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Semi-Industrial Preparation of Versatile Panel Rolls from Micronized Hemp Stalks

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Abstract

In recent years, agricultural biomass-filled materials have been increasingly explored as sustainable alternatives to fossil-based polymers and for the development of biocomposites. In this study, micronized hemp stalks, a byproduct of the cannabis industry, were loaded into 10–20% of polypropylene/polyethylene bicomponent fibers in a cost-effective original airlaying process. The production process was developed to achieve high hemp content (up to 80%), while maintaining suitable structural and mechanical properties. Experimental analyses confirmed that the hemp-based biocomposite exhibited promising thermal conductivity values (0.068 ± 0.002 W/mK) and effective sound-attenuation capabilities that are comparable to commonly used insulating materials, such as stone wool. Furthermore, X-ray diffraction and field emission scanning electron microscopy measurements analyzed the insulation features of the hemp-based biocomposite prepared with its morphological and structural properties, revealing its high internal porosity and polymeric crystallinity. These results highlight the potential of hemp biocomposites as sustainable, economically viable alternatives for thermal and acoustic insulation applications.

Keywords: airlaying process; biocomposites; biomass; hemp stalks; renewable resources

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1. Introduction

The emergence of bioplastics and biocomposites represents a significant advancement in the polymer industry and is driven by the need to address the environmental consequences of non-biodegradable plastics [1–3]. The development of sustainable materials through economically viable methods is a promising avenue for reducing our dependence on fossil-fuel-derived plastics, boosting innovation in the fields of material science and engineering. As part of this approach, the incorporation of plant-derived fibers into pure polymers represents a compelling solution for reducing the use of petroleum-based polymers [4,5].

A variety of naturally occurring resources, such as hemp, flax, and bamboo, exhibit numerous advantageous properties, rendering them particularly well-suited for use in the development of composite materials. Meanwhile, the issue of noise pollution is gaining increased attention in the construction industry, as demonstrated by the growing recognition of its potential implications for public health, and the increasing demand for effective and sustainable noise-insulating materials [6]. Glass fiber materials, which are derived from petroleum resources, are currently among the most prevalent insulation materials in the construction industry. In response to the current demand for sustainable and naturally sourced industrial solutions, lignocellulosic materials exhibit numerous advantages over glass fibers. These materials possess distinctive characteristics, including low cost, minimal energy consumption, zero CO_2 emissions, low density, biodegradability, non-toxicity and high availability [4,7].

Hemp (*Cannabis sativa* L.) crop is known to yield up to five harvests [8], and is thus responsible for a substantial amount of biomass production. In particular, hemp stalks have attracted considerable attention during the last few decades for various industrial applications [9]. Hempcrete, for instance, has already found potential applications within the construction industry due to its thermal and acoustic insulation properties mainly provided by hemp stalks [10,11]. Indeed, the lightweight and high lignocellulosic content of this undervalued byproduct of the cannabis-related industry make it an ideal candidate for biocomposites development. Hemp stalks contain mainly hurds and bast fibers. Hemp hurds contain around 40–48% cellulose, 18–24% hemicellulose, and 21–24% lignin [12], which eases binding with hydrophilic polymers. Hemp is known to possess distinctive insulating properties, which are mainly linked to the retained stalks [9]. Indeed, the low particle size and density of hemp stalks make them well-suited for preparing panels and biocomposites with promising thermal and acoustic insulating features [13,14]. Another interesting property of hemp stalks is their natural hollow structure, which makes them particularly suitable for application in sound-absorbing composite materials, as shown in a study by Su et al. [15]. In another relevant work, Wang et al. prepared hemp-based composites, the results of which demonstrated their sound-absorbing properties [16]. Viel et al. prepared composite materials from hemp hurds and the results showed good thermal insulation properties [17].

