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# Preparation and Characterization of Particleboard Made from Industrial-Type Wood Particles and Discarded Duck Feathers

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**Abstract:** Global poultry waste production is substantial, with billions of poultry raised annually for meat and egg production, resulting in significant feather waste. Conventional poultry waste disposal methods are restricted due to environmental concerns. Meanwhile, wood-composite panel industries face raw material shortages, emphasizing the need for sustainable, renewable fiber sources. In this study, in the core layer of panels, wood particles were replaced with 5 wt% clean duck feathers without pretreatment to take advantage of feather attributes like hydrophobicity, thermal insulation, and sound damping as an alternative construction material. Three adhesives—urea-formaldehyde (UF), polymeric 4,4′-diphenylmethane diisocyanate (pMDI), and polyvinyl acetate (PVAc)—were examined for resin–feather compatibility. The control panels in this study were identical but wood was not replaced with feathers. The results revealed that wood–feather particleboard with pMDI and PVAc resins meets the requirements of the relevant standard for P2 boards (where applicable) concerning their modulus of rupture (MOR: 11 $N \cdot mm^{-2}$), modulus of elasticity (MOE: 1600 $N \cdot mm^{-2}$), internal bond (IB: 0.35 $N \cdot mm^{-2}$), and screw withdrawal resistance (SWR). However, those produced with UF resin did not meet the standards for IB and MOE. Furthermore, the physical properties showed similar water resistance and thickness swelling to control panels with pMDI. Notably, substituting 5 wt% wood with feathers improved thermal insulation by approximately 10% for UF and pMDI resins. Additionally, particleboard with feathers demonstrated improved sound absorption at high frequencies, ranging from 2500 to 500 Hz, particularly with pMDI resin, approaching Class B classification according to EN ISO 11654:1997. This study identifies the higher compatibility of pMDI over PVAc and UF adhesives for feather-based composite materials in construction applications.

**Keywords:** particleboard; composites; poultry waste; duck feathers



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## 1. Introduction

The global consumption of poultry meat, including duck, turkey, goose, and chicken, is projected to increase to 154 Mt by 2031, accounting for nearly half of the additional meat consumed. Consumers are attracted to poultry because it is cheaper (farming and fast growth), consistent, and has a lower fat/protein ratio [1]. Based on OECD data from 2024, global consumption projections indicate an average consumption of 136,808.8 thousand tonnes worldwide, equivalent to approximately 14.9 kg per capita [2]. The European Union is one of the largest producers and traders of poultry products globally and produces around 13.4 million tonnes of products annually [3]. Feathers are a major waste of this food industry sector, accounting for an average volume of 3.6 million tonnes annually in Europe [4]. Disposing of such poultry wastes, especially feathers, in incinerators or landfills increases financial and environmental costs due to their extreme resistance to physical, chemical, and biological agents [5] and their emission of hazardous greenhouse gases [6]. As a result, the use of these methods has been restricted. Feathers comprise approximately half fiber and half quill (by weight) [7]. The fiber and quill consist of 90% hydrophobic keratin [8,9], a rigid protein consisting of several amino acids, largely made up of cystine, lysine, proline, and serine [8,9]. These amino acids crosslink via disulfide and hydrogen bonds, making them extremely resistant to degradation and lightweight, and they have good thermal and acoustic insulating properties [10,11]. The quills, as hard keratins, have marginal commercial applications in industries like the textile, rubber, cosmetics, biomedical, bioenergy, and pharmaceutical industries [12]. However, due to the low volume requirements of these applications, waste feathers remain a significant waste product each year. For instance, the cost of disposing of one tonne of feathers in Poland can be up to EUR 77 [13], and in Malaysia, the annual disposal cost reaches approximately EUR 380,000 [14].

From another perspective, the wood-based composite industry continuously needs raw materials [15]. Therefore, natural fibers of renewable resources other than wood and lignocellulosic materials should be considered to maintain sustainable production. Composite building materials and interior fitment panels, such as fiberboard and particleboard, are high-volume and have the potential to consume large quantities of waste feathers efficiently. Even if we only consider the 3.6 million tonnes of feather waste generated in Europe annually, this would be enough to manufacture 90 thousand tonnes of composite panels with a five percent feather content. Considering the average demand for wood raw material in a single line of particleboard plants is about 25 tonnes per hour, working 24/7, excluding one month per year for service works, it consumes about 201,000 tonnes of wood per year [16]. Replacing 5% of this with feathers would yield savings of approximately EUR 1,507,500 annually, based on the current cost of wood at EUR 150 per tonne [17]. This substantial saving underscores the financial viability of using feathers in particleboard production, offering a cost-effective, renewable source of fiber that benefits both the poultry and wood industries. A new Circular Economy Action Plan was launched in 2020 to accelerate the EU sustainability transition and move from a fossil-fuel-based economy to a circular bioeconomy. This includes the Sustainable Product Policy Framework (SPPF), which aims to address high-impact products, including textiles, construction products, electronics, and plastics, and to ensure that production in the EU is resource-efficient, climate-neutral, and aligned with principles of a circular bio-based economy (European Commission 2020) [18]. The construction sector is responsible for over 35% of the EU's total waste generation. The greenhouse gas (GHG) emissions from material extraction, manufacturing of construction products, and renovation of buildings are estimated at 5–12% of the total national GHG emissions. Using more efficient materials could save 80% of those emissions [18]. Researchers have developed materials that are thermally and acoustically insulating using natural waste biomass such as reed straws [18,19], bagasse [20,21], cattail [22], corn cob [23], cotton stalks [24,25], coconut chips [26], rice and wheat straw [27], regenerated cellulose [28], and seaweeds [29], among other alternatives. Moreover, recycled materials such as glass [28], waste paper and textile fibers [29], and plastics [30] have been investigated. Chicken feathers have been reported to be used partially, along with wood chips and fibers, as a low-cost option [30–33]. Medium-density fiberboard (MDF) and particleboard with a portion of chicken feathers demonstrated promising physical and mechanical properties [31]. However, adding poultry feathers in amounts greater than 10% resulted in lower mechanical properties and higher water repellency in the composite materials.

Additionally, the building sector has become one of the most energy-consuming sectors in recent years in terms of heating and cooling loads and elaboration of sound-absorbing materials based on petrochemicals, with Europe accounting for 40% of energy consumption and 36% of $CO_2$ emissions [34]. Therefore, building insulation materials need to be developed at lower costs, and feather waste is one of the most effective and cheap insulation materials for reducing energy consumption, with thermal conductivities ranging from 0.024 to 0.034 $W \cdot mK^{-1}$ depending on the type of feather [35], and they have a highest noise absorption coefficient of 0.6 [36]. This is due to their chemical composition and honeycomb microstructure (Figure 1), which effectively traps air, promoting sound absorption and acting as a thermal barrier. In this study, various wood composite particleboards were prepared by substituting 5 wt% of the wood particles with clean duck feathers without any pretreatments in the core layer, keeping the density of the panels constant (0.66 g·cm$^{-3}$) and the structure of the panels even. In addition to this, three different binders were used as adhesives, urea-formaldehyde (UF), polymeric 4,4′-diphenylmethane diisocyanate (pMDI), and polyvinyl acetate (PVAc), to study the resin–feather compatibility. The emphasis was on evaluating waste duck feathers as a component of natural insulation composites and mixed waste wood residues, ensuring their physical and mechanical properties meeting the requirements of EN 312 standard for P2 boards. The physical, mechanical, thermal, and acoustic properties of wood particleboard containing feathers were investigated and compared to those of control panels without feathers. Additionally, the effect of adhesive type on the exploitation properties of the particleboard was evaluated.

