

Feather Keratin Binder for Particleboards: A Sustainable Alternative to Urea-formaldehyde and Food-based Protein Adhesives

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GRAPHICAL ABSTRACT



Feather Keratin Binder for Particleboards: A Sustainable Alternative to Urea-formaldehyde and Food-based Protein Adhesives

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Keratin was evaluated as a formaldehyde-free adhesive for three-layer particleboards for EN 312 (2010) P1-type by developing a sustainable alternative to urea-formaldehyde (UF) resins while decreasing reliance on food-derived protein adhesives. Keratin was extracted from duck feathers using ultrasound-assisted alkaline hydrolysis. Particleboards were made with keratin-based adhesives and compared to particleboards bonded with UF resin and food protein isolates (casein, pea, and soybean). Resination was set at 10% for the core layer and 12% for the face layers. Protein adhesives were activated with NaOH (protein:NaOH:water = 50:5:100). Mechanical performance was assessed by measuring modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), and screw withdrawal resistance (SWR), along with thickness swelling (TS) and water absorption (WA). The protein-bonded particleboards exhibited higher face-layer densities than UF, leading to improved stiffness and strength. Keratin-bonded particleboards achieved an MOR of 12 N·mm⁻², an MOE above 3000 N·mm⁻², an IB of 0.25 N·mm⁻², and an SWR of 139 N·mm⁻², meeting EN 312 P1 (2010) requirements. Results demonstrate the potential of feather keratin as a scalable, green, and cost-effective adhesive for dry-use particleboards. This approach promotes renewable adhesive systems, aligning with current regulatory trends toward formaldehyde-free materials and circular bioeconomy strategies.

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Keywords: Particleboard; Formaldehyde-free adhesive; Feather keratin; Ultrasound-assisted hydrolysis; Protein

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INTRODUCTION

Wood adhesives have been essential to the wood-based particleboard industry for more than five decades (Hussin *et al.* 2022), enabling the efficient use of lignocellulosic resources in engineered wood products, such as particleboard, fiberboard, and plywood, which account for more than 55% of adhesive consumption (Future Market Insights 2025). Global production of wood-based particleboards has risen steadily with urbanization and construction demand, reaching hundreds of millions of cubic meters annually by the early 2020s (Market Growth Reports 2026). Particleboard and fiberboard are particularly important due to their cost-effectiveness and compatibility with recycled and low-grade wood, thereby reinforcing this sector's dependence on efficient adhesive systems.

A recent market analysis has estimated the global wood adhesives and binders' market at approximately USD 20.7 billion in 2025, with projections reaching USD 30.7 billion by 2035, corresponding to an average annual growth rate of about 4% (Future Market Insights 2025). Despite increasing regulatory pressure, the sector remains largely dominated by synthetic resins, with formaldehyde-based systems making up 90 to 95% of total industrial use (Kristak *et al.* 2022). Urea–formaldehyde (UF) resins alone account for approximately 37% of global use due to their low cost and fast curing (Market Growth Reports 2025). Other resins, such as phenol–formaldehyde (PF), melamine–formaldehyde (MF), and melamine–urea–formaldehyde (MUF), are used when higher moisture resistance is required (Altun and Tokdemir 2016). However, formaldehyde is associated with respiratory effects and is classified as carcinogenic (Ahmad *et al.* 2024), leading to stricter regulations worldwide. In Europe, new limits set under the Regulation on the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) will apply from August 2026, establishing a maximum of 0.062 mg m⁻³ for furniture and wood articles and 0.080 mg m⁻³ for other products (European Commission 2023). In the United States, the Toxic Substances Control Act (TSCA) risk assessments reaffirm formaldehyde as an unreasonable health risk even at 0.3 parts per million (ppm), prompting the development of additional regulations (States *et al.* 2025). In Asia, China's GB 30981.1/30981.2 (2025) standards will be effective in June 2026 (CIRS Group 2025), and Japan's Japanese Industrial Standards (JIS) F★★★★ classification, representing the lowest formaldehyde emission level for unrestricted indoor use, is all aimed at reducing exposure and improving indoor air quality (Nguyen 2024).

In response to these concerns, the market is increasingly focused on bio-based and formaldehyde-free solutions, with over 25% of wood-adhesive formulations reported between 2020 and 2026 incorporating lignin, starch, tannins, or soy, based on an analysis of 3,607 Scopus-indexed publications identified using the keywords “wood” and “adhesive”. Bio-based adhesives are expected to grow by over 8% annually through 2035 (Future Market Insights, 2025). Proteins are particularly attractive due to their abundance of polar functional groups, which can interact with wood surfaces through hydrogen bonding, electrostatic interactions, and, under appropriate conditions, covalent linkages (Raydan *et al.* 2021). However, their performance strongly depends on molecular structure and interaction mechanisms, as shown by FTIR, Raman, and SDS-PAGE analyses (Raydan *et al.* 2024a). Plant-derived proteins such as soybean and pea are mainly composed of globular proteins (7S and 11S), whose interactions are dominated by hydrogen bonding and hydrophobic effects. These proteins dominate the literature on protein-based wood adhesives, accounting for about half of the reported studies ($\approx$ 194 out of 408 Scopus-indexed articles as of February 2026), largely due to their availability and favorable chemical composition. However, their hydrophilic nature often leads to poor moisture resistance and necessitates chemical modification or crosslinking, increasing costs, complexity, and environmental impact (Md Murshed Bhuyan 2025).

Animal-derived proteins, including casein, exhibit a more flexible and less ordered structure with a high density of accessible polar functional groups, which promotes strong interfacial adhesion and generally better water resistance than plant proteins (Schwarzenbrunner *et al.* 2020). Nevertheless, their use remains limited by availability, price volatility, and competition with food resources (Mylan *et al.* 2023). Keratin, in contrast, is a structural protein rich in cysteine residues, enabling disulfide bond formation and strong intermolecular cohesion. Its fibrous structure and sulfur-containing amino acids

provide a distinct adhesion mechanism based on internal cohesion in the protein matrix and secondary interactions (Banasaz and Ferraro 2024).

A major challenge in protein-based adhesive research is that successful lab results often do not translate to industrial conditions, where high adhesive loadings, extended press times, or the use of costly crosslinkers hinder large-scale adoption (Dunky 2020). In particleboard manufacturing, adhesives can account for 30 to 50% of total material costs (Bekhta *et al.* 2021), while energy consumption and processing account for an additional 40 to 50% of overall production expenses (Lee *et al.* 2022). Importantly, most protein-based adhesive systems reported in the literature rely on high binder contents, crosslinkers, or non-industrial processing conditions, limiting their scalability. Moreover, the behavior of adhesives in multilayer particleboards complicates the assessment of mechanical performance, which is influenced by adhesive chemistry, density profiles, and heat transfer during pressing.

