



SOUND-ABSORBING SUSTAINABLE MATERIAL FROM PELAGIC SARGASSUM SEAWEED: EXPERIMENTAL INVESTIGATION, MODELLING AND PANELS DESIGN

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Abstract

The sea represents 70% of the earth's surface and the possible use of sound-absorbing materials with this origin is little investigated. The purpose of this article is to investigate the possible acoustic applications of a floating seaweed (Pelagic Sargassum) very common in the Caribbean area. The presence of these floating algae and their stranding on the coasts is constantly increasing due to climate change, and constitutes an economic and environmental problem. To mitigate these problem projects have been proposed for the collection of this algae, and research is underway for the use of these materials as natural resources within production cycles in various industrial sectors. This article investigates the potential use of dried Pelagic Sargassum for the production of sound-absorbing panels that combine good acoustic properties and attractive design, and presents an experimental investigation aimed at modelling the acoustic propagation inside the material with variable apparent density.

Keywords: sustainable materials, sound absorption, design, acoustic modelling.

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1 Introduction

The global reduction objective of CO₂ emissions increase the research on sustainable sound-absorbing materials, obtained from the recycling of end-of-life materials, from processing waste or from invasive plants that represent an environmental problem.

In the literature there are many review articles that collect numerous research on the sound-absorbing properties of sustainable materials, and in particular [1] and [2] focus on materials of natural origin (vegetable and animal). Some of these materials derive from agricultural processing waste (tea leaf residues [3], pineapple leaves [4], straw fibers and olive tree pruning residues [5], coconut fibers [6]) while others from invasive plants without other applications (Broom [7], Yucca gloriosa [8]).

However, there are few studies on the use of waste materials of marine origin, despite the fact that the seas cover 70% of the earth's surface. In [9] the acoustic properties of Posidonia fibers are studied, a marine plant endemic to the Mediterranean which produces, following sea storms, large quantities of leaf residues landing on the coasts, constituting a problem for the tourist exploitation of the beaches. In [10] some sound absorption results obtained on different types of dried algae collected on the Ukrainian coasts of the Sea of Azov are presented.

The idea behind this research derives from the environmental problem constituted by the enormous increase in floating masses of Sargassum, a brown macroalga widespread in the Caribbean area of the Atlantic Ocean and recently expanding on the equatorial African coasts. These algae, which include the pelagic species Fluitans III, Natans I and Natans VIII, accumulate in the sea and along the coasts causing problems for fishing and tourism activities (figure 1) [11].

In recent years, due to climate change, there has been a progressive increase in the presence of Sargassum in the seas and stranding phenomena on the coasts, and an extension of the diffusion areas of these algae in the Atlantic up to the African West coast (figure 2).

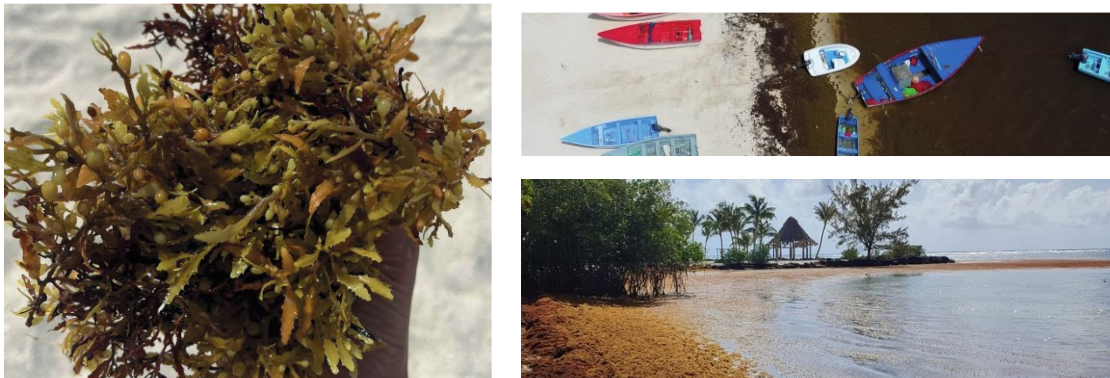


Figure 1 – Sargassum beached, photos courtesy of SOS Carbon.