The process known as airlaying is one of the most technologically viable and cost-efficient solutions for composite production within the bio-building industry. The process involves the mixing of fibers with air to create a uniform air–fiber mixture, which is then deposited onto a moving, air-permeable belt [18]. In the construction and bio-building sectors, the use of airlayers plays a crucial role mainly for improving the thermal performance of buildings and minimizing energy consumption [19]. The use of abundant biomass, such as hemp byproducts, for the development of insulating air layers, panels and rolls has emerged recently as a novel strategy to contribute to the sustainability of modern buildings while valorizing the residual biomass annually generated [20].

The objective of the present study is to contribute to the sustainable valorization of hemp byproducts by producing panels based on hemp stalks that can be used as sound and thermal insulation materials. To this end, an innovative airlay pilot plant was used with the goal of producing versatile panel rolls for industrial applications.

2. Materials and Methods

2.1. Panel Preparation

Micronized hemp (400–500 µm) stalks were provided by CHC Chiaramonte Canapa Consapevole Srls (Santa Cristina Gela—Palermo Italy). The micronization system used for the hemp stalks operates by impact. Specifically, the material enters a grinding chamber, where it hits a grooved surface with fixed hammers to pulverize it. The micronized product is then separated via a cyclone with a rotary valve and collected in bags, while the remaining dust-laden air is passed through a self-cleaning bag filter. The rotor can reach speeds of up to 5000 rpm (Arfa R-600 75 HP by Favini & C. sas, Fornovo, Bergamo Italy). The pre-treatment of the plant material was chosen to be as simple as possible before airlaying and so the micronized hemp stalks supplied were used for loading as they were. Biomass–polymer blends were prepared via airlaying, using an experimental pilot airlay system (Cormatex—Montemurlo, Prato, Italy) that has the capacity to produce up to

105 kg/h of finished product. Polypropylene/polyethylene (PP/PE) biocomponent fiber (from the IntraLoc™ 1 series, FiberVisions, Covington, GA, USA), which is designed to provide high efficiency and low cost-of-use in the formation of composite structures, was used as a binder. The PP/PE fiber is a commercially available bicomponent fiber commonly used in many nonwoven production processes. These fibers consist of a PP core with a melting point of approximately 160 °C, surrounded by a PE sheath with a significantly lower melting point of around 130 °C. The developed production process includes an opening and blending section, where the bicomponent fiber is blended with the micronized hemp stalks, and a thermobonding section, where the material is heated to a temperature between 130 and 160 °C. This allows only the PE sheath to melt, which, upon cooling, consolidates the panel. The produced panel rolls have a weight ranging from 1500 g/m^2 (flexible and rollable material) to over 2400 g/m^2 (stiffer product that was cut into panels of desired size), a thickness between 5 and 10 mm, and a width of 1 m. A representative scheme of the preparation process of the panels is illustrated in Figure 1.

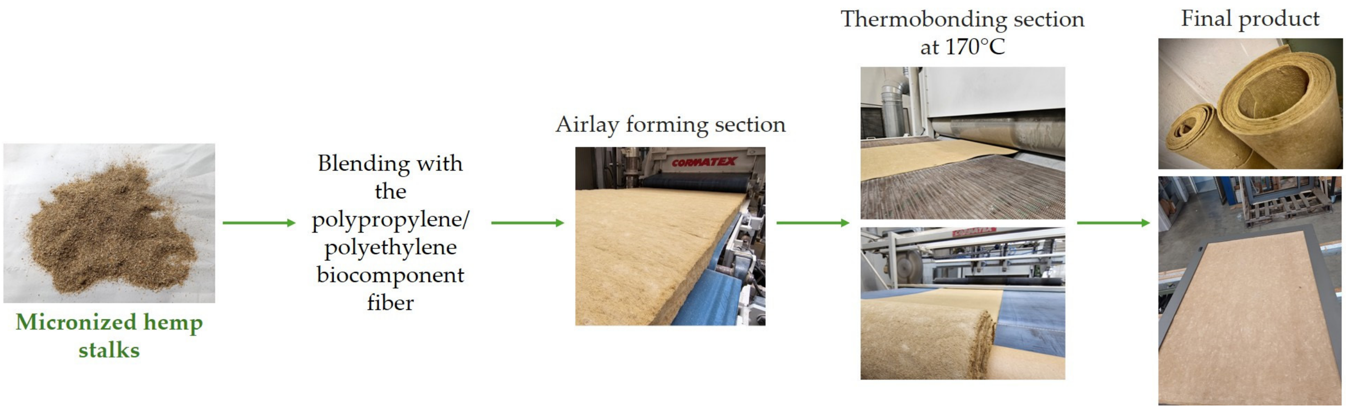

Figure 1. Representative scheme of the airlaying process.