Within the broader landscape of protein-based adhesives, keratin has emerged as a promising candidate for non-food protein adhesives. In this study, plant- and animal-derived proteins (*e.g.*, soybean, pea, and casein) are referred to as “food-based protein adhesives,” as they originate from human food-related resources and may compete with food supply chains, in contrast to keratin derived from feather waste. Statistical data indicate that approximately 40 million tons of keratin-rich waste are produced each year globally (Peydayesh *et al.* 2023), with limited high-value uses and disposal often involving landfilling or incineration, making it particularly attractive from circular-economy and sustainability perspectives.

The primary challenge of keratin-based adhesives lies in extraction and processing. Conventional enzymatic or thermal extraction routes are often time-consuming, energy-intensive, or costly, limiting their scalability (Mungwari *et al.* 2025). More recently, physical routes, including ultrasound-assisted hydrolysis, have been shown to accelerate recovery while reducing energy demand (Wang and Tong 2022). This study builds upon earlier research using ultrasound-assisted alkaline hydrolysis of poultry feathers, which achieved approximately 70% keratin recovery compared with conventional thermal alkaline hydrolysis, highlighting a rapid and cost-effective extraction pathway (Raydan *et al.* 2024b). Sonication is a scalable technology that supports the growing trends of energy-efficient biomass processing and extraction. It utilizes continuous-flow and large-volume sonochemical reactors (Flores *et al.* 2021).

Additionally, the adhesive formulation can be kept simple by using alkaline conditions to activate the proteins (*i.e.*, inducing ionization, unfolding, and exposing functional groups), thereby eliminating the need for additional, energy-intensive modification steps (Luukkonen *et al.* 2019; Zhou *et al.* 2021). Under alkaline conditions, the pH relative to the pKa values of functional groups leads to deprotonation of carboxylic acid groups ($\text{--COOH} \rightarrow \text{--COO}^-$) and deprotonation of protonated amine groups ($\text{--NH}_3^+ \rightarrow \text{--NH}_2$). This promotes electrostatic repulsion, protein unfolding, and increased exposure of reactive groups (--NH_2 , --COO^- , --OH), enhancing their solubilization and interaction with hydroxyl-rich lignocellulosic surfaces through hydrogen bonding, electrostatic interactions, and van der Waals forces (Momen *et al.* 2021; Rashad *et al.* 2025; Raydan *et al.* 2024). This treatment also facilitates protein dispersion and penetration into the porous wood structure, enhancing interfacial contact and mechanical interlocking. During hot pressing, temperature, and progressive dehydration promote the formation of a cohesive protein network that binds wood particles, while in keratin-based systems, this cohesion is

further reinforced by thiol–disulfide exchange and disulfide-bond rearrangements, thereby enhancing internal crosslinking within the protein matrix (Babaniyi *et al.* 2025).

Despite these advances, current studies remain largely limited to simplified systems and do not systematically address how protein origin influences performance in multilayer particleboards under industrially relevant conditions. To address this gap, the present study investigated, for the first time, the use of ultrasound-recovered feather keratin as an adhesive for three-layer particleboards produced under industrially relevant conditions, including realistic adhesive loadings and multilayer configurations. A direct comparison is made with casein, pea protein, soybean protein, and conventional urea-formaldehyde (UF) resin to clarify how the protein source influences adhesion mechanisms and particleboard performance. By correlating mechanical and physical properties with density profiles and intrinsic protein characteristics, this research provides new insights into the balance between interfacial bonding and cohesive strength in protein-based adhesive systems. This study establishes keratin as a scalable, non-food, and low-emission alternative for engineered wood and lignocellulosic composites within a circular bioeconomy framework.

EXPERIMENTAL

Materials

Industrially-used wood particles containing *ca.* 95 wt% of pine *Pinus sylvestris* L. and 5 wt% spruce *Picea abies* (L.) H. Karst and some deciduous species, with about 6% moisture content (MC), intended for face- and core-layer particleboard production, were received from a plant in Poland. An industrial partner generously supplied white duck feathers (Plum'Export, Saint-Sever, France). Reagents included sodium hydroxide (NaOH, CAS 1310-73-2) and oxalic acid (HO₂CCO₂H, CAS 144-62-7), both obtained from Thermo Fisher Scientific. For the reference formulations, casein, pea, and soybean protein isolates were purchased from BulkTM. The urea-formaldehyde (UF) resin (65% solids) was sourced from Silekol Sp. z o. o. (Kędzierzyn-Koźle, Poland). The hardener for UF adhesive mass was a 40 wt% aqueous ammonium nitrate (NH₄NO₃) (CAS 6484-52-2, supplied by WARCHEM Sp. z o. o., Trakt Brzeski St. 167, 05-077 Zakręta, Poland) in an aqueous solution.

Methods

Ultrasound-assisted alkaline hydrolysis of raw duck feather

Keratin was extracted from raw duck feathers, which initially contained 82.97 ± 0.98% (dry basis), determined by the Kjeldahl method (Alvarez *et al.* 2023). The nitrogen content was converted to protein using a factor of 6.25, assuming an average nitrogen content of 16% in proteins (Jiang *et al.* 2014). The extraction was performed through ultrasound-assisted alkaline hydrolysis, following previously described protocols (Raydan *et al.* 2024b). In brief, the feathers were ground to approximately 5 mm and hydrolyzed in a 3 wt% NaOH solution (with a solid-to-liquid ratio of 1:10 w/v). The hydrolysis was conducted using a 19.7 kHz ultrasonic homogenizer (UP200St, Hielscher, Germany) at 80% amplitude in a 500-mL round-bottom flask for 25 min. After hydrolysis, insoluble residues were filtered out. The soluble keratin fraction was precipitated by adding oxalic acid to adjust the pH to 4.5. The precipitated keratin was then washed multiple times with distilled water using a 25-μm nylon mesh until the filtrate reached a pH of approximately 5.5. Finally, the neutralized keratin was lyophilized using a freeze-dryer (Alpha 1-4, Martin

Christ GmbH, Germany). The resulting keratin powder was used directly as a dry feedstock for particleboard manufacturing without prior solubilization or chemical modification. The overall keratin recovery process, including ultrasound-assisted alkaline hydrolysis, isoelectric precipitation, washing, and lyophilization, is schematically illustrated in Fig. 1.

The keratin hydrolysate yield (Y) was calculated based on the freeze-dried mass of recovered keratin relative to the estimated initial keratin content of the raw feathers, according to Eq. 1,

$$Y(\%) = [M_{\text{dry}} / 0.83M_0] \times 100 \quad (1)$$

where M_0 is the initial mass (g) of raw feathers used in hydrolysis, M_{dry} is the mass (g) of lyophilized recovered keratin, and $0.83 M_0$ is the estimated initial keratin fraction in RF, obtained from Kjeldahl nitrogen determination.