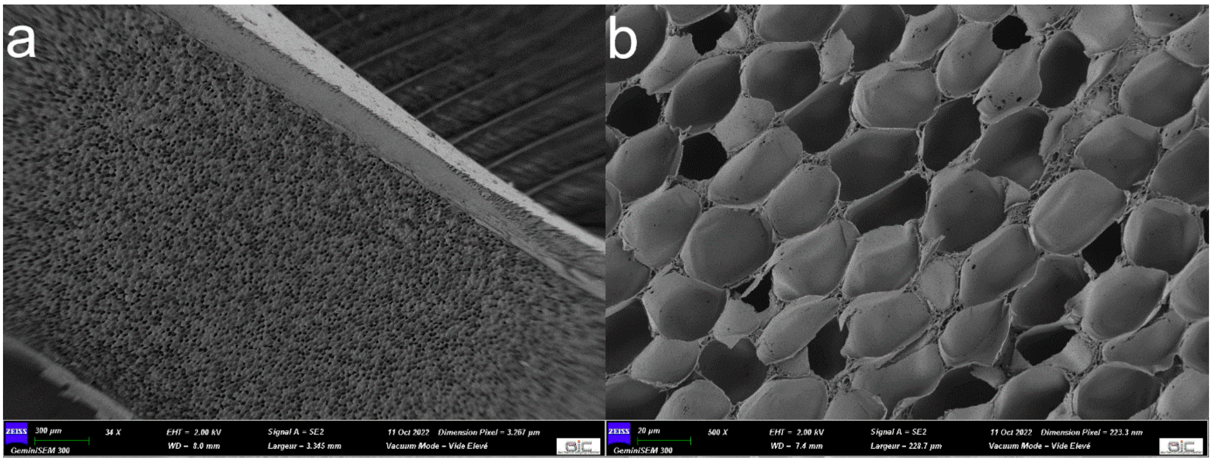


**Figure 1.** Scanning ELECTRON MICROSCOPY (SEM) images of the cross-section of a feather rachis showing the hollow honeycomb-shaped structures: (**a**) bar = 20 µm; (**b**) bar = 1 µm. The SEM analysis used a Gemini SEM 300 FESEM (Zeiss, Oberkochen, Germany). The samples were mounted on specific stubs, platinum-coated using a Q150T sputter coater (Quorum Technologies, Kent, UK), and observed at 2 kV.

## 2. Materials and Methods

### *2.1. Materials*

The industrial particles, ca. 95 wt% of pine *Pinus sylvestris* L. and 5 wt% spruce *Picea abies* (L.) H. Karst and some deciduous species, with an about 6% moisture content (MC), which were intended for the face and core layers particleboard production, were received from a plant located in Poland. An industrial partner generously supplied white duck feathers (Plum'Export, Saint-Sever, France). As binders, an industrial urea-formaldehyde (UF) resin Silekol S-123 (Silekol Sp. z o. o., Kędzierzyn—Koźle, Poland) of about 66% dry content was used. The hardener for UF adhesive mass was a 40 wt% water solution of ammonium nitrate. The UF bonding mass composition had a weight ratio of 100:8:8 (resin, water, hardener solution, respectively) to reach the curing time of the adhesive mass at 100 °C for about 86 s. PVAc was prepared by adding distilled water to 40% of the total solid content to achieve the consistency of a thick liquid. PMDI was used directly. The viscosity of all used binders before application was about 420–450 mPa·s. No hydrophobic agents were added.

### *2.2. Wood Material Fraction*

The fraction share of wood particles was examined with an IMAL vibrating laboratory sorter with six sieves of 8, 4, 2, 1, 0.5, 0.25, <0.25 mm. For each fraction, 100 g of raw material was used. The set time for conducting the vibrating was 5 min; the sieving results of both the face and core layers correspond to an average of three examinations in Figure 2.

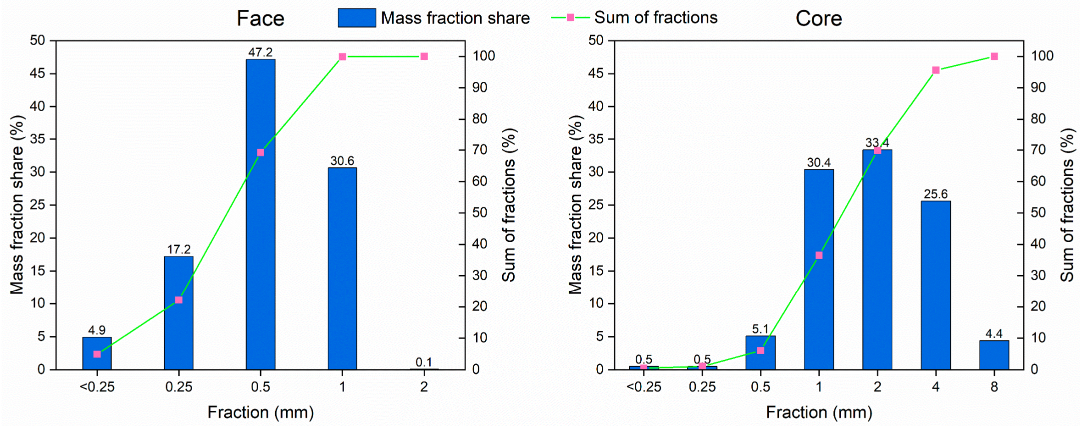


**Figure 2.** Mass fractions of the wood particles for both face and core layers.

## 2.3. Feather Fibers

According to a preliminary analysis of the costs, separating feather fibers from the quills would be costly and not encouraging for composite factories. Therefore, it was decided to use the whole feather in this study to enable any positive results to be applied commercially. In this study, only the contour feathers of the body, comprising the rachis, barbs, and barbules, were used. These feathers, which exhibited less fluffiness than the high-value down feathers typically used for commercial purposes, were mixed with the core wood particles in a drum mixer to form the wood–duck feather composite mat. The length of the feathers ranged from one to five centimeters.

## 2.4. Preparation of Panels

All the composites were manufactured with a goal density of 660 kg·m$^{-3}$ and dimensions of 320 mm × 320 mm with a nominal thickness of 16 mm, and the mass share of the face layers was 32%. Resin application to the panels was carried out using the three different adhesives previously mentioned, adhering to the common practices of particleboard plants based in Poland. The application consisted of 10% resin for the core layer and 12% for the face layers. For each adhesive, four replicates were created. In two replicates, 5 wt% of the wood panel weight was substituted with clean duck feathers in the core layer. The remaining two replicates were produced without adding feather fibers, serving as control boards for comparative analysis. Fine face- and core-layer particles were blended separately; the face particles with the liquid binder were poured gradually through the periphery of a rotary mixer (Figure 3a).

In contrast, the core particles were blended using a drum mixer (Figure 3b) to avoid breaking into smaller particles, and the binder was sprayed with an air gun. Subsequently, the three layers were distributed sequentially in one mold (Figure 3c). The panels were then cold pressed with a ZUP-NYSA PH-1P125 (Zup Nysa sp. z o.o. sp.k., Konradowa, Poland) press with a maximum specific pressing pressure of 1.23 MPa and a pressing time factor of 5 s·mm$^{-1}$ of the nominal thickness of the panel; after that, they were pressed in a hot press (AKE, Mariannelund, Sweden) at a pressing temperature of 180 °C, and a pressing time factor 20 s·mm$^{-1}$ of the nominal thickness of the panel, with a specific maximum unit pressure of 2.5 MPa. Figure 3d shows the different panels after the hot-pressing process. The boards were conditioned in a climatic chamber (Research and Development Centre for Wood-Based Panels Sp. z o.o. in Czarna Woda, Poland) at 20 °C and 65% air humidity until a constant mass was obtained. Calibration (by sanding an about 0.15 mm thick layer per every panel side) was conducted with a Houfek Buldog SPB 1100 RC sanding machine (Houfek a. s., Golčův Jeníkov, Czech Republic) after hot pressing and conditioning the panels.

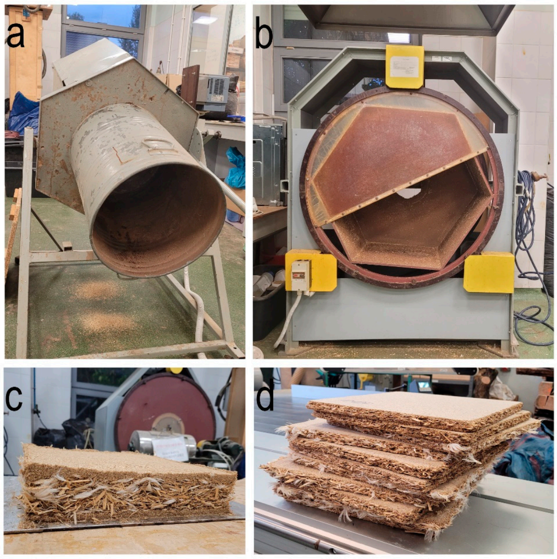


**Figure 3.** Set up of the experimental procedure: (**a**) blending mixer for the face's fine particles (here in unloading position); (**b**) drum mixer for the core large particles and feathers; (**c**) mat after molding, before hot pressing; (**d**) panels after hot pressing.

