is the dominant element, constituting 36.4% of the total mass tested, followed by oxygen (O) with 35.6% [45].

These properties enable the prolongation of heat flow from one end to the other, leading to enhanced thermal conductivity. As a result, this leads to reduced thermal transmittance values for construction solutions [46]. This context is linked to algae native to Chile, and while certain chemical properties are consistent across all macroalgae, they can vary depending on the species, season, and location [47].

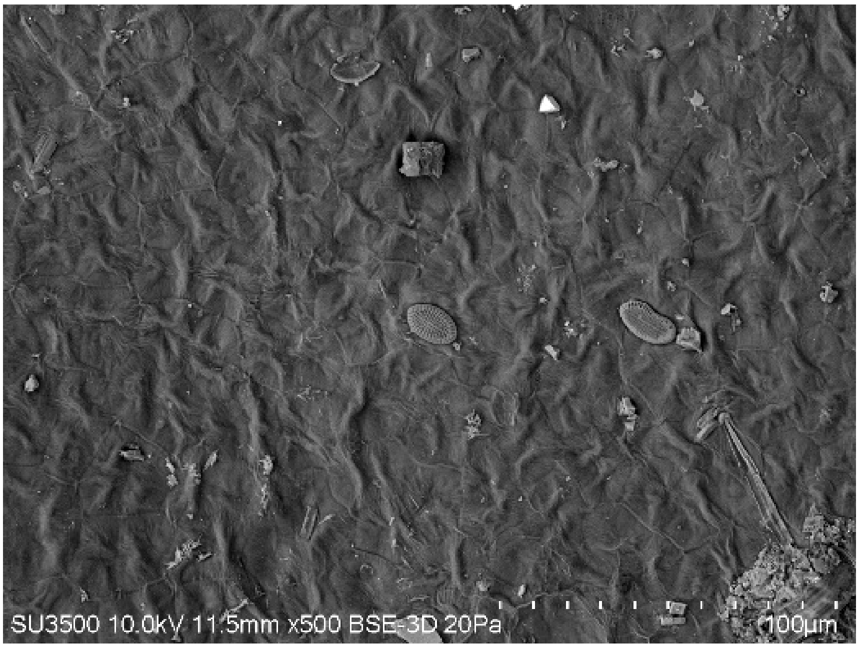

Figure 7. SEM samples of Lamilla.

4. Conclusions

The evaluation and characterization of the algae have provided crucial insights demonstrating the feasibility of developing a thermal insulation prototype using native Chilean algae. These algae exhibit thermal conductivities averaging 0.036 [W/mK], which are comparable to traditional materials available in the Chilean market, such as expanded polystyrene, glass wool, or mineral wool. This favorable result can be attributed to the low moisture content of the fibers (following natural or artificial drying processes) and the extended, porous fiber structure found in both types of algae. It is worth noting that these fibers remain stable up to 150 °C, a critical factor to consider during material processing.

In this study, both types of algae are highlighted as promising candidates. They are abundant along the Chilean coasts, have a low cost, and can be cultivated, dried, and partially cleaned using techniques well-known to the personnel engaged in this work on site. Consequently, their acquisition would not necessitate a significant investment.

It is important to note that thermal insulation material is an integral component of a building system whose elements work together. As such, the design of construction solutions must adhere to regulatory standards and incorporate vapor and humidity barriers to protect the material.

Finally, it is important to mention that an intriguing avenue of exploration involves breaking down algae fibers, but it is crucial to assess their properties in a specific way because each type has its own distinct characteristics. Macroalgae typically contain oxygen and carbon as their primary components, but they also offer essential nutritional compounds, such as proteins, carbohydrates, vitamins, and minerals. In this scenario, the surface roughness and certain pores in Pelillo and Lamilla algae stand out because processing them allows us to extract long, fine fibers, which can improve thermal performance. This could potentially lead to the development of a consistent material resembling traditional fiber wools such as sheep's wool or glass wool. This project will enable us to advance our research on how algae's energy dynamics impact overall home energy efficiency, using thermal energy simulations.

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