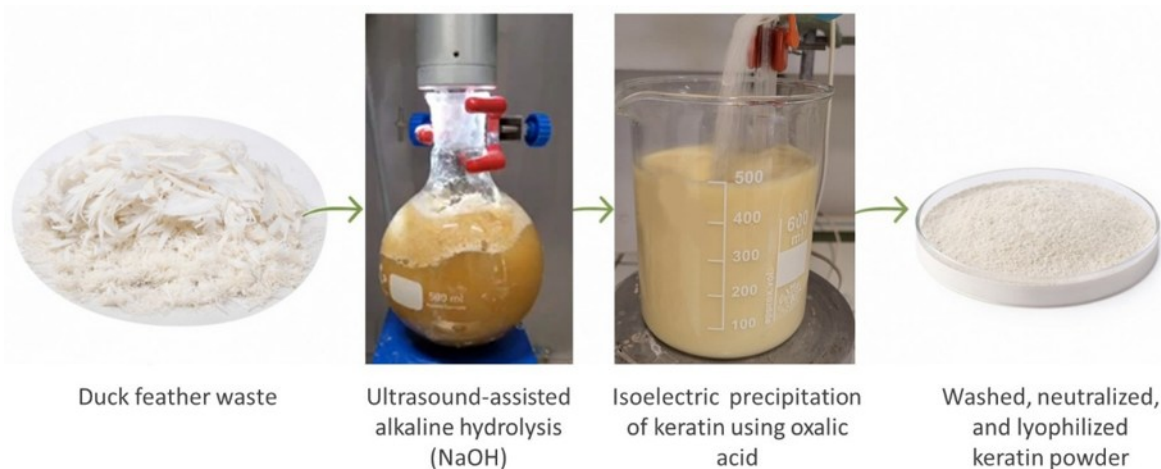


Fig. 1. Schematic representation of the keratin recovery process from duck feather waste, including ultrasound-assisted alkaline hydrolysis, isoelectric precipitation, washing, and lyophilization steps

Particleboard Preparation

The particleboards were manufactured with a target density of $670 \text{ kg}\cdot\text{m}^{-3}$, dimensions of $320 \text{ mm} \times 320 \text{ mm}$, a nominal thickness of 16 mm , and a mass share of 32% for the face layers, corresponding to 16% for each face layer (top and bottom). Adhesive loading was 10% for the core layer and 12% for the face layers. These adhesive contents were kept constant for all adhesive systems in this study. The higher adhesive content in the face layers is related to the smaller particle size and, consequently, to a higher specific surface area, which requires increased binder coverage to ensure effective bonding. Two replicates were created for each protein adhesive formulation, together with UF as control particleboards. Face- and core-layer particles were blended separately using a rotary mixer. The selection of adhesive content followed standard practices in industrial particleboard plants and recommendations in the literature (Thoemen *et al.* 2010). For the UF-based particleboards, the adhesive was prepared at a weight ratio of 100:8:8 (resin:water:hardener solution) to achieve a curing time of approximately 86 s at 100°C , and it was added directly to the particles during mixing. For protein-bonded particleboards (casein, pea, soybean, and keratin), a 5% NaOH solution was first sprayed to slightly moisten the wood particles, after which the protein powder was added to the wood in the mixer, applying a weight ratio of 50:5:100 (protein:NaOH:water). The remainder of the NaOH solution was added after full incorporation of the protein. The alkaline solution triggered protein unfolding,

increasing the accessibility of reactive functional groups and enhancing interactions with the wood surface. No hydrophobic additives were included in any of the particleboard formulations. The three layers were formed sequentially in a single mold and cold-pressed using a PH-1P125 press (ZUP Nysa Sp. z o. o. sp. k., Konradowa, Poland) with a maximum specific pressing pressure of 1.23 MPa and a pressing time factor of $5 \text{ s} \cdot \text{mm}^{-1}$ of the nominal thickness of the particleboard. Following this, they were pressed in a hot press (AKE, Mariannelund, Sweden) under conditions resembling industrial practice: a temperature of 180 °C, a maximum unit pressure of 2.5 MPa, and a pressing time of $20 \text{ s} \cdot \text{mm}^{-1}$, corresponding to the particleboard's nominal thickness. These pressing conditions were selected based on previous research on particleboards with alternative raw material particles and were applied identically to all adhesive systems (Wronka and Kowaluk 2024; Wronka *et al.* 2025). The particleboards were conditioned in a climatic chamber at 20 °C and 65% relative humidity until constant mass was reached. After conditioning, the particleboards were calibrated by double-sided sanding on an industrial sanding machine, Bulldog SPB 1100 RC sander (Houfek a. s., Golčův Jeníkov, Czech Republic), to reach the nominal thickness.

Physical and Mechanical Characterization of the Manufactured Particleboards

The test specimens were cut according to EN 326-2 (2014) and EN 326-1 (1993a). The MOR and MOE were determined according to EN 310 (1993). The IB was determined according to EN 319 (1993b). Screw withdrawal resistance (SWR) was determined according to EN 320 (2011), with screws inserted perpendicular to the particleboard surface, while water absorption (WA) and thickness swelling (TS) were determined after 2 and 24 h of immersion according to EN 317 (1993c). All mechanical properties were examined with an INSTRON 3369 computer-controlled laboratory-testing machine (Instron, Norwood, MA, USA), and, whenever applicable, the results were referenced to standard EN 312 for P1 and P2-type particleboards (2010). A minimum of 10 replicates per particleboard variant (adhesive system) were used for the mechanical and physical tests. The density of the samples was measured as referenced in EN 323 (1993). The density profiles of the tested particleboards were measured using a DA-X device (Fagus-GreCon Greten GmbH & Co. KG, Alfeld/Hannover, Germany) with samples of nominal dimensions 50 mm × 50 mm. Up to 3 test specimens from each sample were measured per particleboard type. The profiles were compared in terms of their shape and characteristic features, and one representative profile, consistent with the overall trend observed across replicates, was selected for each particleboard type. Averaging was not applied in order to preserve localized density gradients relevant to the analysis.

Statistical Analysis

Analysis of variance (ANOVA) and t-test calculations were applied to examine significant differences among factors and levels, with a significance level established at $p < 0.05$. These analyses were performed using OriginPro 2023 (OriginLab Corporation, Northampton, MA, USA). When the ANOVA revealed a significant difference, the means were compared using the Tukey test. Where applicable, the mean values of the examined features and the standard deviation, represented as error bars, are shown in the plots.

RESULTS AND DISCUSSION

Ultrasound-assisted Keratin Recovery

The *ultrasound*-assisted alkaline hydrolysis of duck feathers enabled disruption of the compact keratin structure and exposure of reactive functional groups involved in adhesion (see schematic process in Fig. 1, Materials and Methods). These desirable active functional groups ($-\text{NH}_2$, $-\text{COO}^-$, $-\text{OH}$) and sulfur-containing groups will eventually interact with the wood functional groups during the bonding process (Adhikari *et al.* 2019). The yield of keratin hydrolysate was approximately $72.5 \pm 5\%$.