### *2.5. Physical and Mechanical Examination*

The test specimens were cut according to EN 326-2 [37] and EN 326-1 [38]. The modulus of rupture (MOR) and elasticity (MOE) were determined according to EN 310 [39]. The internal bond (IB) was determined according to EN 319 [40]; screw withdrawal resistance (SWR) was determined according to EN 320 [41]; water absorption (WA) and thickness swelling (TS) were determined after 2 h and 24 h of immersion according to EN 317 [42]. All the mechanical properties were examined with an INSTRON 3369 (Instron, Norwood, MA, USA) computer-controlled laboratory-testing machine, and, whenever applicable, the results were referenced against standard EN 312 for P2-type panels [43]. No less than 10 replicates of each sample were used for the mechanical and physical tests. The density was measured according to [44]. The density profiles of the tested particleboards were measured on a GreCon DAX 5000 device (Fagus-GreCon Greten GmbH & Co. KG, Alfeld/Hannover, Germany) using samples with 50 mm × 50 mm nominal dimensions. As many as 3 test specimens of every sample were measured, but 1 representative density profile per panel type was selected for display.

### *2.6. Apparent Density Measurement*

The studied panels, with their apparent density values, are presented in Table 1. The apparent density of the panels differed slightly from the theoretical density fixed when preparing the panels. This was mainly due to the differences in the compactness and compatibility of the products, where an increase in material compactness reflects an increase in apparent density [45].

**Table 1.** Tested panels and their average density.

| Sample | Binder | Feather Share in Core Layers [% by Weight] | Nominal Average Density [kg·m$^{-3}$] |
|---|---|---|---|
| 1 | UF | 0 | 665 ± 4 |
| 2 | UF | 5 | 664 ± 4 |
| 3 | pMDI | 0 | 663 ± 4 |
| 4 | pMDI | 5 | 663 ± 4 |
| 5 | PVAc | 0 | 664 ± 5 |
| 6 | PVAc | 5 | 664 ± 6 |

### 2.7. Thermal Conductivity Measurement

Thermal characteristics of the panels were determined via the transient plane source method using a TPS 2500S apparatus ( Hot Disk AB, Göteborg, Sweden) with a radius of 6.403 mm. The power was set to 10 mW, and the measuring time was set to 160 s. The measurements were performed at 22 °C. All measurements were performed with two samples and a thermal sensor between them. In this test, the thermal conductivity is measured as the amount of heat that can be conducted through a plate of unit thickness per unit time and unit area. A minimum of three test specimens were measured for each sample.

### 2.8. Acoustic Analysis

The sound absorption capacity of the panels was evaluated using the Kundt tube method. The setup involves a cylindrical tube with a 37 mm interior diameter with a rigid piston at one end to control the sound transmittance zone, a loudspeaker at the other end generating a flat incident wave, a frequency generator (DG1022), and an oscilloscope (DS1102E). The test specimen consists of a flat cylinder positioned against the piston and a mobile microphone that records acoustic pressure variations. The six samples were tested, each with dimensions of d = 37 mm and thickness of 16 mm, and a 14 mm entry hole to facilitate their entry into the Kundt tube setup. Each variant test included three examined specimens.

The Kundt tube impedance measurement technique enables accurate determination of the material's acoustic impedance and absorption coefficient upon exposure to a perpendicular incident wave. The mobile microphone captures the highest and lowest pressure points of the sinusoidal signal emitted by the loudspeaker. As the incident wave interacts with the sample, a portion is absorbed, and the remainder generates stationary waves by reflecting within the tube. The reflection coefficient was calculated using the standard wave ratio method, which is based on the voltage (V) measurements of maximum and minimum sound levels, as outlined in the ISO standard ISO10534-1 [46]. The equation defining the reflection coefficient (R) is given by Equation (1):

$$R = \frac{\mathrm{Vmax} - \mathrm{Vmin}}{\mathrm{Vmax} + \mathrm{Vmin}} \quad (1)$$

The acoustic absorption coefficient is defined following Equation (2):

$$\alpha = 1 - |\, R \,|^2 \quad (2)$$

Measurements were conducted within a semireverberant room to mitigate distortion from environmental noise, covering frequencies in the 400–5000 Hz range. Measures without samples were conducted as a control.

### 2.9. Statistical Analysis

Analysis of variance (ANOVA) and t-test calculations were used to test ($p < 0.05$) for significant differences between factors and levels using OriginPro 2023 (OriginLab Corporation, Northampton, MA, USA). The means were compared when the ANOVA indicated a significant difference by employing the Tukey test. Where applicable, the mean values of the investigated features and the standard deviation, indicated as error bars, are presented on the plots.

## 3. Results and Discussion

The results of the modulus of elasticity investigation are presented in Figure 4a. According to the EN 312 standard for P2-type panels (interior furnishing purposes, including furniture) [43], the minimum MOE requirement is 1600 $N \cdot mm^{-2}$. In this sense, the highest MOE was found for panel 5, followed by panel 4, with panel 2 having the lowest MOE. This could be attributed to PVAc resin's ability to form strong physical bonds through mechanical interlocking via surface wetting and penetration into the feather structure [47], providing better stress distribution than UF and pMDI. Nevertheless, despite the lower modulus of elasticity in panels 2, 4, and 6 compared to the panels without feathers (1, 3, and 5, respectively), these values meet the requirements of the European standard (EN 312). The results of the modulus of rupture investigation are displayed in Figure 4b. As seen, in the presence of feather fibers, the MOR was lower than in the control panels. The lowest MOR value (9.93 N·mm$^{-2}$) was found for panel 2, indicating the low feather/UF resin compatibility. The same explanation applies to panel 4 with feathers, where a higher MOR (16.11 N·mm$^{-2}$) was reached than that in panel 6, which could be due to crosslinking achieved with the pMDI resin, involving the reaction of isocyanate groups (-NCO) with amine groups present in keratin (-$NH_2$) to form urea linkages [48], making it more resistant to fracture than PVAc. When comparing the results of the MOR to the requirements in the EN 312 standard [43] for P2-type panels, a minimum of 11 N·mm$^{-2}$, all the three-layer panels meet the mentioned requirements, but panel 2, which was bonded using UF.