Since the objective was to achieve maximum biomass loading, the hemp-to-polymer ratio was selected to be as high as possible, ranging between 75–25% and 90−10% on a weight basis. From an economic feasibility perspective, the incorporation of higher biomass within the matrix will contribute to the economic viability of the process, promote the use of hemp stalks and reduce the reliance on polymeric materials. Tests carried out using the ratio of 80% biomass (around 85% of hurds and 15% of bast fibers) and 20% polymeric binder proved to provide the most promising product based on a visual and manual inspection. The thickness of the prepared samples was measured manually using a caliper. Measurements were taken at multiple points across the panel surface to account for possible variations, and the average value was reported.

2.2. Thermal Insulation Analysis

Thermal conductivity was measured according to the European standard EN ISO 11092 (September 2014 edition), designed to simulate and measure the transfer of heat and moisture through materials next to human skin [21].

2.3. Sound Insulation Analysis

Acoustic insulation was measured in the 20–20,000 Hz frequency range to simulate human hearing. Band-pass filters were applied to precisely determine acoustic pressure at various frequencies. Rock wool was used as a positive control in the acoustic insulation test, while a normal textile product was used as a negative control.

2.4. Structural and Morphological Analysis

X-ray diffraction (XRD) patterns were acquired using a PANalytical PW3050/60 X'Pert PRO MPD diffractometer (Malvern, UK), operating in Bragg–Brentano geometry. The system employed a high-powered ceramic tube (PW3373/10 LFF) with a copper anode, emitting Cu Kα_1 radiation (λ = 1.5406 Å), and incorporated a nickel filter to suppress K_β radiation. Scattered X-rays were detected using a real-time multiple strip X'Celerator detector. Data was recorded over an angular range of 2θ = 3° to 50°, with 0.02° 2θ steps. All samples were analyzed in their as-received state and posed in a spinning sample holder to reduce preferred orientation effects (Figure S1 in Supplementary Materials).

Field emission scanning electron microscopy (FESEM) analyses were performed using a TESCAN S9000G FESEM 3010 microscope (30 kV) (Brno, Czech Republic), equipped with a high-brightness Schottky emitter. Elemental composition was assessed via energy-dispersive X-ray spectroscopy (EDS), using an Ultim Max Silicon Drift Detector (Oxford Instruments, Abingdon-on-Thames, UK). Samples were deposited on conductive adhesive-coated stubs and introduced into the chamber through a fully motorized loading system. To prevent charging effects, samples were metallized with a thin platinum layer (~5 nm) using an Emitech K575X sputter coater (Quorum, East Sussex, UK). Imaging was conducted using both secondary electron and backscattered electron detectors.

3. Results and Discussion

The samples were of low weight with a thickness of 8 mm, a property that can facilitate their use, transportation and applications. Previous research studies have reported that hemp hurds exhibit high porosity and low apparent density, with reported values ranging from 88 to 133 kg/m^3 [22,23]. This characteristic renders them well-suited for use in paneling products, since lower density results in greater compaction ratios, thereby improving particle contact and inter-particle bonding [24]. Furthermore, there has been an increase in demand for lightweight panels, a trend that can be linked to the growing popularity of ready-made furniture [25]. The increased popularity of this type of furniture can be attributed to its enhanced strength-to-weight ratios, design flexibility and ease of transportation [26].