Mechanical Properties

Figure 2 presents the mechanical properties of the different particleboard samples, displayed as box plots with whiskers representing the standard deviation. In Fig. 2a, the variation in MOR values among the samples is shown. The MOR indicates the highest bending stress the material can withstand in flexure. Keratin-bonded particleboards exhibited an average MOR of $12.3 \text{ N}\cdot\text{mm}^{-2}$, with relatively low variability, comparable to the other tested protein-bonded particleboards. Notably, the casein-bonded particleboards exhibited the highest average MOR at $16.9 \text{ N}\cdot\text{mm}^{-2}$, while UF-bonded particleboards showed the lowest average MOR at $12.0 \text{ N}\cdot\text{mm}^{-2}$. Notably, all samples met the MOR requirement for P2-type particleboards (intended for interior furnishings, including furniture), as specified in EN 312 (2010), with a minimum of $11 \text{ N}\cdot\text{mm}^{-2}$. Figure 2b shows the MOE values, with keratin-based particleboards reaching $3182 \text{ N}\cdot\text{mm}^{-2}$, higher than UF ($2725 \text{ N}\cdot\text{mm}^{-2}$), indicating enhanced stiffness. Casein also exhibited the highest average MOE of $3252 \text{ N}\cdot\text{mm}^{-2}$. All samples met and exceeded the EN 312 (P2-type) (2010) requirement for MOE, which is set at $1600 \text{ N}\cdot\text{mm}^{-2}$. The higher MOE observed in keratin-based particleboards than in UF, despite similar MOR values, can be attributed to differences in deformation and failure mechanisms. MOE reflects the elastic stiffness at low deformation and depends on the rigidity of the adhesive network and the efficiency of stress transfer between wood particles, which is governed by the adhesive system. In keratin-based systems, the reformation of disulfide bonds results in a stiffer, more cohesive protein network, thereby increasing resistance to elastic deformation. In contrast, MOR is governed by failure initiation and propagation, which are more strongly influenced by interfacial bonding. Although keratin exhibits weaker interfacial interactions with wood than UF does, the MOR remained similar, with lower variability than that of the other tested proteins. These results surpassed the MOR and MOE values reported in the literature for particleboards with a density around $700 \text{ kg}\cdot\text{m}^{-3}$ (Fagbemi and Sithole 2021). According to their study, the MOR and MOE for particleboards made with both unmodified and modified keratin-based adhesives from chicken feathers *via* alkaline hydrolysis were $6.52 \text{ N}\cdot\text{mm}^{-2}$ and $1184 \text{ N}\cdot\text{mm}^{-2}$, respectively, for the unmodified adhesive, and $8.01 \text{ N}\cdot\text{mm}^{-2}$ and $1118 \text{ N}\cdot\text{mm}^{-2}$ for citric acid-incorporated polyamide epichlorohydrin keratin-based adhesive. This disparity can be attributed to the feather source (duck vs. chicken), keratin extraction method, and major differences in adhesive formulations and bonding mechanisms.

In the IB strength tests shown in Fig. 2c, keratin-based particleboards reached an average IB of $0.25 \text{ N}\cdot\text{mm}^{-2}$, exceeding the EN 312 (2010) requirement for P1-type particleboards, while casein exhibited the highest average IB value at $0.45 \text{ N}\cdot\text{mm}^{-2}$, similar to UF adhesive, while soybean recorded the lowest at $0.10 \text{ N}\cdot\text{mm}^{-2}$. According to the ANOVA, the variation of IB among the samples was statistically significant, with only

casein and UF exceeding the EN 312 (2010) standard for P2-type particleboards (minimum of $0.35 \text{ N}\cdot\text{mm}^{-2}$). Meanwhile, pea and keratin both exceeded the EN 312 (2010) standard for P1-type particleboards (minimum of $0.24 \text{ N}\cdot\text{mm}^{-2}$), which are intended for general-purpose use in dry conditions. Figure 2d shows the SWR; keratin-based particleboards achieved the highest average SWR, at $139 \text{ N}\cdot\text{mm}^{-1}$, among all systems, while soybean had the lowest, at $95 \text{ N}\cdot\text{mm}^{-1}$. The SWR values across all samples showed no significant variation, except for soybean.

The results from Fig. 2 indicate that casein generally demonstrated the best mechanical properties among the tested samples, meeting the EN 312 (2010) standard for P2-type particleboards. This performance was followed by pea and keratin, both of which met the EN 312 (2010) standard for P1-type particleboards. The superior mechanical performance of casein compared to keratin can be attributed to its higher hydrogen-bond content, suggesting that hydrogen bonding is a primary adhesion mechanism. This is supported by a previous study comparing casein, soybean, pea, and keratin in lap-shear tests on beech wood (Raydan *et al.* 2024a).