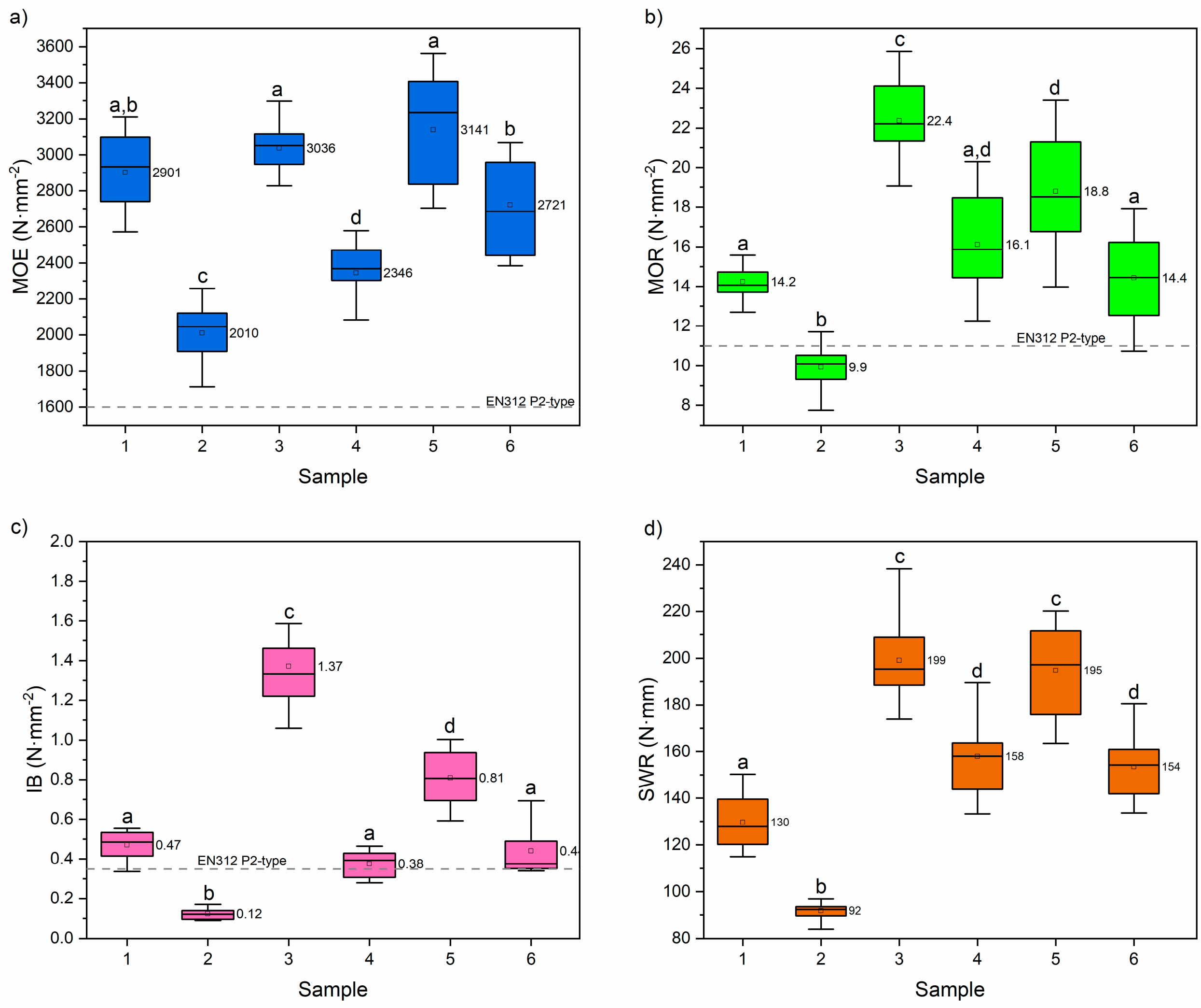


**Figure 4.** (**a**–**d**) Mechanical properties of the different panels, with error bars representing the standard deviation of multiple measurements. Letters (a, b, c, and d) indicate significant statistical differences among groups ($p < 0.05$).

The results of the internal bond investigation are displayed in Figure 4c. The tests showed that a 5 wt% feather fiber content in the core layer significantly reduced the IB with all three binders. The lowest value was observed for panel 2, of 0.12 N·mm$^{-2}$. In Figure 5, however, panels glued with UF show an internal break on the feather surfaces rather than wood surfaces, and feathers were not well coated with resin. In contrast, feathers blended better with pMDI and PVAc adhesives, and breakage was more common in the center across wood and feathers (confirmed by the destruction of the feather structure). The poor performance of the UF resin likely stems from its chemical incompatibility with the keratin in feathers. UF primarily bonds with the hydroxyl groups found in wood cellulose, unlike the protein structures in feathers, which lack abundant hydroxyl groups and do not offer similar reactive sites for UF [31,49]. Even though there was a decrease in the IB values for the panels with feathers, they still met European standards (EN 312) requirements, except for panel 2.

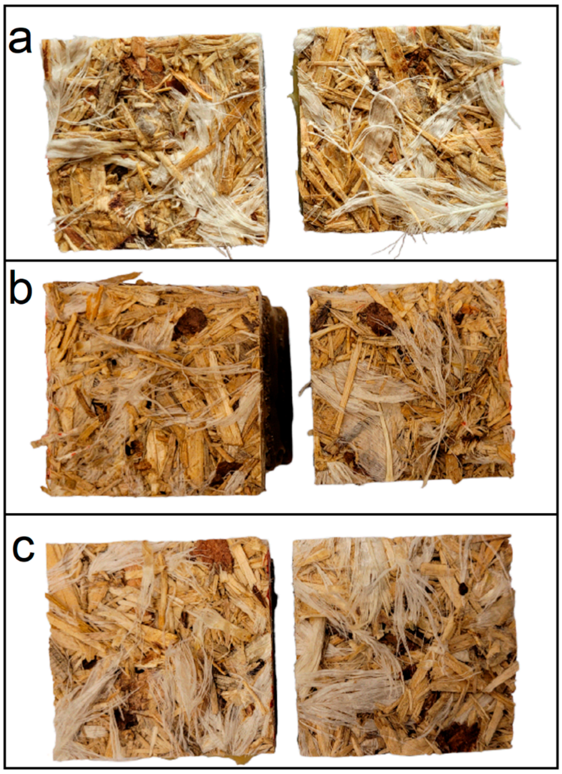


**Figure 5.** Representative forms of damage after the internal bond test: (**a**) panel 2; (**b**) panel 4; (**c**) panel 6.

The results of the screw withdrawal resistance investigation are shown in Figure 4d. The maximum SWR of the panels with feather fiber in the core layer decreased by about 30% compared to that of the reference panels for all three binders. It should be noted that 5 wt% feathers in the core layer did not significantly impact the SWR as it did on the IB; this can be explained by the fact that thee SWR tends to rely more on the strength of the face layers than the core layers, owing to their denser and more substantial composition relative to the core layers within particleboard [50].

Overall, the results show that all particleboards containing feathers had lower mechanical properties than their control panels. This can be attributed to the different surface chemical properties of feathers compared to wood, which may not interact as effectively with the resins. Additionally, the structure of feathers might not distribute stress as uniformly as wood fibers, leading to weaker mechanical properties.

The density profiles across the thickness of particleboards are illustrated in Figure 6. Panels 1 and 2, bonded with UF resin without and with feathers, respectively, exhibited no notable differences in their density profiles. This suggests that the particleboards bonded with UF resin maintained a consistent density throughout despite the chemical compatibility issues between the UF resin and feather keratin.

