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Investigating Polylactic Acid Foam–Plant Fiber Composites for Sound Absorption and Insulation

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Abstract: This study explores the acoustic properties of composite biomaterials using a polylactic acid (PLA) matrix reinforced by plant fibers for sound insulation applications. Acoustic tests evaluated the absorption coefficient, reflection factor, and characteristic impedance, examining various configurations with different thicknesses of the composite biomaterial. The combinations of PLA/grape stem and PLA/wood straw were analyzed for their acoustic behaviors. Grape stems and wood straw were chosen because they are abundant, undervalued waste materials, especially in Italian regions like Tuscany. Therefore, using these materials in composite biomaterials could offer opportunities for valorization. The findings highlight the impact of plant fiber characteristics on acoustic properties, emphasizing the need to optimize these factors for desired acoustic outcomes. The results suggest implications for developing eco-friendly construction materials that balance environmental sustainability with performance requirements. This investigation contributes to the ongoing discourse on sustainable material utilization for acoustic purposes, reinforcing the potential for innovative and environmentally conscious building solutions.

Keywords: bio-foam; sound polylactic acid foam; PLA-foam; sound insulation; sound absorption; sustainable composite biomaterial; plant fiber; waste material; reuse

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1. Introduction

In recent decades, the pursuit of sustainable practices has become increasingly imperative across various industries, driven by concerns over environmental degradation, resource depletion, and the need for resilient infrastructures. In this context, the construction sector has emerged as a focal point for innovation, with efforts concentrated on developing eco-friendly materials and techniques to mitigate the industry's ecological footprint [1,2]. Among the plethora of sustainable solutions, composite materials have garnered considerable attention for their potential to revolutionize sound insulation panel manufacturing while reducing environmental impact [3–8]. Composite materials, characterized by their heterogeneous composition comprising a matrix and reinforcing fibers have gained importance due to their mechanical properties, design flexibility, and lightweight nature. By integrating sustainable elements into these composites, researchers aim to address environmental concerns while maintaining or even enhancing performance characteristics. Notably, polylactic acid (PLA), a biodegradable polymer derived from renewable resources such as corn starch or sugarcane, has emerged as a matrix material for sustainable composites [9]. Its low environmental impact, biocompatibility, and processability make it an attractive candidate for various applications, including sound insulation panels [10]. The incorporation of natural fibers, sourced from renewable plant-based materials such as bamboo, hemp, flax, or jute, further enhances the sustainability profile of composite materials. These fibers not only improve mechanical properties [11] but also contribute to reducing the dependency on non-renewable resources. The combination of PLA matrices with natural fibers results in biocomposite and compostable materials with improved environmental credentials, making them viable alternatives to traditional petroleum-based composites in fields like packaging [12,13] and building materials [10,14,15].

Indeed, the environmental sustainability of PLA-based composite panels compared to conventional materials is a crucial aspect that has garnered significant attention in recent years. In such a context, life cycle assessment (LCA) studies have been conducted to evaluate the environmental impact of these materials throughout their entire life cycle, from raw material extraction to end-of-life disposal [16]. These assessments consider factors such as energy consumption, greenhouse gas emissions, and waste generation, providing insights into the overall ecological footprint of PLA-based composites. By conducting LCAs, researchers can identify areas for improvement and refine manufacturing processes to enhance the environmental sustainability of composite materials. Accordingly, PLA has become a potential alternative to petroleum-based polymers due to its renewability, biocompatibility, and good mechanical properties. Additionally, the use of PLA-based bio-composites has been shown to compete with petroleum-based plastics in the market, especially considering the increased availability of PLA [17] and rising petroleum costs.

In conclusion, the extensive research on the LCA of PLA-based composites in comparison with petroleum-derived materials has provided insights into the environmental and performance aspects of these materials. The studies have underscored the potential of PLA-based composites as sustainable alternatives to petroleum-based polymers, offering environmental benefits and competitive performance.

Numerous studies have investigated the mechanical properties of PLA-based composites reinforced with different types and percentages (by mass) of natural fibers [1,2,15,18–20]. Concerning the acoustic performance of both natural fibers and natural fiber-reinforced composites, many studies can be found in the literature [3,15,21,22], where some of them focus on PLA-natural fibers composites [10,23–28]. For instance, it has been found that the sound absorption performance of composites can be heavily influenced by the compatibility between fibers and polymers [24]. In these studies, it emerged that by increasing the fiber content, the sound absorption of the composites also increases at specific frequencies. Another research work, focused on micro-perforated panels made by PLA-based composites, found that when the number of fibers increases in the composite, the peak frequency of the absorption coefficient moves toward lower values [26]. Additionally, a recent study demonstrated that natural fiber composite is a sustainable and natural resource capable of reducing the negative impact on the environment when compared to the common usage of metallic materials [28].