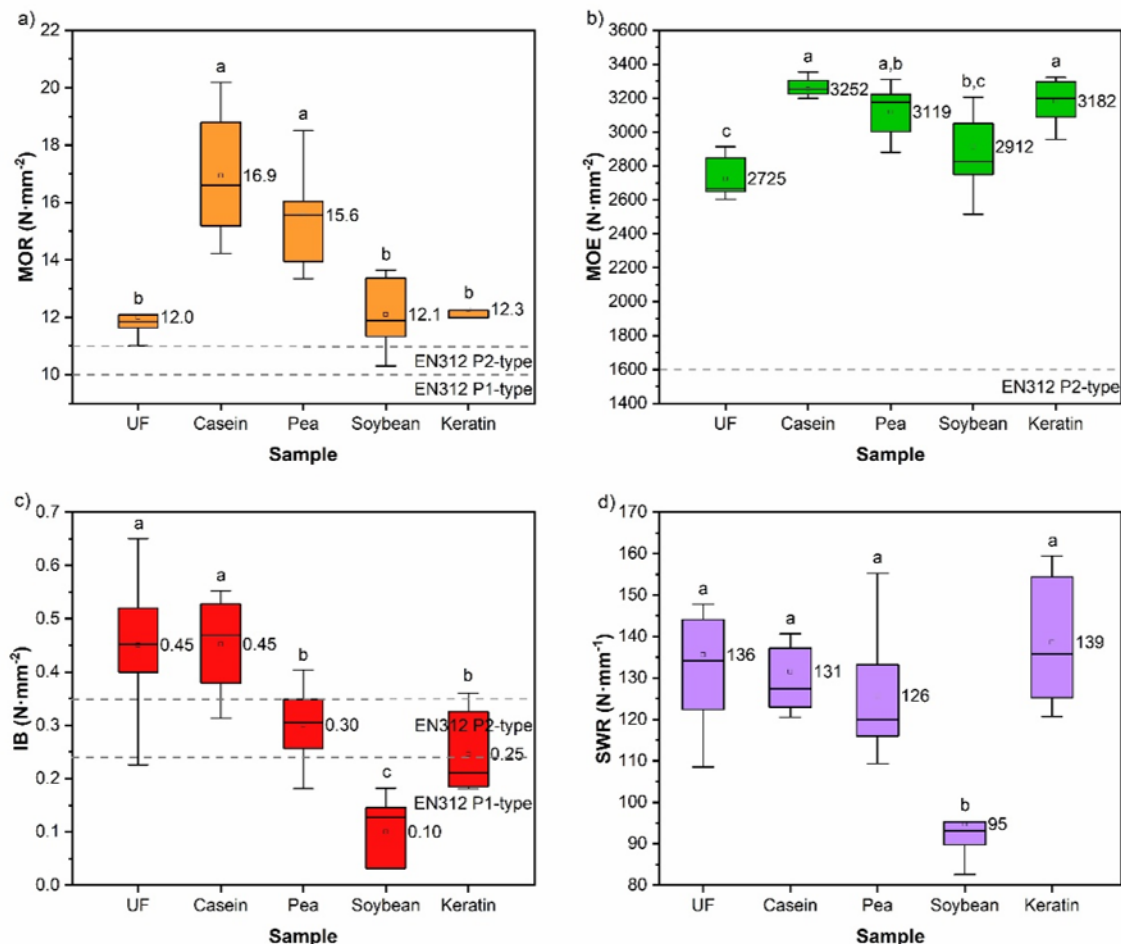


Fig. 2. Mechanical performance of particleboards bonded with different adhesives: (a) MOR, (b) MOE, (c) IB, and (d) SWR. Values are expressed as boxplots with mean and median. Different letters above the boxes indicate statistically significant differences between groups ($p < 0.05$). Dashed lines represent the minimum requirements according to EN 312 (2010) for P1-type and P2-type particleboards.

In this context, the comparatively lower IB strength of keratin can be attributed to weaker interfacial interactions, as its lower polarity and fewer accessible hydrogen-bonding sites limit effective bonding with the hydroxyl-rich wood surface, particularly in the core layer, where larger particles require strong interfacial anchoring. At the same time, keratin contains stronger reconstituted disulfide bridges resulting from self-heat ultrasound-assisted alkaline hydrolysis. This process leads to the cleavage and reformation of disulfide bridges, as demonstrated in previous research (Raydan *et al.* 2026). The reformed disulfide bridges exhibit greater stress tolerance due to enhanced internal cohesion within the protein matrix, consistent with their high screw withdrawal resistance (SWR) and competitive bending properties. In contrast, soybean lacks disulfide bridges, which are prevalent in keratin, resulting in a less rigid adhesive matrix. Overall, keratin-based particleboards demonstrate a distinct balance between cohesive strength and interfacial performance: while exhibiting slightly lower IB than casein and UF, they achieve comparable MOR, higher MOE than UF, and the highest SWR among all systems. This highlights keratin's ability to form a mechanically robust adhesive network, despite limitations in interfacial bonding.

Physical Properties

The density profiles across the thickness of particleboards are illustrated in Fig. 3, with mean values converging around $670 \text{ kg}\cdot\text{m}^{-3}$. Typically, wood composite particleboards exhibit higher density in the surface layers than in the core, resulting from particle-size, heat, and pressure gradients during hot pressing across the particleboard's cross-section (Laskowska 2024). In the case of the UF sample, the average surface-layer density up to 2 mm was approximately 30% lower than that of the protein-bonded particleboards. Keratin-bonded particleboards had a lower core density than those bonded with other protein adhesives, particularly pea protein, by about 14%. This discrepancy may be attributed to keratin's lower density of accessible polar functional groups relative to casein or plant proteins, which can create challenges for larger particles in the core than in the face layer. Consequently, this may explain the inferior IB results for keratin compared with UF and other protein-based adhesives. It is important to note that protein-based adhesives do not exhibit thermosetting behavior. Instead, they remain fluid during pressing, allowing for better coating and particle penetration. Their bonding mechanism relies on forming hydrogen bonds with cellulose in wood rather than on heat-assisted curing. As these protein adhesives cool and dehydrate, they solidify, forming a cohesive protein-wood network. However, differences between adhesive systems can arise from the accessibility of polar functional groups and their ability to interact with the wood surface. In particular, for keratin-based systems, the lower accessibility of polar functional groups may limit interfacial interactions with the wood surface, particularly in the core layer. The observed density distribution suggests that the efficiency of adhesive impregnation differs between particleboard layers. The face particles used in this study were fine and flexible (approximately 0.25 to 1 mm in thickness), facilitating effective coating and bonding with protein adhesives. This characteristic supports the satisfactory mechanical performance of the surface layers, as evidenced by MOR, MOE, and SWR, which were governed more by cohesive strength than interfacial bonding.

In contrast, the core particles were significantly coarser and more rigid (ranging from 0.5 to 8 mm in thickness) to ensure adequate interparticle bonding. The comparatively lower exposure of polar functional groups and the structural rigidity of keratin—associated with its high content of disulfide bonds—may limit its uniform dispersion and penetration

into these larger core particles. This discrepancy likely contributed to the reduced core density and internal bonding performance observed in keratin-bonded particleboards.