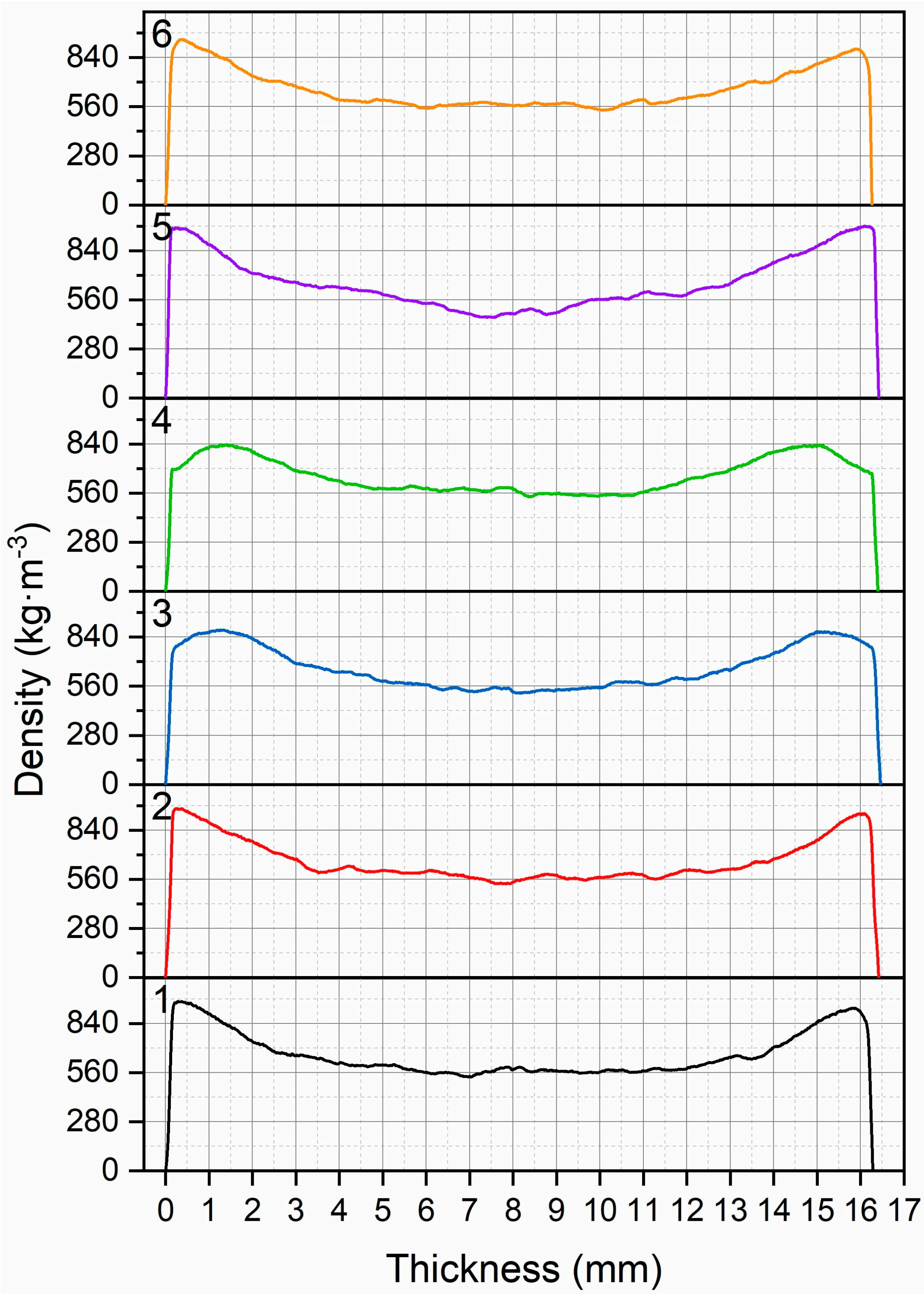


**Figure 6.** Density profiles of the different panels.

Conversely, panels bonded with pMDI and PVAc showed significant differences in density profiles upon the inclusion of feathers, where panels 4 and 6 displayed higher core densities than their respective control panels 3 and 5, which did not include feathers. This phenomenon could be attributed to the enhanced interaction of the pMDI and PVAc resins with feathers, which likely improved the cohesive and adhesive forces within the core. The resins possibly encapsulated the feather fibers more effectively, resulting in the better distribution of resin, which would have been required for the higher volume of feathers and increased core density, while reducing the face densities compared to that of the panels bonded with UF.

The results of the thickness swelling and water absorption after soaking for 2 h and 24 h are presented in Figure 7. As shown, the composite thicknesses after 2 h had the following trend: panel 6 > 5 > 2 > 1 > 4 > 3; this trend remained approximately the same after 24 h but with fewer differences, meaning that a longer soaking time did not cause a large thickness change in the panels. After 24 h of soaking, samples from panel 6 bonded by PVAc (44%) reached the highest thickness swelling. In the case of water absorption (WA), composites followed the same trend after 2 h and 24 h, being panels 6 > 2 > 5 > 1 > 4 > 3. The highest WA was found in panel 6 after 2 h and 24 h. It is worth noting that panels 3 and 4, bonded with pMDI, had the best physical properties, showing no significant differences in physical properties between those with and without feathers and with less swelling equilibration between 2 h and 24 h compared to those of the panels produced with UF and PVAc adhesives. This superior performance of pMDI-bonded panels can be attributed to the extensive crosslinking reactions between the isocyanate groups of the resin and the hydroxyl groups present in wood, as well as the amines in feathers during curing [51,52], resulting in a highly crosslinked polymer network that enhances water resistance and reduces swelling. Conversely, UF and PVAc resins may exhibit lower resistance to moisture due to their less robust crosslinking and polar nature compared to pMDI [53–55], resulting in inferior physical properties. Furthermore, PVAc is a nonresistant moisture polymer, particularly thermoplastic, compared to UF resin. This characteristic means that strength can substantially decrease when such adhesive joints are exposed to a moist environment [56]. It should also be noted that no hydrophobic agents were applied during the panels' production.

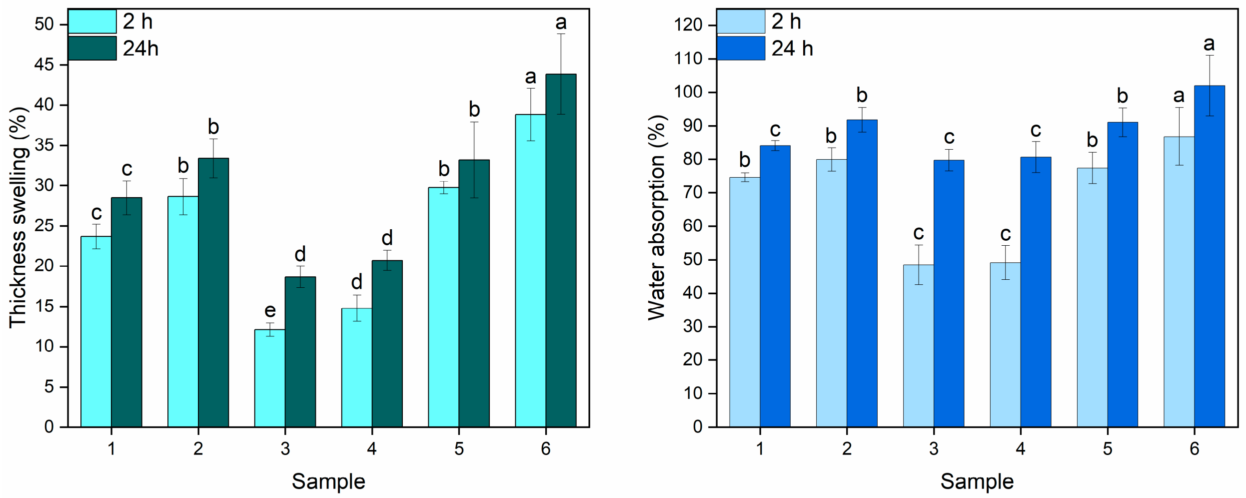


**Figure 7.** Thickness swelling and water absorption of the different panels, with error bars representing the standard deviation of multiple measurements. Letters (a, b, c, d, and e) indicate significant statistical differences among groups ($p < 0.05$).

The thermal conductivity values of the studied panels and their respective standard deviations are presented in Table 2. The thermal conductivity of the different panels averaged around 0.1 W·mK$^{-1}$, which aligns with the literature values for wood-based panels (0.12 W·mK$^{-1}$) at a density of 660 kg·m$^{-3}$ [57]. This is lower than that of particleboard made from fibrous chips [58] and comparable to that of wood fiberboard made with poultry feathers (0.11 W·mK$^{-1}$), where the feathers themselves exhibit low thermal conductivity values ranging from 0.024 to 0.034 W·mK$^{-1}$ [59,60]. Explaining the decrease in thermal conductivity of these materials is complex, as it involves multiple factors, including the compactness, nature of the materials, and resin compatibility. The manufacture of insulating panels considers factors such as pressing temperatures, durations, and resin distribution.

As expected, panels 2 and 4, which included feathers, demonstrated a 10% reduction in thermal conductivity compared to their respective control panels 1 and 3, with panel 2 exhibiting the lowest thermal conductivity of 0.09 W·mK-1. However, this trend was not observed for panels using PVAc resin. This could be explained by the natural properties of feathers; in UF- and pMDI-bonded panels, the addition of feathers generally reduced the thermal conductivity due to their porous honeycomb structure and air-trapping properties, which helped insulate by reducing effective heat transfer through the material. However, PVAc did not seem to enhance the insulative properties when adding feathers. This could be attributed to the adhesive's nature, which tended to capture more moisture as observed in the physical properties, generally resulting in higher thermal conductivities than UF and pMDI. Additionally, the high wettability of PVAc, as demonstrated in the mechanical properties, might have resulted in the feathers being coated too effectively, thereby sealing or filling their porous structure and reducing the air pockets that are crucial for insulation.