PLA foaming, a process of introducing gas bubbles into PLA, aims to further enhance some material properties such as lightening weight and providing thermal insulation. Investigations reveal how manipulating crystallization kinetics, molecular modification, and nanoparticle addition influence foaming behavior and the resultant foam characteristics, presenting opportunities and challenges in material engineering [29]. In particular, it has been observed that PLA foams have comparable mechanical characteristics to polystyrene foams, but with a considerable reduction in CO_2 emissions [30]. Nevertheless, another study found that PLA foams can have an even greater environmental impact compared to polystyrene foams [31]. Corn-based PLA dominates research due to its biodegradability, but its environmental impact varies based on raw material sourcing. Key categories include ozone layer depletion, global warming potential, and freshwater/marine eutrophication. PLA's sustainability depends on factors like agricultural practices and end-of-life management, urging the need for alternative biomass sources and improved disposal methods [32]. Accordingly, it has been found that one of the main negative contributions of PLA composites is contributed by the PLA transportation phase [33–36]. In addition, it has been found that one of the major sources of negative emissions is associated with the growing of the fiber crop [37].

Another significant aspect that hinders the diffusion of PLA as a substitute for petroleum derivatives is undoubtedly the cost for the end user [38]. For example, 1 kg of

PLA foam costs about three times as much as 1 kg of expanded polystyrene. Therefore, despite equivalent performance, bioplastic suffers from a diffusion barrier due to processing costs, which then reflect on the purchase price. A further factor limiting the spreading of plant fiber-based composite biomaterials for acoustic insulation applications is the fact that, to transform these fibers into industrial products like panels, they need to be made cohesive by using binding agents. These agents make the resulting composite material difficult to dispose of at the end of its life through biological decomposition processes [21]. Therefore, the use of PLA foam as the binding agent could solve this problem since it is completely compostable.

In this context, the underpinning rationale of the work presented in this paper is based on the concept of using widely acknowledged biomaterials to obtain a sustainable composite to be used in the fabrication of sound-absorbing panels. Specifically, the objective is to compare the sound adsorption characteristics of the PLA foam with those of a composite biomaterial made by PLA foam and waste plant fibers in different percentages. This has been conducted to verify the possibility of employing plant fibers to substitute for a certain mass of PLA foam to preliminarily check the impact on the sound insulation properties and the use of PLA as the binding agent. The sustainability potential of the investigated material has been hypothesized by relying on studies available in the literature, with particular attention to the negative impact that both PLA and fibrous materials can have. Indeed, the underlying intention is to exploit the sound absorption performances of PLA foams [39–41] as much as possible, but at the same time to reduce the use of PLA (and its potential negative environmental impact) by introducing organic materials. The use of waste fibrous materials is considered here as a valid way to reduce the environmental impact of such materials in terms of CO_2 emissions. Indeed, the CO_2 emissions related to the acquisition of the fibrous waste materials belong to other processes, i.e., those from which the waste has been generated. Eventually, waste plant fibers themselves act as carbon sink since they fixate the CO_2 they captured previously, at least for the lifetime in which they are used. Furthermore, the possibility to use waste natural fibers in the composite material allows the reduction of the PLA mass, thus having a direct not negligible impact on costs.

The work presented in this paper has to be considered a preliminary step toward the identification of both the optimal mixture and the best manufacturing process for obtaining compostable sound absorption panels. Indeed, the composite material has been tested only with two different plant fibers, with only one dimension of particles, and only with a specific mass concentration of fibers (i.e., 50%).

Nevertheless, the obtained results show that the two waste plant fibers considered for the tests led to similar results for the bio-composite material, with a slight preference for the wood straw. In addition, it has been found that the presence of the waste plant fiber makes the sound absorption performance more constant in a wide range of frequencies with respect to the PLA foam. Eventually, the bio-composite material behaves better than the PLA foam for frequencies beyond 1500 Hz.

2. Materials and Methods

2.1. Theoretical Background

The mechanisms associated with vibration damping and acoustic absorption can be attributed to different physical processes. Vibration damping occurs when sound energy is transferred through direct contact between solid bodies [15,42]. Sound absorption, on the other hand, involves the dissipation of acoustic energy as it interacts with a solid object while traversing through the atmosphere. Acoustic energy induces air displacement, causing changes in air pressure, which propagate as pressure waves through a medium. This phenomenon can be exemplified by the conversion of fluid kinetic energy into heat due to viscous stresses from fluid shearing, facilitating the transfer of thermal energy from fluid to solid through heat conduction. The generation of heat resulting from friction between the fluid and solid aids in this transfer [15,43]. In particular, the main mechanism behind the energy loss of sound in the absorption of fibrous materials is attributed to viscous effects and thermal transfer [21,44]. These losses manifest as the sound propagates within the interconnected pores of a fibrous absorber. Viscous losses occur when a thin layer of air adjacent to the pore wall, situated within the fibers' surface, dissipates sound through friction. Additionally, sound energy is lost due to thermal conduction between the air and the absorber, which tends to have a greater impact at lower frequencies [21]. It is also acknowledged that the amount of absorbed energy is heavily influenced by the physical properties of the fibers (i.e., thickness, density, porosity, and airflow resistivity) [22]. In particular, thicker specimens are supposed to work better at low frequencies [22].