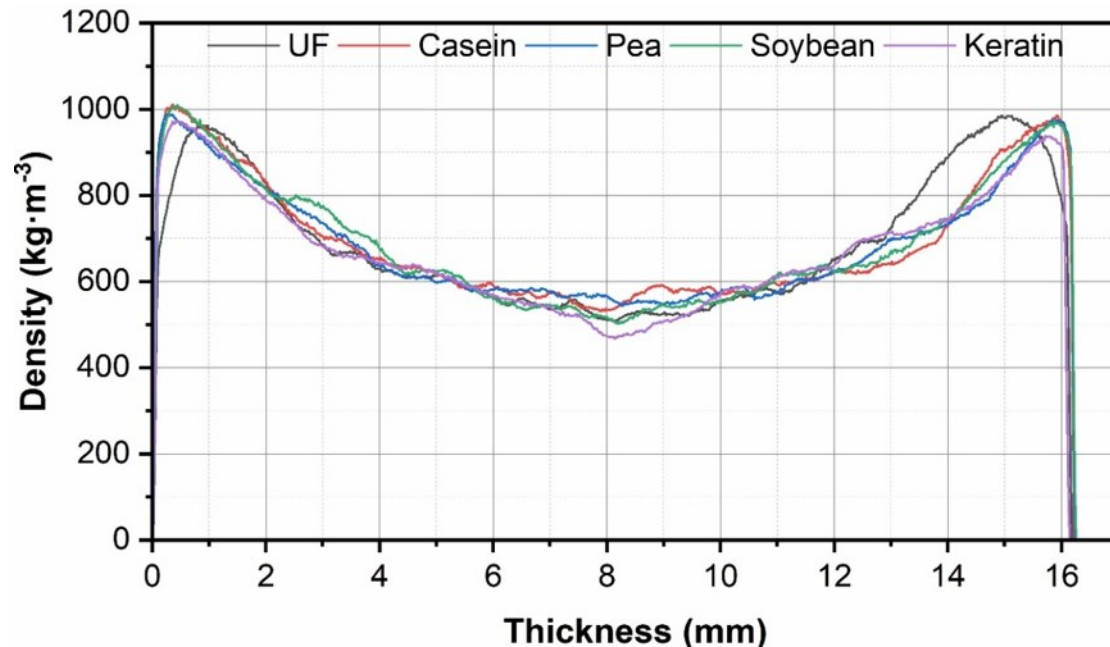


Fig. 3. Density profiles of particleboards bonded with different adhesives: UF, casein, pea, soybean, and keratin. All particleboards show typical high-density surface layers and lower-density core regions, with keratin exhibiting the lowest core density.

Figure 4 presents the TS and WA of the particleboards after immersing them for 2 h and 24 h. The error bars indicate the standard deviation of the measurements. As shown in Fig. 4a, keratin-bonded particleboards exhibited the highest swelling at 68.1% after 2 h, followed by soybean at 57.2%, while casein and pea protein showed lower TS values of approximately 44.0% and 42.9%, respectively. The UF-bonded particleboard exhibited the least swelling at 40.1%. In commercial particleboards, about 1% paraffin emulsion is typically added to improve water resistance (Baharoğlu *et al.* 2014); however, no hydrophobic agents were used in this study. The incorporation of approximately 1% paraffin emulsion, combined with the optimization of adhesive distribution, interfacial bonding efficiency, and core-layer consolidation, is expected to reduce the 24 h TS of keratin-bonded particleboards below 30%. After 24 h of immersion, the TS values for UF, casein, and pea particleboards remained comparable, increasing respectively by approximately 13% to 13.5% compared to the 2 h measurements. The soybean particleboards showed a slightly greater increase of around 16%. Keratin, however, showed the greatest change, with a difference of approximately 54% between the 2 h and 24 h measurements. In the WA analysis shown in Fig. 4b, UF again exhibited the lowest water absorption, at 95.2%, after 2 h. Casein, soybean, and pea proteins yielded similar results, with WA values ranging from 113% to 115%. Keratin-based particleboards exhibited higher water absorption, reaching 114.8% after 2 h and increasing significantly to 148.6% after 24 h. All materials experienced an increase in water absorption of approximately 7% to 8% after 24 h relative to 2 h measurements, except for keratin, which showed a significant increase of approximately 29%. These results align with the density profile analysis of keratin-bonded particleboards, which revealed reduced core-layer density. This

performance suggests that higher TS and WA values are primarily associated with reduced adhesive impregnation efficiency in the coarse core layer. It is important to note that density alone does not govern swelling behavior, as particleboards with similar core densities (e.g., soybean- and UF-bonded systems) can exhibit different TS values depending on the adhesive system. Moreover, the weaker interfacial interactions in keratin-based systems, characterized by fewer hydrogen bonds with the wood substrate than in other proteins, make the adhesive–wood interface more susceptible to disruption upon water uptake. This susceptibility is more related to the adhesive-wood interaction than to the intrinsic hydrophilicity of the keratin protein itself. This interpretation is further supported by previous research on high-density fiberboards made with the same keratin hydrolysate, where keratin demonstrated superior water resistance compared to UF and soybean adhesives, meeting the requirements for humid conditions (MDF.H type) with TS values below 30% after 24 h (Raydan *et al.* 2025). Therefore, the results further highlight the importance of adhesive distribution and mixing efficiency, particularly in multilayer particleboard systems where bonding performance is strongly governed by core-layer consolidation.

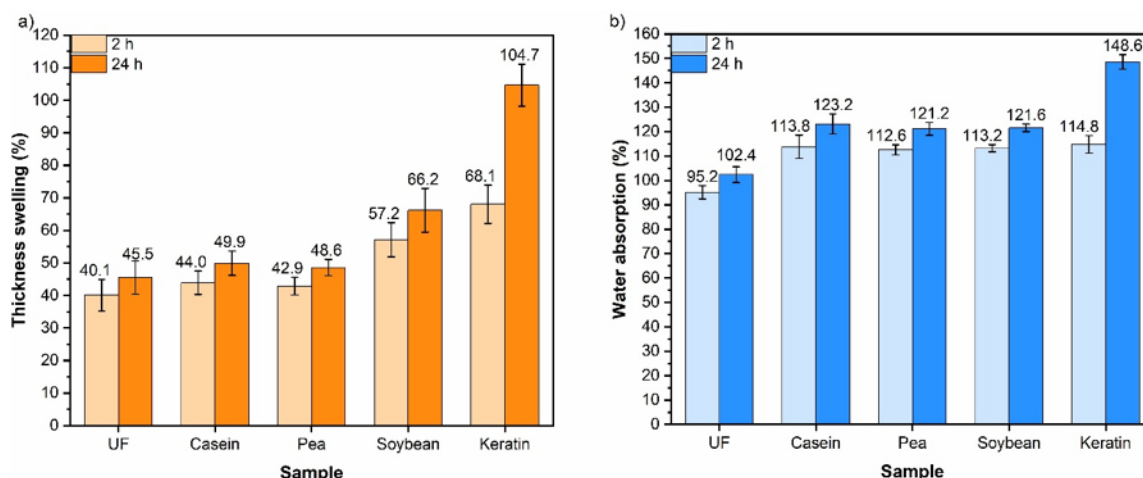


Fig. 4. Physical properties of the particleboards: (a) TS and (b) WA after 2 h and 24 h of immersion in water; Error bars indicate standard deviation

CONCLUSIONS

1. Keratin derived from duck feathers and recovered through ultrasound-assisted alkaline hydrolysis presented a promising alternative to conventional urea-formaldehyde resins and food protein-based adhesives (casein, pea, and soybean) for multilayer particleboards manufactured under industrially relevant hot-pressing conditions (180 °C, 20 s·mm⁻¹). The keratin-bonded particleboards met the mechanical performance criteria of EN 312 (2010) for P1-type particleboards, making them suitable for general-purpose interior applications.
2. The keratin adhesives achieved a modulus of rupture of approximately 12 N·mm⁻² and a modulus of elasticity exceeding 3000 N·mm⁻², both meeting or exceeding P2-type thresholds, while the internal bond strength reached 0.25 N·mm⁻², meeting P1-type requirements. The screw withdrawal resistance was about 139 N·mm⁻¹. These results

indicate competitive mechanical performance compared to urea–formaldehyde and tested protein adhesives.