**Table 2.** Thermal conductivity (λ) of the different panels, with standard deviation (σ) in $W{\cdot}mK^{-1}$.

| Sample | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| λ ($W{\cdot}mK^{-1}$) | 0.10 | 0.09 | 0.11 | 0.10 | 0.11 | 0.11 |
| σ ($W{\cdot}mK^{-1}$) | 0.004 | 0.005 | 0.005 | 0.007 | 0.005 | 0.005 |

In acoustics, materials within the frequency range of 250 Hz to 3 kHz are of considerable interest. This frequency band encompasses musical tones and human speech while aligning with octave frequencies. Figure 8 shows the values obtained for the acoustic absorption coefficient (α), with error bars representing the standard deviations from the tests performed on three specimens of each type of experimental particleboard. It can be observed in Figure 5 that there were major differences between the boards based on the differences of the face and core densities in correlation with the adhesives employed and the addition of feathers. As previously observed, these feathers affected the composite densities, resulting in different absorption coefficients across distinct sound octave frequencies. Material density significantly impacts sound absorption.

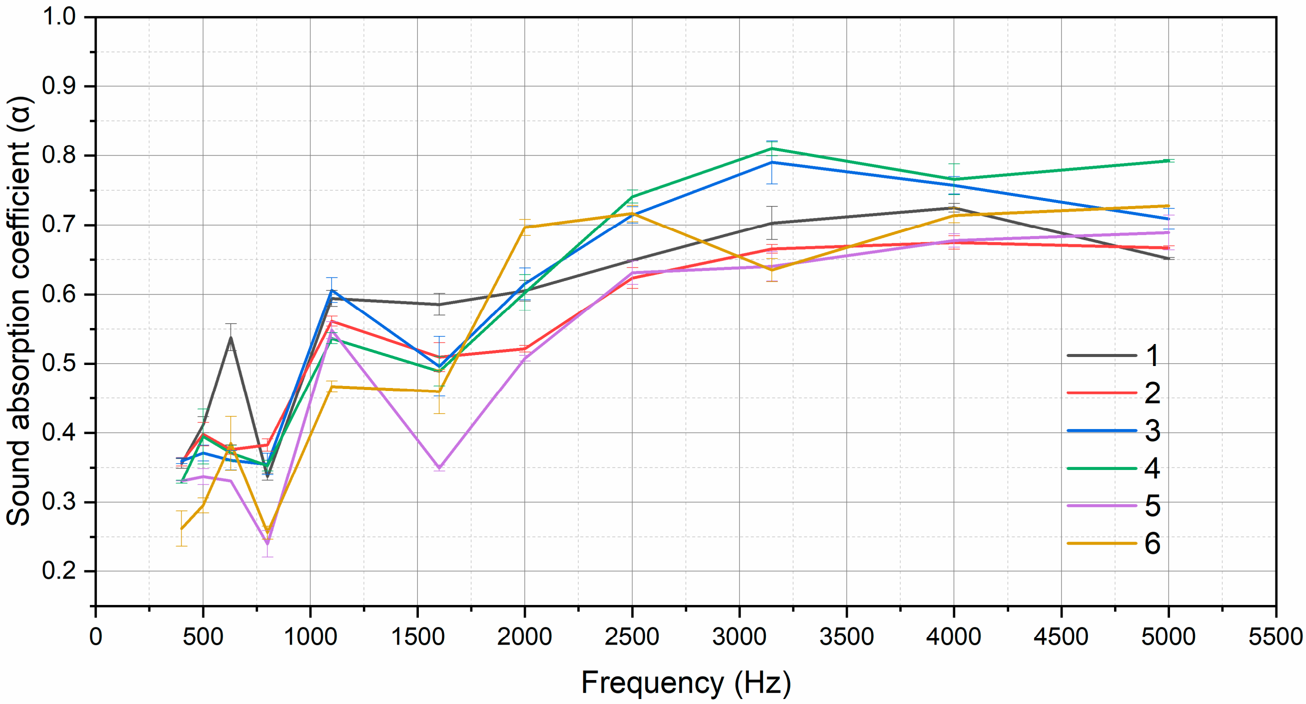


**Figure 8.** Sound absorption coefficients (α) of the different panels, with error bars representing the standard deviation of triplicate measurements.

Additionally, absorption tendencies rely on the elaboration of the board, adhesive characteristics, face and core densities, and the honeycomb configuration of the incorporated feather fibers. It is known that materials with less structural density tend to be better at absorbing sounds of lower frequencies (400–2000 Hz), while denser structures perform better at frequencies exceeding 2000 Hz [61]. At an initial frequency of 400 Hz, higher sound absorption coefficients were apparent in samples with lower core densities devoid of feathers, as indicated by the density profiles in Figure 5. This pattern remained consistent for frequencies ranging from 1 kHz to 2 kHz in panels bonded with UF and pMDI. In the case of pMDI resin, materials with lower core density, and, in the case of UF resin, the presence of voids disrupted sound waves more effectively.

However, the peak values of the sound absorption coefficients within the samples were noticeable across the 2000 and 5000 Hz frequencies. Adding feathers to the particleboards increased the core densities and the honeycomb fiber content per unit area, notably enhancing sound absorption at these higher frequencies. At higher frequencies, variations in absorption coefficients tend to decrease due to the stabilization of wave–material interactions and the limitations of the pore or fiber efficiency in disrupting sound wave propagation. Optimal sound absorption was achieved in wood-based materials with low-density face layers, particularly with pMDI, as demonstrated in Figure 5, due to the improved feather compaction and adhesive effects. This phenomenon underscores the material's ability to facilitate sound penetration through its voids or pores, leading to decreased sound reflection. Subsequent damping occurs within higher-density honeycomb [62].

Unlike other panels, this effect was particularly pronounced in panels 4 and 5. Maximum sound absorption coefficients of 0.74, 0.81, 0.77, and 0.79 were recorded for the lowest face density (starting at 49 $kg \cdot m^{-3}$), at the frequencies of 2500 Hz, 3150 Hz, 4000 Hz, and 5000 Hz, respectively, within panel 4. This could be attributed to the incorporation of lightweight feathers, which increased the fiber content per unit area and contributed to a higher core density, requiring more resin compared to the volume of wood particles. A similar trend was observed when comparing panel 6 with panel 5. It is important to note that this phenomenon was not as strongly evident in panels 1 and 2, where lower internal bonding resulted in less-compact samples after being prepared and cut for the diameter of Kundt's tube. Boards are classified in building construction based on their acoustic coefficient according to EN ISO 11654:1997 [63]: Class B boards have values between 0.80 and 0.85, class C between 0.60 and 0.75, and boards with acoustic coefficients between 0 and 0.1 are unclassified. In general, all studied particleboards with and without feathers were classified as class C, with those bonded with pMDI approaching class B classification in the frequency range from 2500 to 5000 Hz.

## 4. Conclusions

This study assessed particleboard manufactured from industrial wood particles and waste duck feathers. The findings highlight the potential for producing environmentally friendly particleboard panels that meet European standards. By incorporating 5 wt% waste duck feathers into wood particleboard and employing pMDI and PVAc adhesives, which are known for their favorable environmental profiles compared to UF adhesive, the resulting panels met the requirements of P2 boards for mechanical properties, a distinction not achieved with UF adhesive. Additionally, wood–feather particleboards bonded with pMDI exhibited comparable resistance to water absorption and thickness swelling, likely due to better compatibility and crosslinking between the adhesive and feather keratin. Including feathers also improved thermal insulation properties by 10%, observed with both UF and pMDI adhesives. However, PVAc, despite its higher wettability, which enhanced the MOR, showed poor water resistance and did not enhance thermal insulation, indicating that its properties might be less suitable for this application.

Furthermore, feather-enriched particleboards showed improved sound absorption at higher frequencies, ranging from 2500 to 5000 Hz, with pMDI and PVAc adhesives. PMDI resin achieved the highest sound absorption coefficient, approaching the class B classification. Among the adhesives studied, pMDI exhibited promising compatibility with feathers, meeting the minimum requirements of mechanical properties according to European standards and better physical properties than UF and PVAc; in addition, it enhanced both thermal insulation and acoustic insulation at high frequencies.