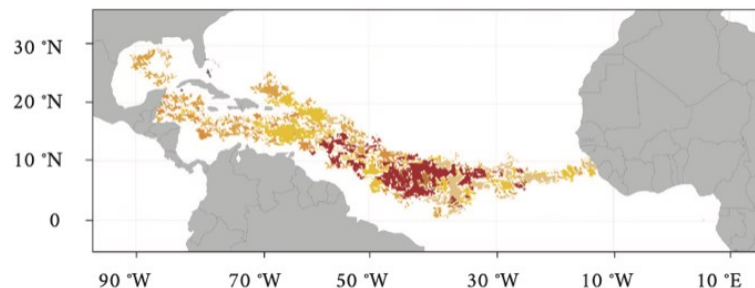


Figure 2 – The Great Atlantic Sargassum Belt, July 2022.

The invasive presence of Sargassum represents a situation to which local communities must adapt. The invasion of beaches with algae biomass creates an emergency situation in terms of environmental and economic impact. Removing decaying biomass is expensive and has become a burden for both the tourism industry and local governments. Typically, collected Sargassum is sent to landfill or left to degrade in piles near beaches; the effects generated by decaying Sargassum such as the release of carbon dioxide and hydrogen sulfide are likely everlasting in some areas, where entire coastal ecosystems have been altered [12], [13].

The great availability of Sargassum has stimulated strong interest in its use as a raw material to make a wide range of products, thus transforming waste into a resource. Entrepreneurs and research groups work on the development of innovative businesses and projects [12], [14], [15].

There are various techniques and methodologies taken into consideration, from anaerobic digestion to cosmetic extracts, from the production of plastic to construction materials. On the other hand, variability in terms of quantity, quality and location creates high uncertainty for the development of reliable industrial processes.

In this context, this article proposes the design of sound-absorbing panels obtained from sundried Sargassum, supplied by SOS Carbon, a spinoff organization of the Department of Mechanical Engineering of the Massachusetts Institute of Technology (MIT) operating in Santo Domingo [16].

The research was developed in two subsequent phases: a first acoustic characterization of the dried material, aimed at developing an analytical model that allows optimizing the acoustic properties of the proposed panels, and a subsequent phase which concerned the development of a design proposal for a possible final Sargassum-based product. In this second phase, important aspects concerned the valorisation of the sustainability and natural origin of the material, and the identification of a natural binder that allows the creation of a dimensionally stable and robust panel.

It is important to underline that this study was developed as part of an Industrial Design thesis without the involvement of companies interested in the industrial production of panels: it is therefore limited to the aspects of acoustic optimization and product design, and did not delve into other fundamental aspects for their marketing such as resistance to fire, humidity, aging or emission of odors.

2 Materials and methods

2.1 Description of the Sargassum samples

The material used for this research consists of sundried Sargassum, supplied by the spin-off organization SOS Carbon, which collects it directly on the water surface with equipped naval vessels. It is an organization founded by researchers from the Department of Mechanical Engineering of the Massachusetts Institute of Technology (MIT) which has developed an economical and low environmental impact collection technique that uses a machine called the Littoral Collection Module (LCM). This system can be mounted on any artisanal vessel in the Caribbean and allows you to collect seaweed off-shore without the presence of sand (figure 3). The seaweed was finally dried in the sun for 48 hours.

The experimental acoustic tests were initially conducted on the binder-free material (figure 4), inserting a quantity of dried algae known by weight and progressively compressing it to measure its properties for different bulk densities (range between 94 kg/m^3 and 240 kg/m^3).

Subsequently, tests were carried out in order to create a compact and resistant design panel. The proposed process for the creation of these modular panels will be described in paragraph 2.3.



Figure 3 – Harvesting process of Sargassum in the sea, photos courtesy of SOS Carbon



Figure 4 – Binder-free dried Sargassum tested

2.2 Physical and acoustic characterization of Sargassum samples

The objective of the first phase of the research was to develop an analytical model that allows the acoustic properties of dried Sargassum to be calculated for different the bulk densities. The experimental sound absorption measurements were conducted on Sargassum aggregates, without binder.