3. Density profile analysis indicated that the protein-bonded particleboards developed higher surface-layer densities than those bonded with urea-formaldehyde. This characteristic contributed to improved bending stiffness and screw withdrawal resistance. However, the keratin-bonded particleboards had a lower core density, which is attributed to less effective adhesive impregnation and distribution within the coarse core layer, and this was correlated with reduced internal bond strength compared to casein and urea–formaldehyde systems.
4. The increased thickness swelling and water absorption observed in keratin-bonded particleboards can largely be attributed to limited adhesive penetration and weaker interfacial interactions in the core layer, rather than the inherent hydrophilicity of keratin. While moisture resistance is not a requirement for EN 312 (2010) P1-type particleboards, these findings underscore the need to optimize adhesive distribution and explore alternative application methods for keratin-based adhesives, such as liquid formulations or testing in higher-density systems.
5. These findings demonstrate the feasibility of transforming poultry feather waste into functional adhesive systems without competing with food protein resources, providing a sustainable and low-emission alternative binder for lignocellulosic composite particleboards.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Generative AI

Generative AI tools, such as Chat GPT v5.2 was used solely for clarifying text and refining grammar during the preparation of the manuscript. The authors thoroughly reviewed and validated all content, interpretations of data, and scientific conclusions.

REFERENCES CITED

- Adhikari, B. B., Chae, M., Zhu, C., Khan, A., Harfield, D., Choi, P., and Bressler, D. C. (2019). "Pelletization of torrefied wood using a proteinaceous binder developed from hydrolyzed specified risk materials," *Processes* 7(4), article 229. <https://doi.org/10.3390/pr7040229>
- Ahmad, A., Afzal, M., Goyal, A., Gupta, G., Thapa, R., Hassan, W., Kazmi, I., Alzarea, S. I., Shahwan, M., Raj, K., *et al.* (2024). "Chemico-biological interactions the impact of formaldehyde exposure on lung inflammatory disorders: Insights into asthma, bronchitis, and pulmonary fibrosis," *Chemico-Biological Interactions* 394, article 111002. <https://doi.org/10.1016/j.cbi.2024.111002>
- Altun, S., and Tokdemir, V. (2016). "Modification with melamine formaldehyde and melamine-urea formaldehyde resin to improve the physical and mechanical properties of wood," *BioResources* 12(1), 586-596. <https://doi.org/10.15376/biores.12.1.586-596>
- Alvarez, S., Raydan, N. D. V., Svahn, I., Gontier, E., Rischka, K., Charrier, B., and Robles, E. (2023). "Assessment and characterization of duck feathers as potential source of biopolymers from an upcycling perspective," *Sustainability* 15(19), article 14201. <https://doi.org/10.3390/SU151914201>
- Baharoğlu, M., Nemli, G., Sari, B., Ayrilmis, N., Bardak, S., and Zeković, E. (2014). "Effect of paraffin application technique on the physical and mechanical properties of particleboard," *Science and Engineering of Composite Materials* 21(2), 191-195. <https://doi.org/10.1515/secm-2013-0074>
- Banasaz, S., and Ferraro, V. (2024). "Keratin from animal by-products: Structure, characterization, extraction and application—A review," *Polymers* 16(14), article 1999. <https://doi.org/10.3390/polym16141999>
- Bekhta, P., Noshchenko, G., Réh, R., Kristak, L., Sedliačik, J., Antov, P., Mirski, R., and Savov, V. (2021). "Properties of eco-friendly particleboards bonded with lignosulfonate-urea-formaldehyde adhesives and PMDI as a crosslinker," *Materials* 14(17), article 4875. <https://doi.org/10.3390/ma14174875>
- CIRS Group (2026). "China two new mandatory standards on the limitation of hazardous in paints will take effect from June 1, 2026," CIRS Group, Hangzhou, China.
- Dunky, M. (2020). "Wood adhesives based on natural resources: A critical review: Part I. Protein-based adhesives," *Reviews of Adhesion and Adhesives* 8(3), 199-332. <https://doi.org/10.7569/RAA.2020.097309>
- EN 310 (1993). "Wood-based particleboards – Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels, Belgium.
- EN 312 (2010). "Particleboards – Specifications," European Committee for Standardization, Brussels, Belgium.
- EN 317 (1993). "Particleboards and fibreboards – Determination of swelling in thickness after immersion in water," European Committee for Standardization, Brussels, Belgium.

- EN 319 (1993). "Particleboards and fibreboards – Determination of tensile strength perpendicular to the plane of the particleboard," European Committee for Standardization, Brussels, Belgium.
- EN 320 (2011). "Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws," European Committee for Standardization, Brussels, Belgium.
- EN 323 (1993). "Wood-based particleboards – Determination of density," European Committee for Standardization, Brussels, Belgium.
- EN 326-1 (1993). "Wood-based particleboards – Sampling, cutting and inspection – Part 1: Sampling and cutting of test pieces and expression of test results," European Committee for Standardization, Brussels, Belgium.
- EN 326-2 (2010). "Wood-based particleboards – Sampling, cutting and inspection – Part 2: Initial type testing and factory production control," European Committee for Standardization, Brussels, Belgium.
- European Commission Regulation (EU) 2023/1464 (2023). "Amending Annex XVII to Regulation (EC) No 1907/2006 as regards formaldehyde and formaldehyde releasers," European Union, Brussels, Belgium.
- Fagbemi, O. D., and Sithole, B. (2021). "Evaluation of waste chicken feather protein hydrolysate as a bio-based binder for particleboard production," *Current Research in Green and Sustainable Chemistry* 4, article 100168. <https://doi.org/10.1016/j.crgsc.2021.100168>
- Flores, E. M. M., Cravotto, G., Bizzi, C. A., Santos, D., and Iop, G. D. (2021). "Ultrasound-assisted biomass valorization to industrial interesting products: State-of-the-art, perspectives and challenges," *Ultrasonics Sonochemistry* 72, article 105455. <https://doi.org/10.1016/j.ultsonch.2020.105455>
- Frihart, C. R. (2011). "Wood adhesives: Vital for producing most wood products," *Forest Products Journal* 61(1), 4-12.
- Future Market Insights (2025). *Wood Adhesives and Binders Market: Size, Share and Forecast Outlook 2025–2035*, Future Market Insights, New York, NY, USA.
- Hussin, M. H., Abd Latif, N. H., Hamidon, T. S., Idris, N. N., Hashim, R., Appaturi, J. N., Brosse, N., Ziegler-Devin, I., Chrusiel, L., Fatriasari, W., *et al.* (2022). "Latest advancements in high-performance bio-based wood adhesives: A critical review," *Journal of Materials Research and Technology* 21, 3909-3946. <https://doi.org/10.1016/j.jmrt.2022.10.156>
- Kristak, L., Antov, P., Bekhta, P., Lubis, M. A. R., Iswanto, A. H., Reh, R., Sedliacik, J., Savov, V., Taghiyari, H. R., Papadopoulos, A. N., *et al.* (2022). "Recent progress in ultra-low formaldehyde emitting adhesive systems and formaldehyde scavengers in wood-based particleboards: A review," *Wood Material Science and Engineering* 2022, article 2056080. <https://doi.org/10.1080/17480272.2022.2056080>
- Laskowska, A. (2024). "Characteristics of the pressing process and density profile of MUPF-bonded particleboards produced from waste plywood," *Materials* 17(4), article 850. <https://doi.org/10.3390/ma17040850>
- Lee, S. H., Lum, W. C., Boon, J. G., Kristak, L., Antov, P., Pędzik, M., Rogoziński, T., Taghiyari, H. R., Lubis, M. A. R., Fatriasari, W., *et al.* (2022). "Particleboard from agricultural biomass and recycled wood waste: A review," *Journal of Materials Research and Technology* 20, 4630-4658. <https://doi.org/10.1016/j.jmrt.2022.08.166>
- Luukkonen, T., Heponiemi, A., Runtti, H., Pesonen, J., Yliniemi, J., and Lassi, U. (2019). "Application of alkali-activated materials for water and wastewater treatment: A review," *Reviews in Environmental Science and Biotechnology* 18(2), 271-297.