Future work should focus on refining resin–feather compatibility through pretreatment processes and optimizing feather surface characteristics, allowing for higher feather proportions to be incorporated in subsequent studies. The potential for using waste feathers to reinforce wood composites could help address material scarcity challenges in the wood and poultry industries while also reducing waste disposal costs and generating additional revenue through the sale of feathers to the panel industry.

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## References

1. OECD. Meat Consumption (Indicator). 2024. Available online: https://data.oecd.org/agroutput/meat-consumption.htm (accessed on 3 May 2024).
2. OECD; FAO. *Agricultural Outlook 2023–2032*; OECD Publishing: Paris, France, 2023; ISBN 9789264588707.
3. European Commission (DG ESTAT, D.A.). *Poultry Market Overview*; Directorate-General for Agriculture and Rural Development: Bruxelles/Brussel, Belgium, 2022.
4. Farrelly & Mitchell. *EUs Feather-Based Economy: The Challenges Ahead*; UNLOCK Project; Farrelly & Mitchell: Dublin, Ireland, 2022.
5. Qiu, J.; Barrett, K.; Wilkens, C.; Meyer, A.S. Bioinformatics Based Discovery of New Keratinases in Protease Family M36. *N. Biotechnol.* **2022**, *68*, 19–27. [CrossRef] [PubMed]
6. Acda, M.N. *Sustainable Use of Waste Chicken Feather for Durable and Low Cost Building Materials for Tropical Climates*; Nova Science Publishers: New York, NY, USA, 2010; ISBN 9781608762699.
7. Bharathi, S.V.; Raj, I.V. Studies on the Physical Properties of Chicken Feathers. *Int. J. Curr. Microbiol. Appl. Sci* **2021**, *10*, 309–315. [CrossRef]
8. Ward, W.H.; Binkley, C.H.; Snell, N.S. Amino Acid Composition of Normal Wools, Wool Fractions, Mohair, Feather, and Feather Fractions. *Text. Res. J.* **1955**, *25*, 314–325. [CrossRef]
9. Harrap, B.S.; Woods, E.F. Soluble Derivatives of Feather Keratin. *Biochem. J.* **1964**, *92*, 8–18. [CrossRef] [PubMed]
10. Makar, I.A.; Havryliak, V.V.; Shkromada, S.H. Genetic and Biochemical Aspects of Keratin Synthesis by Hair Follicles. *Cytol. Genet.* **2007**, *45*, 75–79. [CrossRef]
11. Ahmed, A.; Qayoum, A.; Mir, F.Q. Spectroscopic Studies of Renewable Insulation Materials for Energy Saving in Building Sector. *J. Build. Eng.* **2021**, *44*, 103300. [CrossRef]
12. Kurien, R.A.; Biju, A.; Raj, K.A.; Chacko, A.; Joseph, B.; Koshy, C.P. Chicken Feather Fiber Reinforced Composites for Sustainable Applications. *Mater. Today Proc.* **2022**, *58*, 862–866. [CrossRef]
13. Sienkiewicz, J.J.; Wesołowski, A. Zagospodarowanie ubocznych produktów poubojowych. *Zeszyty Naukowe Ostrołęckiego Towarzystwa Naukowego.* **2015**, *29*, 241–249.
14. Tan, C. Poultry plant to turn feathers, blood into useful materials. *Straits Times*, 2022; B6.
15. Team, S. Raw Materials Shortages Explained: The Furniture Industry's Main Challenge for 2022. Available online: https://www.simexa.com/raw-materials-shortage-explained-the-furniture-industrys-main-challenge-for-2022/ (accessed on 3 May 2024).

16. Grzegorzewska, E.; Burawska-Kupniewska, I.; Boruszewski, P. Economic profitability of particleboards production with a diversified raw material structure. *Maderas Cienc. Tecnol.* **2020**, *22*, 537–548. [CrossRef]
17. Fastmarkets. *Global Woodchip Market Outlook 2022 and 2023*; Fastmarkets: London, UK, 2022.
18. Wicaksana, A. *A New Circular Economy Action Plan For a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020.
19. Mucsi, Z.M.; Hasan, K.M.F.; Horváth, P.G.; Bak, M.; Hung Anh, L.D.; Kóczán, Z.; Bejó, L.; Alpár, T. Fabrication and Characterization of Lignocellulosic Coconut and Energy Reed Straw-Reinforced Methylene Diphenyl Diisocyanate-Bonded Sustainable Insulation Panels. *Constr. Build. Mater.* **2024**, *414*, 134992. [CrossRef]
20. Etuk, S.E.; Robert, U.W.; Agbasi, O.E.; Inyang, N.J. Evaluation of Thermophysical and Strength Properties of Composite Panels Produced from Sugarcane Bagasse and Waste Newspapers. *Adv. Mater. Sci.* **2023**, *23*, 19–31. [CrossRef]
21. Silva, S.A.M.; Minillo, L.Q.; Aquino, V.B.D.M.; Lahr, F.A.R.; Christoforo, A.L. Use of Residues From the Cellulose Industry and Sugarcane Bagasse in Particleboards. *Eng. Agríc.* **2021**, *41*, 107–111. [CrossRef]
22. Krus, M.; Werner, T.; Großkinsky, T.; Georgiev, G. A new load-bearing insulation material made of cattail. In Proceedings of the 1st International Conference on Bio-Based Building Materials, International Network on Bio-Based Building Materials (BNBM), AJCE—Special Issue 673, Clermont-Ferrand, France, 22–24 June 2015; pp. 666–673.
23. Bovo, M.; Giani, N.; Barbaresi, A.; Mazzocchetti, L.; Barbaresi, L.; Giorgini, L.; Torreggiani, D.; Tassinari, P. Contribution to Thermal and Acoustic Characterization of Corn Cob for Bio-Based Building Insulation Applications. *Energy Build.* **2022**, *262*, 111994. [CrossRef]
24. Baladivakar, S.; Starvin, M.S.; Raj, J.B. Performance Evaluation of Natural Composites Made from Banyan and Cotton Fibers for Sustainable Thermal Insulation Applications. *J. Nat. Fibers* **2023**, *20*, 2123881. [CrossRef]
25. Sèmiyou, O.A.; Melon, L.M.; Sibiath, O.O.G.; Claude, V.E.; Clément, A. Cotton Stem Fibers and Natural Binders for the Manufacture of Thermal Insulation Panels: State of the Art of the Last Decade. *J. Mater. Sci. Res. Rev.* **2021**, *4*, 651–667.
26. Mucsi, Z.M.; Hasan, K.M.F.; Horváth, P.G.; Bak, M.; Kóczán, Z.; Alpár, T. Semi-Dry Technology Mediated Lignocellulosic Coconut and Energy Reed Straw Reinforced Cementitious Insulation Panels. *J. Build. Eng.* **2022**, *57*, 104825. [CrossRef]
27. Ali, M.; Alabdulkarem, A.; Nuhait, A.; Al-Salem, K.; Iannace, G.; Almuzaiqer, R. Characteristics of Agro Waste Fibers as New Thermal Insulation and Sound Absorbing Materials: Hybrid of Date Palm Tree Leaves and Wheat Straw Fibers. *J. Nat. Fibers* **2021**, *19*, 6576–6594. [CrossRef]
28. Kowaluk, G. Properties of Lignocellulosic Composites Containing Regenerated Cellulose Fibers. *BioResources* **2014**, *9*, 5339–5348. [CrossRef]
29. Rammou, E.; Mitani, A.; Ntalos, G.; Koutsianitis, D.; Taghiyari, H.R.; Papadopoulos, A.N. The Potential Use of Seaweed (*Posidonia oceanica*) as an Alternative Lignocellulosic Raw Material for Wood Composites Manufacture. *Coatings* **2021**, *11*, 69. [CrossRef]
30. Erkmen, J.; Yakut, R.; Hamamcı, B.; Aytuğ Özer, R. Production of Insulation Material Using Styrene Acrylic Resin from Animal and Agricultural Waste Part 1: Thermal Insulation and Water Absorption. *Energy Build.* **2024**, *303*, 113817. [CrossRef]
31. Taghiyari, H.R.; Majidi, R.; Esmailpour, A.; Samadi, Y.S.; Jahangiri, A.; Papadopoulos, A.N. Engineering Composites Made from Wood and Chicken Feather Bonded with UF Resin Fortified with Wollastonite: A Novel Approach. *Polymers* **2020**, *12*, 857. [CrossRef]
32. Kibar, H.; Öztürk, T. Physical and Mechanical Properties of Soybean. *Int. Agrophysics* **2008**, *22*, 239–244.
33. Tesfaye, T.; Sithole, B.; Ramjugernath, D. Valorisation of Chicken Feathers: A Review on Recycling and Recovery Route—Current Status and Future Prospects. *Clean Technol. Environ. Policy* **2017**, *19*, 2363–2378. [CrossRef]
34. European Commission. *In Focus: Energy Efficiency in Buildings*; European Commission: Brussels, Belgium, 2020.
35. Gao, J.; Yu, W.; Pan, N. Structures and Properties of the Goose Down as a Material for Thermal Insulation. *Text. Res. J.* **2007**, *77*, 617–626. [CrossRef]
36. Saravanan, K.; Prakash, C. Study of Acoustic Properties of Chicken Feather Fibre (CFF) and Its Hybrid Composites. *J. Nat. Fibers* **2021**, *18*, 502–509. [CrossRef]
37. *European Committee for Standardization EN 326-2:2010+A1*; Wood-Based Panels: Sampling, Cutting and Inspection. Initial Type Testing and Factory Production Control. European Committee for Standardization: Brussels, Belgium, 2014.
38. *European Committee for Standardization EN 326-1:1994*; Wood-Based Panels. Sampling, Cutting and Inspection. Sampling and Cutting of Test Pieces and Expression of Test Results. European Committee for Standardization: Brussels, Belgium, 1993.
39. *European Committee for Standardization EN 310*; Wood-Based Panels: Determination of Modulus of Elasticity in Bending and of Bending Strength. European Committee for Standardization: Brussels, Belgium, 1993.
40. *European Committee for Standardization EN 319*; Particleboards and Fibreboards—Determination of Tensile Strength Perpendicular to the Plane of the Board. European Committee for Standardization: Brussels, Belgium, 1993.
41. *European Committee for Standardization EN 320*; Particleboards and Fibreboards—Determination of Resistance to Axial Withdrawal of Screws. European Committee for Standardization: Brussels, Belgium, 2011.
42. *European Committee for Standardization EN 317*; Particleboards and Fibreboards. Determination of Swelling in Thickness After Immersion in Water. European Committee for Standardization: Brussels, Belgium, 1993.
43. *European Committee for Standardization EN 312*; Particleboards—Specifications. European Committee for Standardization: Brussels, Belgium, 2010.