3.1. Thermal Insulation Properties

The efficiency of insulating materials is described by thermal conductivity, denoted by the letter λ and expressed as W/mK. Thermal conductivity is a material property that quantifies the ability of a given substance to facilitate heat transfer. A thermal insulation test of the prepared material resulted in a mean λ value of 0.068 $\pm$ 0.002 W/mK. In a study conducted by Kirilovs et al. [27], the panels prepared using hemp hurds mixed with phase-change materials (nanocapsules) and 10% urea formaldehyde resin glue, used as a binding agent, exhibited similar results with a thermal conductivity of 0.067 W/mK [27]. However, the thermal value of the material prepared in this study is higher than that of commonly used insulation materials such as stone wool, polyurethane and glass wool. These materials have previously demonstrated thermal conductivities ranging from 0.033 to 0.040 W/mK, 0.022 to 0.040 W/mK, and 0.031 to 0.037 W/mK, respectively [28]. The thermal conductivity of other unconventional natural raw materials was found to fluctuate within the range of 0.06 to 0.1 W/mK [29–33].

3.2. Acoustic Insulation Capacity

Upon impact with a material, a sound wave may be absorbed, reflected or transmitted, depending on the material's characteristics [34]. Maximizing sound absorption is of utmost interest for noise control. The airlayed hemp hurds–biopolymer blend was tested against a negative control made of a textile with known attenuation and the result achieved is shown in Figure 2.

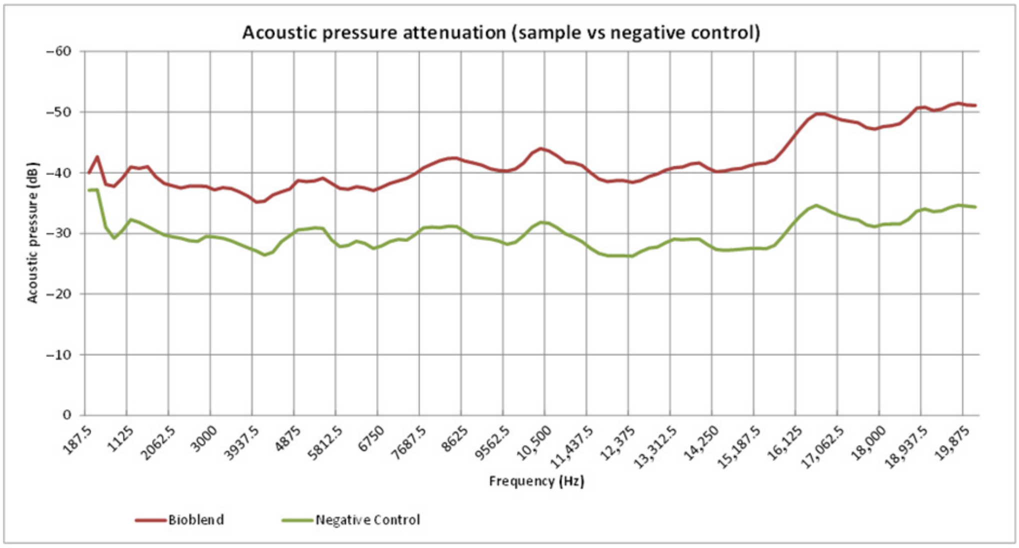

Figure 2. Acoustic pressure attenuation of the sample and negative control.

As illustrated in the figure, the bioblend demonstrates a higher capacity for acoustic pressure absorption than the negative control, thereby indicating its insulating properties. Attenuation is more significant at higher frequencies, with the tested material demonstrating an approximate 10 dB increase in absorption at these, compared to lower, frequencies.

The sound insulation test was subsequently conducted using rock wool, a well-known and widely used insulation material, and the result is reported in Figure 3. Whereas the positive control absorbed more acoustic pressure, the bioblend demonstrated slightly lower absorption values. Sound absorption is dependent upon the thickness of the material, as well as several other factors [35,36]. A thicker structure absorbs sound waves by causing frictional loss between the sound wave and the fibers [34]. This process dampens the effects of the propagating sound wave. These findings support the hypothesis that materials composed of hemp byproducts, particularly hurds, can serve as a cost-effective, abundant and eco-friendly alternative to conventional materials for acoustic insulation.