Energy dissipation from the interaction of sound pressure waves with rigid structures can occur through bending processes. When surfaces are non-porous, incident energy reflects into the environment, dissipating energy. Conversely, highly porous surfaces allow pressure waves to infiltrate a material before encountering a solid surface, facilitating energy dissipation. Effective sound absorption relies on frictional losses from internal reflections, with materials like polymer foam using scattering phenomena. Achieving numerous interactions within the material prevents immediate reflection, necessitating efficient penetration of pressure waves. However, highly porous substances may not be suitable for sound absorption if the air molecule travel distances between collisions hinder pressure wave propagation through the material.

Poroelasticity, observed in some absorptive materials, involves a solid matrix exhibiting both porosity and elasticity, while a permeating fluid adds viscosity [15]. Foams, exemplifying porous materials, find applications as sound absorbers due to factors like material porosity and density. Open-cell foams lack barriers within interconnected pores formed by gas bubbles, with solid structures connecting air bubbles. To be an efficient acoustic absorber, a material needs a structure capable of transferring energy efficiently and an appropriate porosity range for sound wave penetration. Sound absorption mechanisms involve material properties and sample preparation, with factors like sound absorption coefficient, airflow resistivity, density, and tortuosity influencing effectiveness. Sample preparation factors include thickness, multilayer structures, manufacturing process, and fiber orientation.

The sound absorption coefficient depends on both sound frequency and propagation direction. It represents the average absorption across all directions, with specific frequencies for evaluation: 125, 250, 500, 1000, 2000, and 4000 Hz. While all materials absorb sound to some extent, their capacities vary significantly. A material qualifies as sound absorbing if its average absorption coefficient at these frequencies exceeds 0.2 [45].

2.2. Considered Samples and Manufacturing Process

The composite material considered in this work consists of a matrix of PLA, obtained through compostable expanded PLA pellets [46], and reinforced waste plant fiber, which has not been chemically treated.

Information about the basic physical and chemical properties of the considered PLA foam is reported below (this has been taken from the technical sheets):

- Form: Expanded beads
- Color: White
- Odor: Sweetish
- Density (g/mL): 10–200 kg/m^3 at 20 °C
- Melting point/range: (150–160 °C)
- Decomposition temperature: 250 °C
- Autoignition temperature: 388 °C
- Solubility (Water): Insoluble
- Thermal degradation: starts from 230 °C

The composite material is produced by mixing the plant fiber with the expanded bioplastic pellets, in a proportion of 50% of the mass. This particular proportion is considered a preliminary attempt, while the identification of the optimal proportion is reserved for future studies dedicated to understanding the limit for preserving the performance of the composite material and reducing the mass of PLA as much as possible. A desirable ratio between the PLA and waste plant fiber would be 70–30% by mass, as this would make the cost of the employed PLA almost comparable to that of equivalent polystyrene for a product with the same density. The manufacturing process, on a laboratory scale, consists of three main phases:

- molding,
- heating under load,
- cooling.

Molding is carried out through a traditional mechanical press and a mold designed to contain the necessary quantity of PLA and waste plant fiber, depending on the desired density. The PLA is in the form of particles with an approximately spherical shape and a diameter of about 2 mm. The pressure and mass of the mixture depend on the density of the desired product; however, for densities ranging between 50 and 150 kg/m^3, the pressure varies between 1 and 4 MPa.

The heating under load process can be implemented using a traditional oven with a temperature ranging from 90 to 130 °C and an average heating time between 20 and 40 min. These parameters also depend on the density of the composite material. A valid and more efficient alternative to traditional heat exchange is the use of a microwave oven with a radiating power of approximately 600 W for the same duration indicated for the traditional oven. In the case of using a microwave oven, the mold material must be such that it does not absorb electromagnetic radiation to a greater extent than either PLA or waste plant fiber.

The cooling phase occurs in ambient air; from an industrial process perspective, the energy derived from cooling could potentially be reused for other purposes. As mentioned, the described process allows the heating of the natural fiber within the mold; in this way, the waste plant fiber in contact with the bioplastic transmits thermal energy to the latter, causing it to melt around the fiber. Thus, thanks to the pressure exerted by the mold and the simultaneous heating and subsequent cooling, the fiber will be encapsulated in a compressed state due to the bioplastic acting as an adhesive. As said in the Introduction, this feature avoids the need for costly and non-biodegradable binding agents, which are often used in composite biomaterials [11,47].