44. *European Committee for Standardization EN 323*; Wood-Based Panels—Determination of Density. European Committee for Standardization: Brussels, Belgium, 1993.
45. El Hajj, N.; Dheilly, R.-M.; Aboura, Z.; Benzeggagh, M.; Queneudec, M. Procédé de Fabrication des Composites 100% Végétaux: Effet de la Granulométrie des Étoupes de Lin et de l'Ajout des Bios Liants. In *JNC 16*; HAL: Toulouse, France, 2009; 10p.
46. *AFNOR NF EN ISO 10534-1*; Acoustics—Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes—Part 1: Method Using Standing Wave Ratio. AFNOR: La Plaine Saint-Denis, France, 2003.
47. Iždinský, J.; Reinprecht, L.; Sedliačik, J.; Kúdela, J.; Kučerová, V. Bonding of Selected Hardwoods with PVAC Adhesive. *Appl. Sci.* **2021**, *11*, 67. [CrossRef]
48. Emrani, J.; Benrashid, R.; Mohtarami, S.; Fini, E.; Abu-Lebdeh, T. Synthesis and Characterization of Bio-based Polyurethane Polymers. *Am. J. Eng. Appl. Sci.* **2018**, *11*, 1298–1309. [CrossRef]
49. Lu, L.; Wang, Y.; Li, T.; Wang, S.; Yang, S.; Qing, Y.; Li, X.; Wu, Y.; Liu, M. Calcium Carbonate Modified Urea-Formaldehyde Resin Adhesive for Strength Enhanced Medium Density Fiberboard Production. *RSC Adv.* **2021**, *11*, 25010–25017. [CrossRef] [PubMed]
50. Sydor, M.; Potok, Z.; Pędzik, M.; Hitka, M.; Rogoziński, T. The Influence of Feed Rate During Pilot Hole Drilling on Screw Withdrawal Resistance in Particleboard. *Eur. J. Wood Wood Prod.* **2023**, *82*, 5–13. [CrossRef]
51. Kawalerczyk, J.; Dukarska, D.; Barczewski, M.; Dziurka, D.; Mirski, R. Optimization of Isocyanate Content in PF/pMDI Adhesive for the Production of High-Performing Particleboards. *Polymers* **2023**, *15*, 4645. [CrossRef]
52. Nuutinen, E.M.; Virtanen, T.; Lantto, R.; Vähä-Nissi, M.; Jääskeläinen, A.S. Ductile Keratin Films from Deep Eutectic Solvent-Fractionated Feathers. *RSC Adv.* **2021**, *11*, 27512–27522. [CrossRef] [PubMed]
53. Ferdosian, F.; Pan, Z.; Gao, G.; Zhao, B. Bio-Based Adhesives and Evaluation for Wood Composites Application. *Polymers* **2017**, *9*, 70. [CrossRef] [PubMed]
54. Bekhta, P.; Noshchenko, G.; Réh, R.; Kristak, L.; Sedliačik, J.; Antov, P.; Mirski, R.; Savov, V. Properties of Eco-Friendly Particleboards Bonded with Lignosulfonate-Urea-Formaldehyde Adhesives and PMDI as a Crosslinker. *Materials* **2021**, *14*, 4875. [CrossRef] [PubMed]
55. Wang, H.; Cao, M.; Li, T.; Yang, L.; Duan, Z.; Zhou, X.; Du, G. Characterization of the Low Molar Ratio Urea-Formaldehyde Resin with 13C NMR and ESI-MS: Negative Effects of the Post-Added Urea on the Urea-Formaldehyde Polymers. *Polymers* **2018**, *10*, 602. [CrossRef] [PubMed]
56. Gadhave, R.V.I.; Dhawale, P.V. State of Research and Trends in the Development of Polyvinyl Acetate-Based Wood Adhesive. *Open J. Polym. Chem.* **2022**, *12*, 13–42. [CrossRef]
57. Kawasaki, T.; Kawai, S. Thermal Insulation Properties of Wood-Based Sandwich Panel for Use as Structural Insulated Walls and Floors. *J. Wood Sci.* **2006**, *52*, 75–83. [CrossRef]
58. Kowaluk, G.; Boruszewski, P.; Borysiuk, P.; Zbieć, M. Thermal Characteristic of the Particleboards Produced from Fibrous Chips. *Ann. Warsaw Univ. Life Sci.-SGGW For. Wood Technol.* **2010**, *71*, 367–370.
59. Šafarič, R.; Zemljič, L.F.; Novak, M.; Dugonik, B.; Bratina, B.; Gubeljak, N.; Bolka, S.; Strnad, S. Preparation and Characterisation of Waste Poultry Feathers Composite Fibreboards. *Materials* **2020**, *13*, 4964. [CrossRef] [PubMed]
60. Dieckmann, E.; Onsiong, R.; Nagy, B.; Sheldrick, L.; Cheeseman, C. Valorization of Waste Feathers in the Production of New Thermal Insulation Materials. *Waste Biomass Valorization* **2021**, *12*, 1119–1131. [CrossRef]
61. Nandanwar, A.; Kiran, M.C. Influence of Density on Sound Absorption Coefficient of Fibre Board. *Open J. Acoust.* **2017**, *7*, 1–9. [CrossRef]
62. Smardzewski, J.; Kamisi, T.; Dziurka, D.; Majewski, A. Sound Absorption of Wood-Based Materials. *Holzforschung* **2015**, *69*, 431–439. [CrossRef]
63. *ISO 11654:1997*; Acoustics: Sound Absorbers for Use in Buildings: Rating of Sound Absorption. International Organization for Standardization: Geneva, Switzerland, 1997; p. 7.