The procedure adopted involves the insertion of a known weight of fibers inside a cylindrical sample holder, the thickness of which is progressively reduced in order to obtain experimental measurements with variable apparent density. The measurements of the sound absorption coefficient at normal incidence were conducted according to the ISO 10534-2 standard [17] in an apparent density range ρ_a between 94 kg/m^3 and 240 kg/m^3 and a frequency range between 100 Hz and 4300 Hz (diameter of the cylindrical sample equal to 45 mm). To progressively compress the sample during the tests, on the side exposed to the acoustic field, a fixed metal mesh was applied without acoustic effects on the measurement (Figure 5), while on the rear side the position of the rigid bottom was progressively moved, reducing the thickness of the sample .

An experimental porosity measurement was also carried out on the material using equipment based on the method of air compression of a known volume [18]. Through this measurement it is possible to obtain the average density of the structure of the material ρ_m (equal to 1191 kg/m^3) and from this calculate the porosity ϕ of the samples as a function of the degree of compression using the formula:

$$\phi = 1 - \frac{\rho_a}{1191} \quad (1)$$

The Johnson-Champoux-Allard analytical model [19], [20] for equivalent dissipative fluid was adopted for acoustic propagation in the material.

It expresses the complex effective density $\rho(\omega)$ and the complex compressibility modulus $K(\omega)$ as a function of five parameters: porosity ϕ , flow resistivity σ , tortuosity α_∞ , viscous characteristic length A and thermal characteristic length A' :

$$\rho(\omega) = \frac{\alpha_\infty \rho_0}{\phi} + \frac{\sigma}{i\omega} \sqrt{1 + \frac{4i\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 A^2 \phi^2}} \quad (2)$$

$$K(\omega) = \frac{\frac{\gamma \cdot P_0}{\phi}}{\gamma - (\gamma - 1) \left[1 + \frac{8\eta}{i\rho_0 \omega N_{Pr} A'^2} \sqrt{1 + \frac{i\rho_0 \omega N_{Pr} A'^2}{16\eta}} \right]^{-1}} \quad (3)$$

where ρ_0 is the density, η the viscosity, P_0 the static pressure and γ the specific heats ratio of the air. From the effective density and the compressibility modulus it is possible to calculate the characteristic impedance Z_C and the propagation constant of the medium k_C :

$$Z_C = \sqrt{\rho K} \quad (4)$$

$$k_C = \omega \sqrt{\frac{\rho}{K}} \quad (5)$$

and from these, for a thickness h of the material, the surface impedance Z_S and the normal incidence sound absorption α_n :

$$Z_S = -iZ_C \cot(k_C h) \quad (6)$$

$$\alpha_n = \frac{4\text{Re}\left(\frac{Z_S}{\rho_0 c_0}\right)}{\left|\frac{Z_S}{\rho_0 c_0}\right|^2 + 2\text{Re}\left(\frac{Z_S}{\rho_0 c_0}\right) + 1} \quad (7)$$

The physical parameters used in the JCA model were calculated by inversion from the experimental acoustic measurements, through the numerical method described in [21]: it involves the numerical minimization of the mean square deviation between an experimental curve (acoustic absorption or surface impedance) and the analytical curve calculated with the equivalent dissipative fluid model. The only parameter fixed for each bulk density is the porosity, measured experimentally and calculated according to relation (1), while the other four parameters were calculated in the minimization process.



Figure 5 – Apparatus for measuring the sound absorption coefficient at normal incidence and sample mounting method

2.3 Design of Sargassum-based modular panels

The study of the panels follows the logic of "systemic design": from the causes that generate the landing on the beaches up to the collection, drying and valorization. Therefore, a re-evaluation of marine waste and its conversion into sound-absorbing panels, in order to make the most of the properties of the starting material.

The geometry of the design panels draws inspiration from organic forms present in nature, in particular from the circular bladders called pneumatocysts which represent a real peculiarity of Sargassum: air bubbles that allow flotation. The proposed panel (figure 6) has a modular geometry that allows the creation of wall surfaces of variable dimensions that represent a furnishing element.