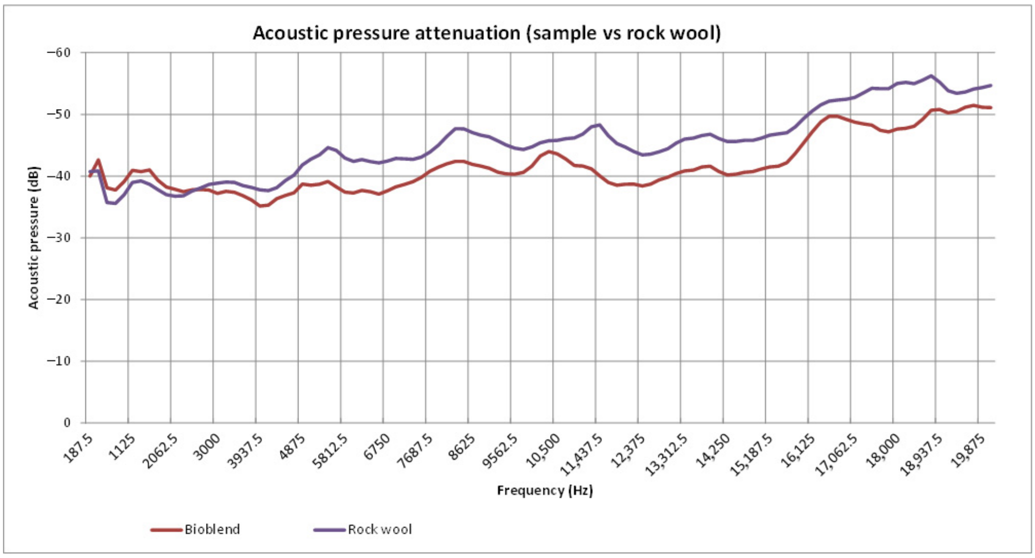

Figure 3. Acoustic pressure attenuation of the sample and rock wool.

3.3. Morphological and Structural Characterization

FESEM and XRD analyses were carried out to reveal the structure and morphology of the prepared hemp-based panels and the used micronized hemp stalks, and the results obtained are presented in Figures 4 and 5, respectively. The morphology of the hemp stalk is shown in the upper images of Figure 4, highlighting the presence of two different structures, i.e., pores highly connected forming hollow structures (yellow circles) and layers in which fibers and particles and pores can be recognized.