The preliminary investigation presented in this article was conducted in two different steps. The first step was dedicated to verifying the acoustic performance of the composite biomaterial by varying the type of waste plant fiber used. Indeed, previous investigations performed on the same composite biomaterial demonstrated its great versatility due to the capability of using a wide range of waste natural fibers [12,13]. The aim of this first phase was to understand if very different plant fibers in terms of type could lead to different acoustic performances. Therefore, two very different fibers were chosen: grape stalks and wood straw. Grape stalks are known to have a highly branched three-dimensional structure and exhibit very tough fibers, while wood straw has a flat and elongated configuration. The grape stalks were chosen considering their widespread availability in the Tuscan region following vineyard cultivation for wine production; currently, grape stalks are unused or not reused in the wine production process. The same consideration applies to wood straw due to the significant availability of biomass resulting from forest management in the famously wooded Tuscan territories, especially in mountainous areas. The length chosen for both fibers was approximately 20 mm, obtained through crushing and sieving in the laboratory, while the fibers' thickness was around 2 mm for both. Therefore, two specimens, A and B (and three samples of each), with a thickness of about 10 mm, diameter of 40 mm, and comparable density of approximately 119 kg/m^3, were produced through the process described above. The diameter was chosen based on the requirements for the acoustic performance measurement apparatus. The characteristics of the samples are summarized in Figure 1 and Table 1.

Figure 1. Samples considered in this work. See Table 1 for details.

Once the acoustic behavior of the composite biomaterial was compared with varying types of waste plant fibers used, a second investigative step was carried out to compare the composite biomaterial with pure PLA in terms of acoustic isolation performance. For this purpose, using the production process described above, two specimens, C and D (and 4 samples of each), consisting of pure PLA and PLA with wood straw in a 50/50% ratio, respectively, were produced. The composite biomaterial based on grape stalks was not considered in this investigation for two reasons: firstly, due to the results obtained in the first step (see the results in Section 3), and secondly, logistically, due to the unavailability of the fiber at the time of sample fabrication. In this second test, the density was increased to around 150 kg/m^3 and the thickness to 50 mm to assess the combined impact of these parameters on acoustic behavior compared to the test conducted in the first step. The considered thickness is comparable to the thickness of common panels available in the market for building acoustic insulation systems, while the selected order of magnitude of the density is to make to results of the test comparable with the evidence collected in other studies available in the literature [14–28]. The other parameters of the sample are summarized in Figure 1 and Table 1.

Table 1. Samples considered for the acoustic tests.

Sample Code	Description
A	3 cylindrical specimens, with nominal diameters of 40 mm, made of grape stalks and bioplastic in a ratio of 50/50 (by weight). Nominal mean weight: 2.33 g (for specimen). Mean thickness: 15.6 mm Density: 119 kg/m^3
B	3 cylindrical specimens, with nominal diameters of 40 mm, made of wood straw and bioplastic in a ratio of 50/50 (by weight). Nominal mean weight: 1.33 g (for specimen). Mean thickness: 9.1 mm Density: 117 kg/m^3
C	4 cylindrical specimens, with nominal diameters of 40 mm, made of 100% bioplastic. Nominal mean weight: 9.65 g (for specimen). Mean thickness: 50 mm Density: 154 kg/m^3
D	4 cylindrical specimens, with nominal diameters of 40 mm, made of wood straw and bioplastic in a ratio of 50/50. Nominal mean weight: 9.87 g (for specimen). Mean thickness: 49 mm Density: 157 kg/m^3

The performance considered (and measured) to compare the materials was assessed by the acoustic absorption coefficient, the acoustic reflection coefficient, and the normalized characteristic impedance, which were determined through the impedance tube (transfer function method) in accordance with standard EN ISO 10534-2:2001 [48]. The authors are aware that several methods exist to determine the acoustic insulation behavior of a material; however, they chose the impedance tube as it is the same used in the literature contributions against which the comparison was performed.

2.3. Testing Equipment

The instrumental equipment used to perform the test is listed in Table 2, and the apparatus for the acoustic experiment is shown in Figure 2.

Table 2. Equipment used to perform the tests.

Instrument	Description
Impedance tube	AcoustiTube "AFD-1000" impedance tube, 40 mm diameter (Sinus, Vienna, Austria).
Real-time analyzer	Sinus "Soundbook" two-channel real-time analyzer (Sinus, Vienna, Austria).
Software	AFD1001.1 impedance tube software (Sinus, Vienna, Austria) [49].
Power amplifier	Atlas Sound "PA601" power amplifier (AtlasIED, Phoenix, AZ, USA).
Scale	Radwag "WLC 20/A2" electronic scale (Radwag, Radom, Poland)
Thermo-hygrometer	Delta Ohm "HD206-2" thermo-hygrometer (Delta Ohm, Padua, Italy)
Barometer	Brüel & Kjær "UZ001" barometer (Brüel & Kjær, Nærum, Denmark)