After an initial study linked to the acoustic properties of Sargassum fibers without binder, the research moved to the process of creating the prototype/artisan panel by building a mold in two half-shells and defining a treatment process for the Sargassum with a binder dissolved in water.

To achieve an optimal result, the hypothesis of using natural binders, in particular pine resin, was taken into consideration. This ensures that the main objectives of the project are maintained: an environmentally sustainable and biodegradable product.

To verify the panel manufacturing process and the effect on the acoustic performance of the resin added as a binder, cylindrical samples with a diameter of 100 mm and a nominal thickness of 60 mm were made. The dried seaweed was mixed with pine resin melted in water, then compressed in a cylindrical mold for approximately 48 hours and left to dry with forced ventilation for another 48 hours.

To verify the effect of the resin, three different samples were made starting from 66 g of dried algae: one without resin, to verify whether the presence of the resin was necessary for the creation of the panel and to have a reference acoustic measurement, one with 50 g of resin (ratio 1:0.75, 43% of resin) and one with 75 g of resin (ratio 1:1.14, 53% of resin). Three samples were thus obtained with effective density increasing between 155 and 300 kg/m³.

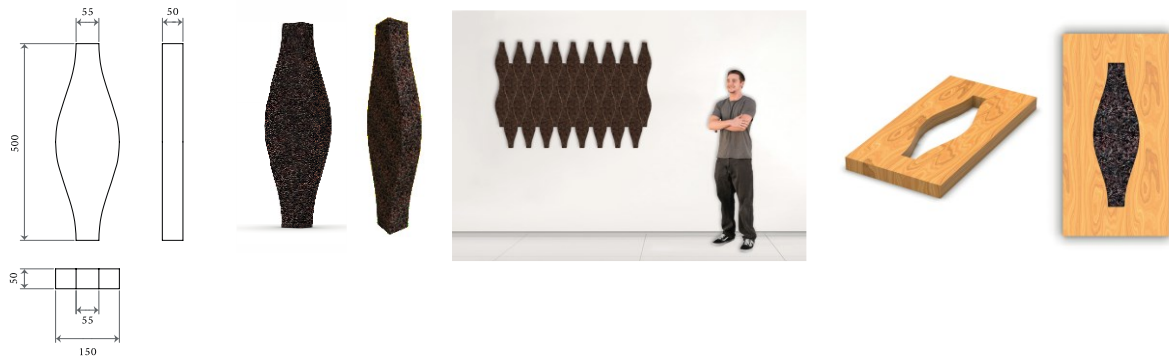


Figure 6 –Modular panel prototype

3 Experimental results

In this paragraph, the experimental results and the acoustic modeling obtained on the samples of binder-free material and on the panels will be presented.

3.1 Binder-free Sargassum experimental results

3.1.1 Sound absorption measurements

Figure 7 shows the sound absorption curves at normal incidence of the tested samples, with variations in apparent density and thickness. This is a progressive compression test, therefore the lower apparent densities refer to samples of greater thickness, and vice versa.

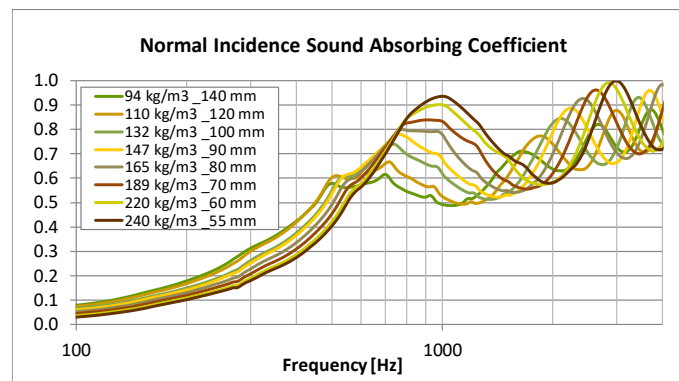


Figure 7 – Sound absorption for different combinations of bulk density and thickness

3.1.2 Inversion of physical parameters and interpolation as a function of bulk density

Table 1 shows the results of the inversions carried out on the absorption measurements as a function of the apparent density. The porosity value was set for each inversion as measured experimentally and calculated using formula (1). The other four physical parameters were obtained with a process of numerical minimization of the difference between the experimental sound absorption curve and that calculated with the analytical model described in paragraph 2.2.