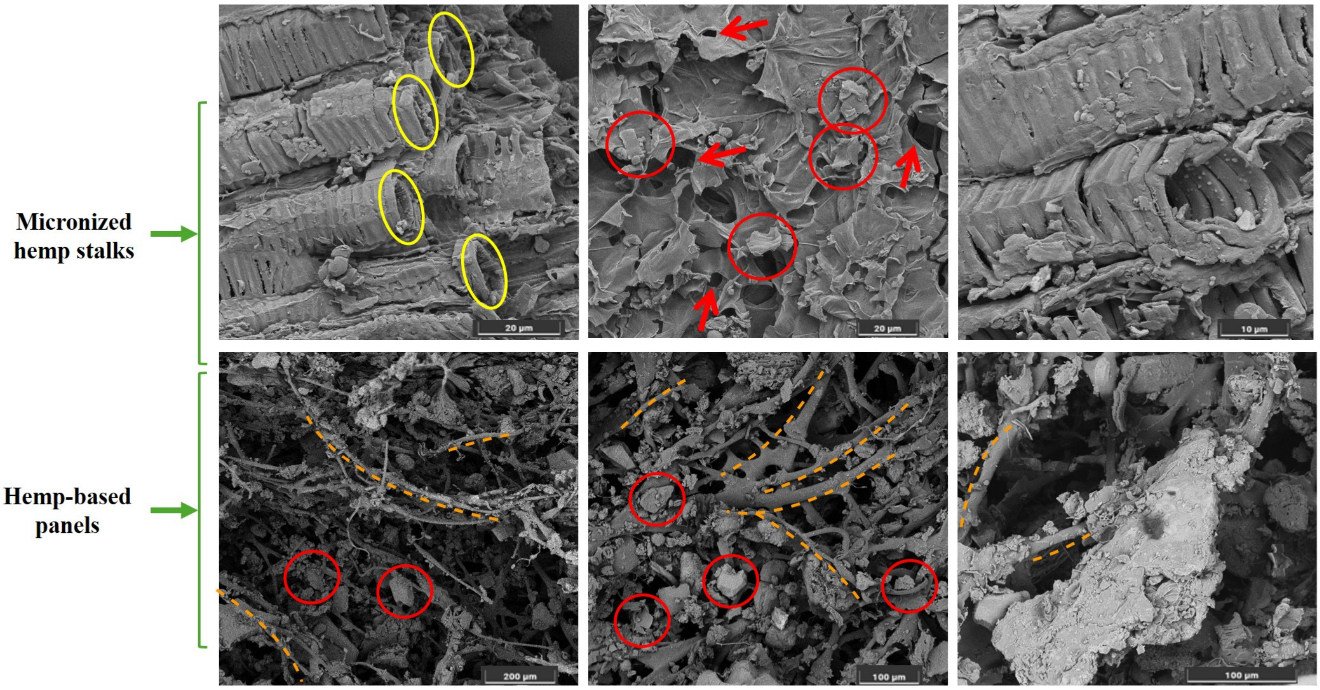

Figure 4. FESEM representative images of micronized hemp stalks (**upper images**) and hemp-based panels (**lower images**). Red circles highlight hemp particles; yellow circles indicate hollow structures of hemp fibers; dashed lines represent the polymer.

On the other hand, the hemp-based panels are characterized by a completely different morphology, characterized by high porosity and well-dispersed hemp particles (red circles) within the reticulated PE/PP framework (Figure 4, lower images). The internal porosity of materials is of pivotal importance for inducing thermal and acoustic insulation properties [9]. Indeed, in highly porous materials, the presence of voids, inner and outer spaces, as well as the density of the material, are directly linked to its thermal and acoustic absorption capacity [37,38]. The effective design of porous sound-absorbing materials involves meeting three main criteria. First, the material should contain a large number of pores to allow sound waves to penetrate. Second, these pores must be appropriately sized and well-interconnected to support the movement and dissipation of sound energy. Finally, there should be continuous pathways relating the internal pore network to the outer surface of the material, ensuring efficient wave penetration and energy absorption [39]. Hence, based on the FESEM representative images presented in Figure 4 and Supporting Materials (Figures S2 and S3), it can be assumed that the internal porosity of the prepared hemp-based panel is responsible for its sound absorption capacity.