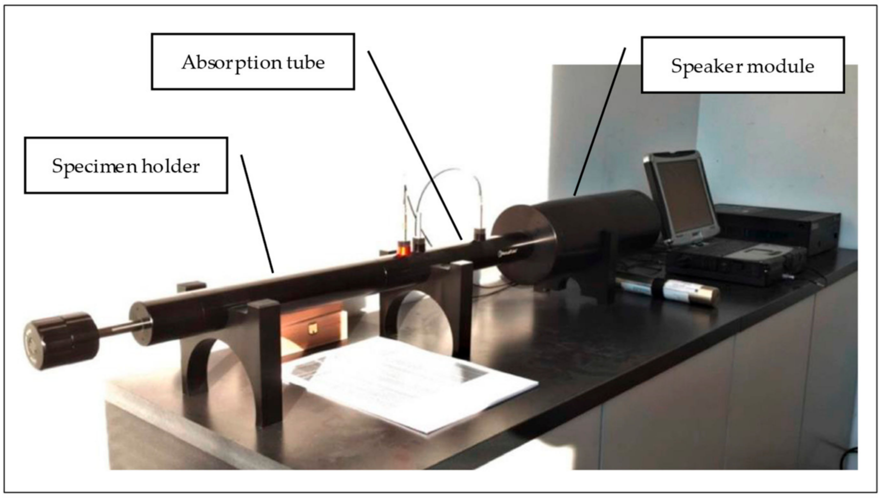

Figure 2. Experimental equipment for the acoustic tests (Akustik Forschung AcoustiTube "AFD-1000" impedance tube, 40 mm diameter in Table 2).

2.4. Testing Procedure and Environment Conditions

Each specimen has been placed inside the impedance tube, in accordance with the requirements of paragraph 6 of ISO standard 10534-2 [48]. After entering the temperature and atmospheric pressure data in the acquisition software, the microphones were calibrated and corrected in phase, following the procedure indicated in the standard and reproduced in the software itself.

The signal level emitted by the loudspeaker inside the impedance tube was set to maintain a difference of at least 10 dB from the background noise at each frequency of the measurement interval. The data acquisition began in the low-frequency range, between 125 Hz and 630 Hz, using dedicated microphone positions. Once the acquisition was completed, the position of the microphones was changed by inserting them in the housings dedicated to data acquisition for high frequencies, that is from 630 Hz to 4000 Hz. The values of the sound absorption coefficient (α) at normal incidence were then obtained, determined by Equation (1) [48,50]:

$$\alpha = 1 - |r|^2 = 1 - r_r^2 - r_i^2 \tag{1}$$

where r is the reflection factor, r_r is the real component of the reflection factor, and r_i is the imaginary component of the reflection factor.

Therefore, the absorption coefficient (α) can be derived by determining the reflection factor experimentally and then subtracting the square of its module from the unit. The complex values "r_r" and "r_i" were determined by the software using the transfer function, for which reference is made to annex E of EN ISO standard 10534-2 [48]. Similarly, the characteristic impedance (Z) is determined by the software, and it is calculated from the reflection factor according to the acknowledged Zwikker–Kosten theory [51].

The mean value was extracted for each set of specimens.

The environmental conditions at the time of the tests are detailed as follows:

- For Specimens A and B (Table 1), the atmospheric pressure was 102,000 (±50) Pa, the average temperature was 21 (±1) °C, and the average relative humidity was 58 (±5)%.
- For Specimens C and D (Table 1), the atmospheric pressure was 100,900 (±50) Pa, the average temperature was 19 (±1) °C, and the average relative humidity was 45 (±5)%.

3. Results

The results of the performed tests are shown in Figures 3–5, the absorption coefficient, the reflection factor, and the characteristic impedance, respectively.

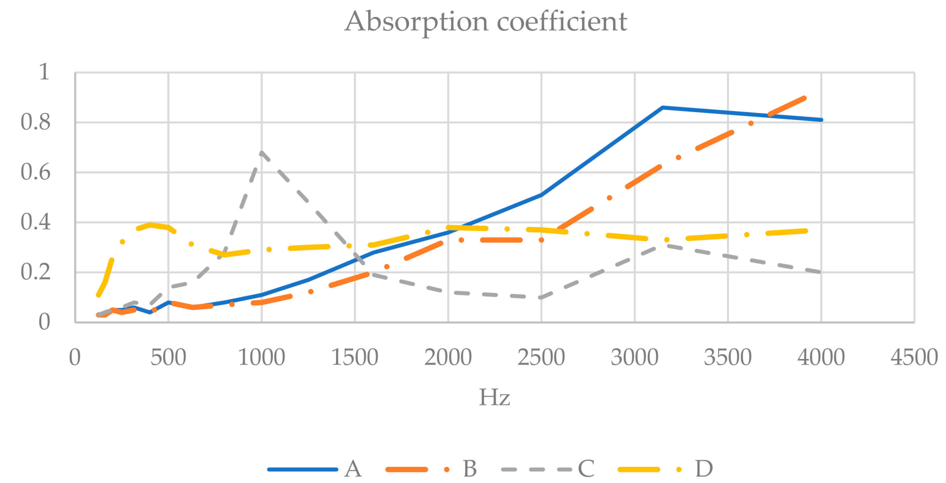

Figure 3. Mean values of the absorption coefficient on the four sets of specimens.