- <https://doi.org/10.1007/s11157-019-09494-0>
- Market Growth Reports (2025). *Urea-Formaldehyde Resin Market: Size, Share & Forecast to 2035*, Market Growth Reports, London, UK.
- Market Growth Reports (2026). *Particleboard Market Size, Share, Growth, and Industry Analysis, Forecast to 2035*, Market Growth Reports, London, UK.
- Md Murshed Bhuyan, J.-H. J. (2025). "Preparation of hydrogel by crosslinking and multi-dimensional applications," *Gels* 11(11), article 896.
<https://doi.org/10.3390/gels11110896>
- Momen, S., Alavi, F., and Aider, M. (2021). "Alkali-mediated treatments for extraction and functional modification of proteins: Critical and application review," *Trends in Food Science and Technology* 110, 778-797.
<https://doi.org/10.1016/j.tifs.2021.02.052>
- Mungwari, C. P., King'onde, C. K., Sigauke, P., and Obadele, B. A. (2025). "Conventional and modern techniques for bioactive compounds recovery from plants: Review," *Scientific African* 27, article e02509.
<https://doi.org/10.1016/j.sciaf.2024.e02509>
- Mylan, J., Andrews, J., and Maye, D. (2023). "The big business of sustainable food production and consumption: Exploring the transition to alternative proteins," *Proceedings of the National Academy of Sciences of the United States of America* 120(47), 1-9. <https://doi.org/10.1073/pnas.2207782120>
- Nguyen, D. (2024). "Everything you need to know about formaldehyde-free cabinets," *Casta Cabinetry*, (<https://castacabinetry.com/post/formaldehyde-free-cabinets/>), Accessed 01 Feb 2026.
- Peydayesh, M., Bagnani, M., Soon, W. L., and Mezzenga, R. (2023). "Turning food protein waste into sustainable technologies," *Chemical Reviews* 123(5), 2112-2154.
<https://doi.org/10.1021/acs.chemrev.2c00236>
- Podlena, M., Böhm, M., Saloni, D., Velarde, G., and Salas, C. (2021). "Tuning the adhesive properties of soy protein wood adhesives with different coadjuvant polymers, nanocellulose and lignin," *Polymers* 13(12), article 1972.
<https://doi.org/10.3390/polym13121972>
- Raydan, N. D. V., Leroyer, L., Charrier, B., and Robles, E. (2021). "Recent advances on the development of protein-based adhesives for wood composite materials—A review," *Molecules* 26(24), article 7617. <https://doi.org/10.3390/molecules26247617>
- Raydan, N. D. V., Loquet, A., Habenstein, B., Kauffmann, B., Charrier, B., Chatel, G., and Robles, E. (2024b). "A comprehensive comparative study of ultrasound-alkaline and thermal-alkaline hydrolysis of duck feather," *Journal of Cleaner Production* 467, article 142927. <https://doi.org/10.1016/J.JCLEPRO.2024.142927>
- Raydan, N. D. V., Richter, K., Charrier, B., Hartwig, A., Robles, E. (2024a). "Cold-set, crosslinker-free wood adhesives: A comparative study of ultrasound-extracted duck feather keratin and traditional food proteins," *Materials Today Sustainability* 2024, article 100905. <https://doi.org/10.1016/j.mtsust.2024.100905>
- Raydan, N. D. V., Wronka, A., Kowaluk, G., and Robles, E. (2025). "Feather keratin hydrolysates as sustainable binders for high-density fiberboards," *Composites Part C: Open Access* 18, article 100668. <https://doi.org/10.1016/j.jcomc.2025.100668>
- Raydan, N. D. V., Loquet, A., Habenstein, B., Kauffmann, B., Chatel, G., and Robles, E. (2026). "Ultrasound-Assisted alkaline hydrolysis of feather keratin using a cup horn sonoreactor," *Ultrasonics Sonochemistry* 124, article 107733.
<https://doi.org/10.1016/j.ultsonch.2025.107733>

- Schwarzenbrunner, R., Barbu, M. C., Petutschnigg, A., and Tudor, E. M. (2020). "Water-resistant casein-based adhesives for veneer bonding in biodegradable ski cores," *Polymers* 12(8), article 1745. <https://doi.org/10.3390/POLYM12081745>
- U.S. Environmental Protection Agency (2025). *Revised Draft Human Health Risk Assessment for Formaldehyde* (CASRN 50-00-0), U.S. Environmental Protection Agency, Washington, D.C., USA.
- Thoemen, H., Irle, M., and Sernek, M. (2010). *Wood-Based Particleboards – An Introduction for Specialists*, Brunel University Press, London, England.
- Wang, R., and Tong, H. (2022). "Preparation methods and functional characteristics of regenerated keratin-based biofilms," *Polymers* 14(21), article 4723. <https://doi.org/10.3390/polym14214723>
- Zhou, Y., Zeng, G., Zhang, F., Luo, J., Li, X., Li, J., and Fang, Z. (2021). "Toward utilization of agricultural wastes: Development of a novel keratin reinforced soybean meal-based adhesive," *ACS Sustainable Chemistry & Engineering* 9(22), 7630-7637. <https://doi.org/10.1021/acssuschemeng.1c01920>
- Zhu, Z., Zhang, E., Tu, Y., Ye, M., and Chen, N. (2022). "An eco-friendly wood adhesive consisting of soybean protein and cardanol-based epoxy for wood based composites," *Polymers* 14(14), article 2831. <https://doi.org/10.3390/polym14142831>

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