In order to extend the analytical model to any bulk density, it is necessary to interpolate the results of the inversions with analytical formulas as a function of the bulk density or porosity. The structure of the adopted formulas is proposed in [9], while the coefficients were calculated by minimizing the standard deviation with respect to the values in Table 1.

Table 1 – Physical parameters of Sargassum with different densities.

Density [kg/m ³]	σ [N s/m ⁴]	ϕ [-]	α_{∞} [-]	Λ [μ m]	Λ' [μ m]
94.3	336	0.92	1.29	631	949
110.0	660	0.91	1.38	516	991
132.0	1143	0.89	1.46	412	835
146.7	1216	0.88	1.55	386	607
165.0	1270	0.86	1.62	279	897
188.6	2253	0.84	1.73	255	581
220.1	3384	0.82	1.90	203	518
240.1	3686	0.80	2.00	177	460

The interpolation process led to the following relationships:

$$\sigma = \frac{\eta}{(2a)^2} \frac{\sqrt{1-(1-\phi)}}{0.21 \left(\frac{0.71}{1-\phi} - 3 \sqrt{\frac{0.71}{1-\phi} + 3} - \sqrt{\frac{1-\phi}{0.71}} \right)} \quad (8)$$

where $a=120 \mu\text{m}$ represents the effective mean radius of the fibers,

$$\alpha_{\infty} = \left(\frac{1}{\phi} \right)^{3,178} \quad (9)$$

$$\Lambda = 2.09\text{E} - 05 (1 - \phi)^{-1,35} \quad (10)$$

$$\Lambda' = 1.35\text{E} - 04 (1 - \phi)^{-0,79} \quad (11)$$

Figure 8 shows the comparisons between the curves obtained from the analytical formulas and the data obtained from the inversions and presented in Table 1.

As can be seen, for all parameters the interpolations are optimal and therefore the proposed equations are suitable for calculating the physical parameters as function of the bulk density of the material.

The determination of the physical parameters of the material allows us to understand the reason for the reduced acoustic performance of the material, at least at lower densities: it can be seen that the airflow resistivity of the material is very low and begins to be significant ($>3 \text{ kNs/m}^4$) only above 200 kg/m^3 . This low resistivity is due to the very large size of the dried algae filaments, which determines a high viscous characteristic length, of the order of hundreds of microns compared to tens of microns of traditional fibrous materials.

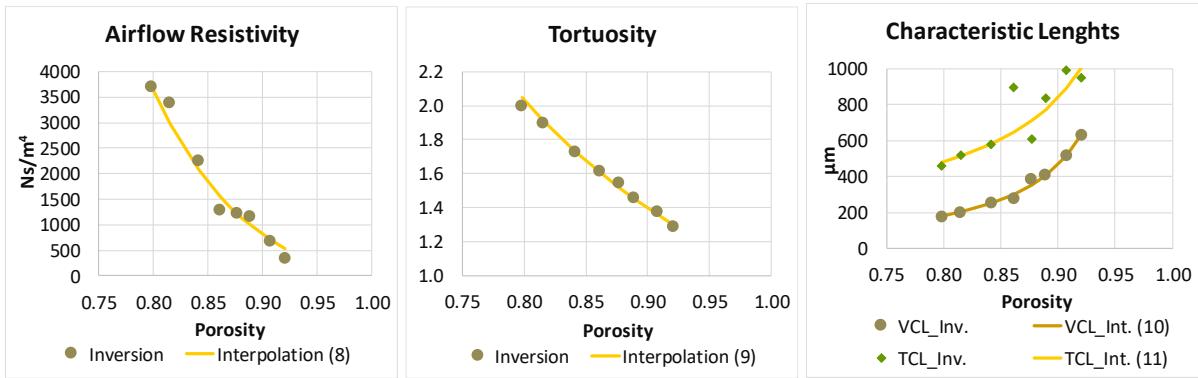


Figure 8 - Comparison between airflow resistivity, tortuosity and viscous (VCL) and thermal (TCL) characteristic length obtained by inversion from the experimental measurements and the interpolation equations (8), (9), (10) and (11).