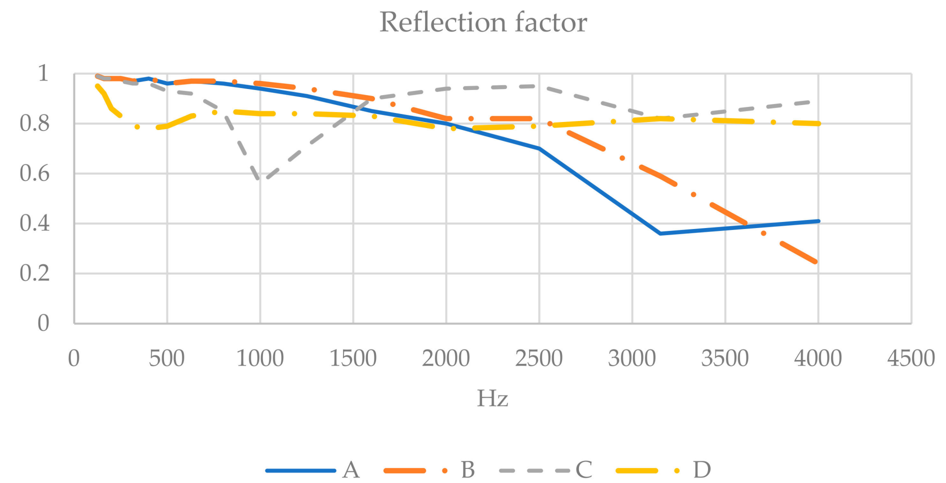

Figure 4. Mean values of the reflection factor measured on the four sets of specimens.

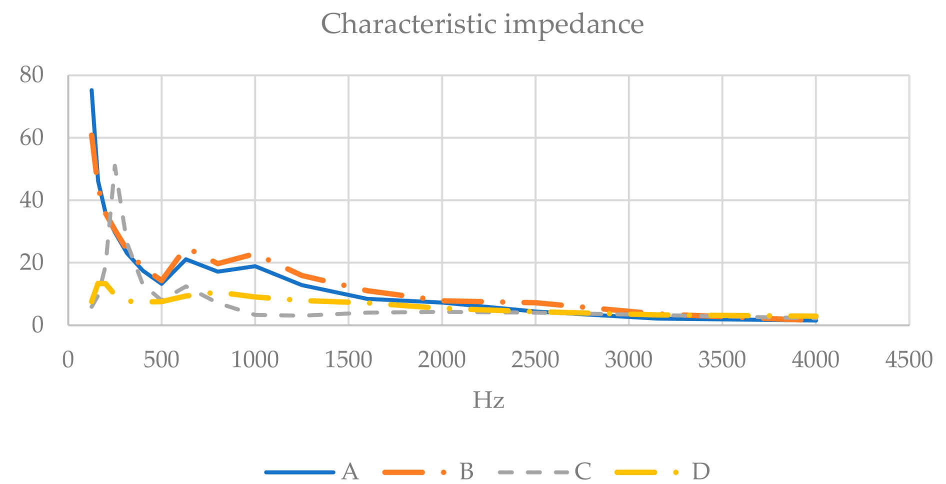

Figure 5. Mean values of the characteristic impedance measured on the four sets of specimens.

In particular, Figure 3 shows that the specimens of sample C present a higher absorption coefficient at 1000 Hz, while Sample D behaves almost constantly from 500 Hz, at a value slightly below 0.4. Samples A and B present similar behavior in terms of absorption coefficient but tend to have higher values at higher frequencies (see Figure 3). In other words, it seems that at least for limited thicknesses, the differences among the considered fibrous material can be observed in terms of magnitude, but the composite material in any case tends to work better at higher frequencies.

Similar considerations can be made for the reflection factor (see Figure 4). As can be observed, the behaviors of both coefficients respect the condition of Equation (1).

Concerning the normalized characteristic impedance, Figure 5 shows that all the considered specimens behave almost in the same way from 3000 Hz, and present limited differences in the range of frequencies between 2000 and 3000 Hz. The highest differences can be observed at lower frequencies, where Samples A and B present the highest values of impedance. Sample C presents a peak at 250 Hz but behaves almost the same as Sample D above 500 Hz.

4. Discussion

4.1. About the Obtained Results

The results obtained from the acoustic testing of the composite materials provide valuable insights into their performance characteristics, particularly regarding absorption coefficient, reflection factor, and characteristic impedance. Figure 3 illustrates the variations in absorption coefficient across different frequencies for the four sets of specimens. Specimens from Sample C exhibit a notable increase in absorption coefficient at 1000 Hz compared to Sample D, suggesting potential differences in the acoustic behavior of the composite materials based on their composition. Indeed, it is acknowledged in the literature that by increasing the thickness of specimens, the sound absorption increases at low frequencies [22,52,53]. Accordingly, Sample D also presents a peak, but with minor intensity and at a different frequency (400 Hz). Therefore, it is possible to assert that for the considered configurations, the introduction of plant fiber shifted and reduced the low-frequency peak of the sound absorption coefficient but increased the performance between 1500 and 3000 Hz.