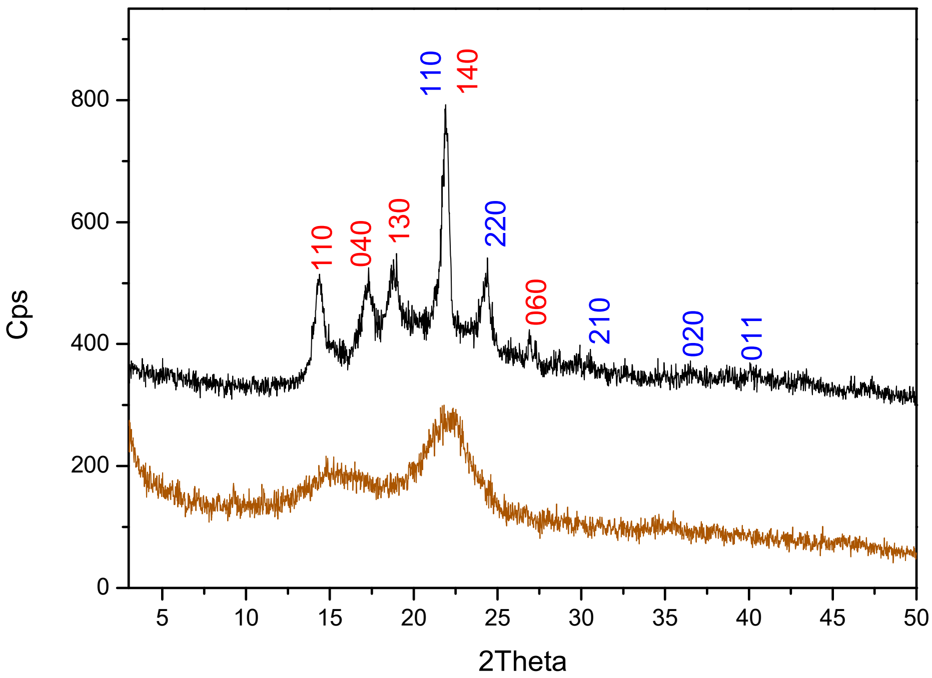

Figure 5. XRD patterns of hemp stalks (brown line) and hemp-based panels (black line). The red numbers refer to the peaks of PP while the ones in blue refer to PE.

Regarding the XRD patterns of hemp stalks, the major typical diffraction peaks were found in the micronized hemp in the 14.99°, 16.49° and 22.78° 2θ ranges, which correspond to crystallographic planes of cellulose (00-050-2241) (Figure 5). This is in accordance with other studies highlighting the presence of cellulose peaks in the XRD patterns of hemp-based biocomposites [15,40–42]. A high crystalline cellulose content results in well-separated peaks around the 14° and 16° 2θ ranges, whereas the presence of a greater amorphous phase causes these peaks to merge into a single broad peak [43].

When loading hemp stalks into the material, only a broad peak overlapped to other new peaks is observed, which indicates the loss of crystallinity of the hemp fibers when loaded into the panel. Meanwhile, other peaks linked to the PE/PP used appeared in the XRD pattern of the hemp-based panel. In detail, the peaks appearing in the 14.09°, 17.09°, 18.48°, 21.79° and 26.07° 2θ ranges are characteristics of monoclinic PP (00-054-1936). The peaks found in the 21.66°, 24.03°, 30.17°, 36.34° and 39.86° 2θ ranges are linked to orthorhombic PE (00-053-1859). These features assessing the presence of amorphous hemp fibers embedded within a crystalline polymeric network (already evidenced by the FESEM measurements), along with an uneven molecular weight in hemp stalk, can lead to loose molecular chains and weak intermolecular forces, thus allowing sound waves to penetrate and dissipate more easily within the polymer matrix [15].

4. Conclusions

In this study, micronized hemp stalks were incorporated into a polymeric binder using an airlaying process. Analyses show the excellent thermal and acoustic insulation properties of the resulting panel rolls. The thermal conductivity of the hemp biocomposite is comparable to that of conventional insulation materials, while its sound insulation properties are comparable to those of other commonly used materials. Structural and morphological analyses revealed the presence of a high internal porosity and well-dispersed hemp particles. This study emphasizes great interest in the use of hemp stalks for the manufacture of panels and rolls, which can be used as sound and thermal insulation materials in a variety of applications. Future interest should focus on further optimizing the thermal and acoustic insulation properties of hemp-based materials, taking into account the long-term durability and resistance to ambient conditions of these biocomposites in real-world applications and their stability to environmental stress. Additionally, keeping in mind that hemp is known to be able to store CO_2, a life cycle assessment study of the hemp-based insulation panels will provide insights into potential environmental impacts throughout their production, use and end-of-life.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jcs9080440/s1, Figure S1: Spinning sample holders of (**a**) micronized hemp stalks and (**b**) hemp-based panel; Figure S2: Other representative FESEM images of the micronized hemp stalks used in this study; Figure S3: Other representative FESEM images of the hemp-based panel used in this study.

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Data Availability Statement: The original contributions presented in this study are included in the article and Supporting Information. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: Author Luca Querci was employed by the company Cormatex S.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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