3.1.3 Comparison between analytical model and experimental measurements

Figure 9-a shows a comparison between the experimental measurements and the results obtained from the proposed analytical model, for some of the bulk densities tested.

It can be observed that the model is able to predict the sound absorption of the material at different bulk densities with excellent precision.

For a more immediate comparison, the analytical model can be used to calculate the absorption curves for the same thickness (for example 50 mm) as the apparent density varies (figure 9-b): it is possible to note that to achieve good sound-absorbing performance with this thickness the material requires high bulk density, greater than 200 kg/m^3 . In figure 9-b the performance of Sargassum is compared with a traditional material such as mineral wool (density 50 kg/m^3).

It is clear that the acoustic behavior of Sargassum presents a more selective absorption characterized by an absorption peak close to unity but which tends to drop before and after the peak and fluctuate at high frequencies, while for a traditional fibrous material the absorption acoustic covers a wider frequency band and the high frequency oscillation is limited and around unity values.

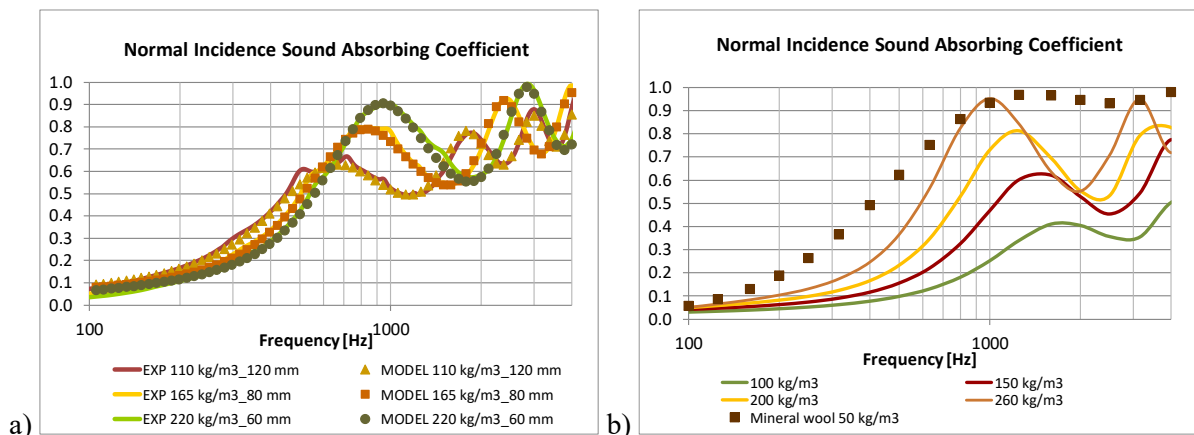


Figure 9- Comparison between experimental and calculated sound absorption coefficient (a) and simulations of sound absorption coefficient with the same thickness and different densities with comparison with a traditional material (mineral wool with density 50 kg/m^3) (b).

3.2 Sargassum panels experimental results

The creation of prototype panels based on Sargassum, described in paragraph 2.3, can impact the acoustic behavior of the panel itself, mainly due to the presence of binder which can alter the geometry of the structure and therefore the physical properties that determine sound absorption; three cylindrical samples with a thickness of 60 mm and a variable quantity of resin were therefore tested, in order to determine the effect of the presence of the binder and to verify the stiffness of the resulting material.

Figure 10 shows the experimental sound absorption curves for the three samples: it is clear that the use of the resin determines a progressive increase in sound absorption, mainly due to an increase in the airflow resistivity of the sample. Table 2 shows the values of the physical parameters obtained by inversion [21] from the acoustic measurements. The same figure 10 also shows the absorption curves obtained from the JCA model with the parameters in table 2, as validation of the inversion process.