Samples A and B display similar behaviors, indicating the relatively limited influence of the fibrous materials on the overall absorption performance. The behaviors observed for specimens A and B (Figure 3) closely resemble those observed in previous studies performed on composites made from rice plant waste and polyurethane foam [8,54], albeit with the best performances significantly shifting towards higher frequencies. This confirms that the proposed composite biomaterial could provide interesting acoustic absorption performances by utilizing the PLA matrix. Furthermore, the use of different waste plant fibers does not alter the behavior of the composite biomaterial; in any case, it exhibits an increase in the absorption coefficient across the entire range of frequencies.

Regarding the effect of specimen thickness and density, as outlined in the literature, thicker and denser specimens demonstrate their optimal performance at low frequencies [22]. Specifically, these parameters facilitate shifting the peak of absorption performance towards lower frequencies while simultaneously flattening the absorption behavior. In fact, considering samples B and C, it is observed that the absorption coefficient shifts from a linear behavior (sample B) to a flat behavior (sample C), with the maximum moving from high to low frequencies. Sample D, like sample C, shows the maximum acoustic absorption at low frequencies, which decreases at higher frequencies. As seen, samples C and D exhibit similar behavior, highlighting a peak in the absorption coefficient at low frequencies. This effect is due to the fact that increasing the material thickness causes the absorption coefficient peak to shift to lower frequencies and then to decrease at higher frequencies. On the other hand, increasing the density allows the material to absorb better over a broader range of frequencies. These results are consistent with the literature [52] and confirm that, even for composite biomaterials, acoustic absorption is highly sensitive to density and thickness parameters, which can be exploited to optimize performance. Furthermore, the composite biomaterial maintains a more consistent absorption coefficient than pure PLA across almost the entire frequency range (or at least between 250 and 4000 Hz). This means that the kind of added plant fiber and its size and shape play a key role in determining the acoustic performance of the composite biomaterials, making these parameters further design variables beyond density and thickness to better customize the behavior.

Regarding the differences in reflection factor among the specimens, as depicted in Figure 4, Sample C shows variations compared to Sample D, while Samples A and B exhibit similar behaviors. These observations underscore the pivotal role of the matrix material (PLA) and the plant fiber reinforcement in determining the acoustic properties of the composite biomaterial. Variations in the percentage of these two components notably influence absorption (and consequently reflection, according to Equation (1) properties. However, especially for low thicknesses and density, the considered composite biomaterial behaves as a good reflector, suggesting potential applications in the field of sound insulation.

The normalized characteristic impedance of the specimens, as depicted in Figure 5, demonstrates similar behaviors among the samples at higher frequencies but notable differences at lower frequencies. Samples A and B display higher values at lower frequencies compared to Samples C and D, suggesting potential variations in sound transmission characteristics due to differing densities and thicknesses, in line with what the literature already suggests [22].

Referring to the evidence outlined in the literature, particularly the comprehensive review presented in [21], which extensively gathers and compares the acoustic characteristics of biobased materials, it is evident that the addition of PLA to plant fiber does not compromise its acoustic absorption properties. In fact, the composite biomaterial aligns with the acoustic performance of pure plant fiber, at least within the considered frequency range and particularly for small thicknesses (<30 mm). More specifically, the obtained values of the absorption coefficient are like those achieved by materials based on pineapple leaf fibers, coir fibers, sisal fibers, and coconut husk fibers. However, as researchers acknowledge in [21], a limitation in using pure plant fiber as a material for acoustic insulation is the necessity to mix it with binding agents to make it manageable in terms of installation, mechanical strength, etc., thus compromising its biodegradability characteristics. From this perspective, the composite biomaterial considered here overcomes this limitation, as PLA can serve as a binding agent, eliminating the need for additional undesired substances. This characteristic renders PLA an intriguing means to enhance the use of plant fibers for acoustic insulation purposes [14].

Considering conventional building insulation materials, the absorption coefficient of the composite biomaterial analyzed here aligns moderately with those found in solutions based on slag wool, expanded polystyrene, phenolic foam, and vacuum insulation panels. Overall, the obtained results underscore the importance of considering the composition of the composite biomaterials with respect to the ratio between the mass of the PLA and the plant fiber for optimizing their acoustic performance in sound absorption applications. Specifically, PLA does not negatively impact the acoustic insulation performance of plant fibers and additionally provides a functional role as a potential binding agent. These findings lay the groundwork for further research into the development of sustainable and effective sound absorption products. Eventually, parameters such as thickness and density confirm the effects and impacts already known and demonstrated in the literature. This confirmation suggests that the absorption behavior of composite biomaterials can be optimized according to well-established guidelines.

In summary, the considerations above presented can be outlined as follows:

- The sound absorption and reflection properties of PLA, in the form of foam or pre-expanded spheres, can benefit from the addition of plant fiber waste.
- The insulation and acoustic absorption performance of the composite biomaterial exhibit similar behavior depending on the type of plant fiber used together with PLA.
- PLA can be used as a binding agent within composite biomaterials, overcoming the need for costly and often non-biodegradable additives. This also reduces the environmental impact of the PLA.
- The possibility of reducing the amount of PLA used within the composite biomaterial brings cost benefits, allowing to improve the competition with traditionally used

petroleum-derived materials for insulation and acoustic absorption. Additionally, this helps reduce the environmental impact of PLA.

- The dependency of the insulation and acoustic absorption performance of the composite biomaterial on parameters such as material thickness and density appears to be consistent with the existing literature, suggesting that optimization of these performances in relation to these parameters could be carried out following already established rules.

4.2. Limits of the Work and Suggestions for Future Developments

While the conducted experiments offer insights into the acoustic performance of the composite biomaterials, there are several limitations to consider. Firstly, the study focuses on a limited number of specimens and may not capture the full range of variability in material properties. Additionally, the choice of fibrous materials (grape stalks and wood straw) and their proportions may influence the results, but this potential impact is not extensively explored in this study.

Furthermore, the acoustic testing is conducted under controlled environmental conditions, which may not fully represent real-world scenarios. Variations in temperature, humidity, and atmospheric pressure could impact the acoustic properties of the materials and warrant further investigation. Moreover, different approaches can be used and compared to obtain reliable data on free fields [55–58].

In terms of future developments, expanding the scope of the study to include a broader range of fibrous materials and sizes, and varying proportions in the composites, could provide deeper insights into their acoustic behavior. Additionally, conducting experiments in real-world conditions, such as outdoor environments or within building structures, could offer a more comprehensive understanding of the materials' performance. It could also be interesting to characterize the composite biomaterial from the perspective of other chemical and physical properties to explore different applications beyond the acoustic field, such as thermal insulation, packaging, etc.

Moreover, further research is needed to optimize the manufacturing process of composite materials to enhance their acoustic properties while maintaining sustainability and cost-effectiveness. This could involve exploring alternative production techniques, such as different heating methods or varying pressure conditions, to achieve the desired acoustic characteristics.

Additionally, long-term durability and performance testing are essential to assess the suitability of the composite materials for practical applications. Evaluating factors such as aging, moisture resistance, and mechanical stability will be crucial in determining their viability for use in sound absorption panels in real-world settings.

Eventually, a further aspect to be evaluated is the fire-resistance behavior of the composite biomaterials based on PLA and plant fibers, which is an important issue—especially in the field of buildings.

4.3. Expected Impact

The findings of this study can have potential implications for academia, society, and industry. Firstly, by investigating the acoustic properties of PLA-based composites reinforced with plant fibers, the study expands the knowledge base on environmentally friendly alternatives to traditional petroleum-based materials.

Furthermore, the insights gained from this research have the potential to benefit society by addressing the growing demand for eco-friendly construction materials. Sound absorption panels play a crucial role in noise control in various settings, including residential, commercial, and industrial spaces. By developing sustainable composite materials with effective acoustic properties, the study contributes to creating healthier and more comfortable living and working environments.

From an industry perspective, the findings offer opportunities for innovation and product development in the construction and building materials sector. Companies involved in the manufacturing of sound absorption panels can leverage the research findings to design and produce eco-friendly products that meet the increasing demand for sustainable building solutions.

Moreover, the adoption of PLA-based composite materials in sound absorption panels aligns with global efforts to reduce reliance on fossil fuels and mitigate environmental impact.

In conclusion, the research findings have the potential to drive positive change by advancing knowledge, fostering innovation, and promoting sustainability in the development and use of sound absorption panels.

5. Conclusions

In this study, the acoustic performance of composite materials comprising a PLA matrix and plant fiber reinforcement for sound absorption panel applications was investigated. Insights into the influence of material composition, thickness, and environmental conditions on the acoustic properties of the composites were gained through a series of experiments and analyses.

The results of the acoustic testing reveal variations in absorption coefficient, reflection factor, and characteristic impedance among the specimens. Overall, the outcomes suggest that the use of waste or underutilized plant fibers in composite biomaterials could be beneficial to improve their customizability, as the required acoustic performance could be achieved not only by playing with traditional design variables, like thickness and density, but also the size, shape, and type of plant fiber. This opens up opportunities for the reusing of waste natural materials by policies based on valorization processes. Eventually, the use of PLA-foam as the matrix of the composite biomaterial constitutes a valid alternative to the traditional binding agents, by preserving the biodegradation properties.

From an academic perspective, this study contributes to the growing body of knowledge on sustainable materials for acoustic applications. By elucidating the acoustic behavior of PLA-based composites, the research expands the understanding of environmentally friendly alternatives to traditional petroleum-based materials. Moreover, the findings have practical implications for industry, particularly in the construction and building materials sector, for companies involved in the manufacturing of sound absorption solutions.

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