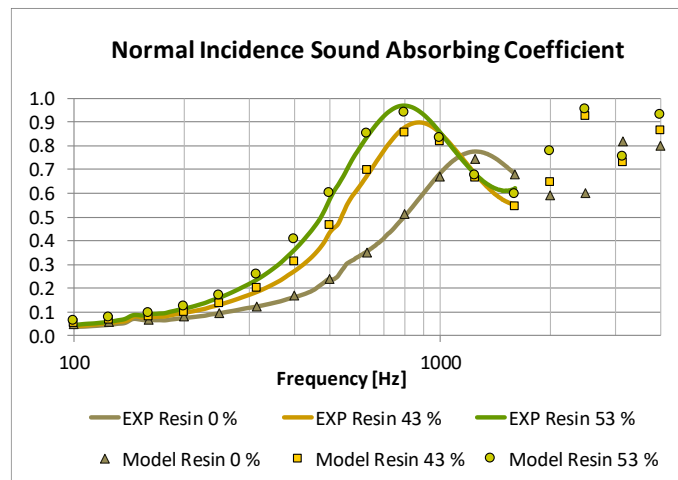


Figure 10 - Variation of normal incidence sound absorption coefficient as a function of the quantity of resin and comparison with the JCA model.

Table 2 – Physical parameters of Sargassum with different resin quantities

Density [kg/m ³]	Resin %	σ [Pa s/m ²]	ϕ [-]	α_w [-]	Λ [μm]	Λ' [μm]
155	0%	1085	0.89	1.36	236	735
240	43%	3299	0.85	1.93	232	985
300	53%	3991	0.82	1.9	170	868

To evaluate the commercial technical potential of modular panels made with Sargassum, the virtual random incidence absorption coefficient and the related α_w determinable according to the ISO 11654 standard were calculated [22].

To carry out this calculation, the London formula [23] is used, which allows the absorption coefficient at random incidence to be calculated for an infinite plate starting from the surface impedance calculated for normal incidence, and a correction is applied for the finite size of the panel proposed by Rhazi [24] and calculated in this case for a dimension equal to 1.79 x 1.25 m (hypothesizing a wall application of 34 modules as shown in figure 6 and neglecting the fact that the perimeter of the panels is not rectangular but has a more complex geometry).

Figure 11 shows the absorption curves at diffuse incidence for three different thicknesses of the panels (40 mm, 60 mm and 80 mm) and a surface equal to 2.24 m², assuming the use of the maximum quantity of resin tested (53%). Note that values of the diffuse field sound absorption coefficient greater than one are determined by the effect of the finite (small) size of the panel.

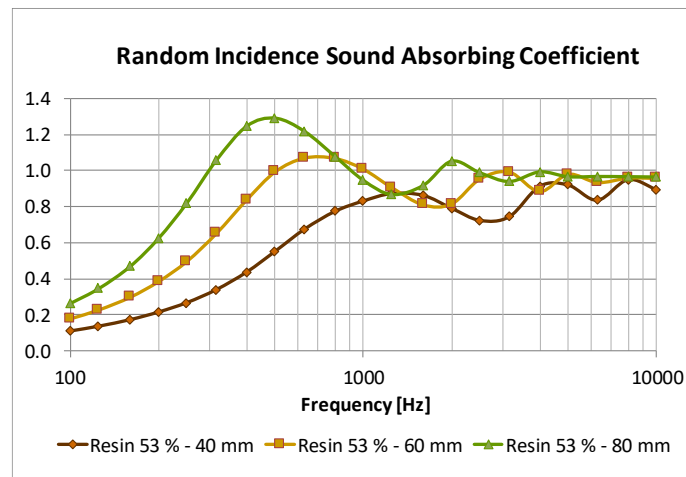


Figure 11 - Variation of diffuse incidence sound absorption with different thicknesses (surface of 2.24 m²).

Figure 12 shows an example of α_w calculation, for the panel with the greatest quantity of resin, a thickness of 80 mm and a surface area of 12 m² (measurement procedure according to ISO 354 [25]). The result in terms of α_w is rather high, equal to 0.90, and corresponds to a class A material. The Sargassum-based panel therefore has excellent sound-absorbing potential, achieved thanks to the presence of the resin which increases the acoustic performance of the base material thanks to higher airflow resistivity.

It should be underlined that the panel manufacturing process was not designed for industrial production, but simply allowed the potential of the application to be explored. In the case of future production of the panel, it will be necessary to study an industrial process and its effect on the final acoustic performance.

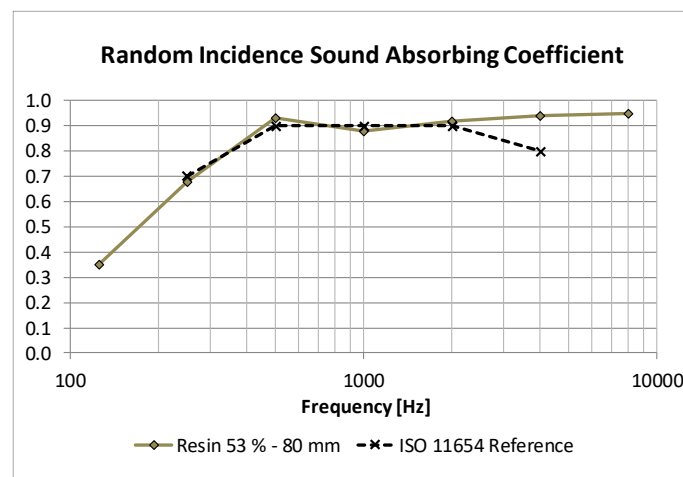


Figure 12 - Determination of the $\alpha_w = 0.90$ for 80 mm thickness panel with 300 kg/m³ density (surface of 12 m²).

4 Conclusions

At the basis of this research there is a design idea that starts from the environmental issues, following a circular design, which implies sharing, borrowing, reusing and recycling materials, preferring the use of natural materials. Natural fibers have gained significant importance in today's world for several reasons. First of all, their sustainability aspect cannot be underestimated. With growing attention on

environmental issues, natural fibers provide a sustainable alternative to synthetic fibres, thanks to a lower carbon footprint than their synthetic counterparts, which are typically derived from non-renewable sources such as fossil fuels. The biodegradability of natural fibers is another crucial factor, unlike synthetic fibers which can persist in the environment for hundreds of years.

This study started from a specific environmental problem, located on the Atlantic coasts of the Caribbean and equatorial Africa, and is aimed at proposing a possible reuse of Sargassum algae which currently constitute waste that is difficult to manage in these countries.

This material, once collected and dried in the sun, could constitute the raw material for making sound-absorbing panels to be applied to indoor walls.

In the first part of the research, dedicated to the characterization and acoustic modeling of the binder-free material, the properties and limitations of this material were highlighted, which can essentially be summarized in a need to achieve high apparent densities in order to obtain interesting acoustic results. Once an analytical model was developed that allows panels of any thickness and density to be sized, in the second phase a design solution was thought of to increase the economic value of the material, creating a modular system with a geometry that recalls the nature of the Sargassum.

To create these panels, the use of a natural binder, based on pine resin, was investigated: this resin, dissolved in water, allows the dried algae to be compacted and its geometry maintained. Some tests were carried out to evaluate the quantity of resin necessary and the relative effect on the acoustic performance, from which it was noted that the resin significantly increases the airflow resistivity of the sample and the sound absorbing properties of the panel.

On the basis of the prototypes, it was seen that a panel with a thickness of 80 mm can reach an $\alpha_w = 0.90$ value and therefore be classified as a “class A” material according to the standard [22].

It can therefore be concluded that this project has confirmed the possibility of creating sound-absorbing panels based on Sargassum algae, and that the final acoustic performances depend on the panel manufacturing process: it will therefore be fundamental, in a possible industrialization of the product, to evaluate the acoustic effect of the panel manufacturing process, including the type of binder used, following the methodology illustrated in this article.

It will also be necessary to delve into fundamental aspects such as the resistance to fire, humidity and aging of these panels since these aspects were not addressed in the degree thesis in Industrial Design which developed the project illustrated in this article.

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