Cureus Journal of Engineering

Open Access Original Article

Development of Oriented Strand Boards Using Leftovers of Veneer-Wood and Non-formaldehyde Lignin or Tannin Adhesive Formulations

Received 06/21/2025
Review began 06/25/2025
Review ended 08/18/2025
Published 09/10/2025

DOI:
https://doi.org/10.7759/s44388-025-08086-9

Luis E. Chávez-García [1] , Joel A. Sánchez-Badillo [1] , Raúl Espinoza-Herrera [1] , Pablo Lopez-Albarran [1]

1. Facultad de Ingeniería en Tecnología de la Madera, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, MEX

Corresponding author: Pablo Lopez-Albarran, plopez@umich.mx

Abstract

The urgent need for sustainable construction materials has catalyzed research into formaldehyde-free adhesives for wood composites and the effective valorization of industrial wood residues. This study addresses the growing demand for sustainable alternatives to formaldehyde-based adhesives in the wood composites industry. The present research focuses on developing oriented strand board (OSB) panels using veneer-wood leftovers bonded with two formaldehyde-free adhesives: phenol-lignin-glyoxal (PLG) and phenol-tannin-glyoxal (PTG) resins. The adhesive formulations were developed with a focus on environmental compatibility, mechanical strength, and moisture resistance, following procedures and compositions previously reported in scientific literature. Thus, while the adhesive systems themselves are not novel, their application in the valorization of wood veneer residues for OSB manufacturing represents a significant advancement. Furthermore, this study presents an innovative approach to mitigate these challenges by repurposing veneer-wood leftovers-a byproduct constituting approximately 20% of plywood manufacturing-as a sustainable feedstock for OSB panels, thereby reducing dependence on raw timber. OSB panels were fabricated through a hot-pressing process and evaluated for physical and mechanical performance, including density, modulus of rupture (MOR), water absorption, and thickness swelling over time. The OSB/PLG panels demonstrated superior mechanical strength, while OSB/PTG panels showed enhanced water resistance, highlighting the distinct advantages of each formulation. Notably, OSB manufacturing typically relies on juvenile hardwoods, raising concerns over deforestation and short-rotation forestry. In contrast, utilizing veneer-wood waste as feedstock offers an environmentally beneficial route to reduce raw wood consumption and promote circular resource use. This research contributes to the advancement of bio-based adhesives for engineered wood products by validating the performance of glyoxal-crosslinked lignin and tannin systems in OSB applications. The findings support the industrial feasibility of replacing conventional synthetic resins with renewable alternatives, aligning with environmental regulations and sustainability goals.

Categories: Materials Engineering, Sustainable Technologies, Polymer Science and Engineering
Keywords: oriented strand board, veneer-wood, lignin-based adhesive, tannin, glyoxal

Introduction

The urgent need to move towards sustainable development has subjected the construction industry, a significant contributor to resource consumption and environmental impact, to close examination [1,2]. Traditional construction materials often entail significant energy consumption, resource depletion, and greenhouse gas emissions, prompting a concerted search for greener alternatives [3]. In this context, engineered wood products have emerged as pivotal materials, offering favorable lifecycle assessments and the ability to sequester carbon [4]. Oriented Strand Board (OSB) is commonly used as a structural panel in residential and commercial buildings due to its mechanical efficiency, cost-effectiveness, and ability to utilize fast-growing tree species and smaller diameter logs [5].

Despite the inherent benefits of wood, the environmental credentials of conventional OSB panels have been significantly challenged by their historical reliance on formaldehyde-based adhesives, such as phenol-formaldehyde (PF), urea-formaldehyde (UF), and melamine-urea-formaldehyde (MUF) resins [6]. Formaldehyde is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) [7], and its emission from wood-based panels poses risks to indoor air quality and human health, including respiratory issues and allergic reactions [8-10]. Consequently, stringent international regulations, such as the European E1/E0 classifications, have been implemented to curtail formaldehyde emissions from these products [11]. This regulatory landscape, coupled with heightened consumer awareness, has intensified the research and development of effective, formaldehyde-free adhesive systems for the wood panel industry [12,13]. Comparative life cycle assessments are increasingly highlighting the environmental advantages of shifting toward bio-based adhesives for OSB production [14,15].

Lignin, the second most abundant terrestrial biopolymer, represents a highly promising, renewable feedstock for the development of such formaldehyde-free adhesives [16]. As a complex phenolic polymer, lignin is abundantly available as a byproduct from the pulp and paper industry (e.g. Kraft lignin, lignosulfonates) and emerging biorefineries (e.g. organosolv lignin), offering a diverse range of chemical structures depending on its source and extraction method [17,18]. Its aromatic backbone and inherent reactive functional groups (e.g. phenolic hydroxyls, aliphatic hydroxyls) make it theoretically suitable for polymerization into adhesive resins [19-21]. The conversion of lignin into higher-value products, such as adhesives, represents an approach in promoting the circular bioeconomy and decreasing dependence on petrochemicals [22,23].

However, the direct utilization of untreated industrial lignins in adhesive formulations is often hampered by their inherent structural complexity, high molecular weight, polydispersity, and relatively low reactivity compared to synthetic phenols [24,25]. To address these limitations, various modification strategies have been explored. Chemical modifications such as phenolation, demethylation, or methylolation can introduce more reactive sites onto the lignin macromolecule [26-28]. Among physical and chemical treatments, depolymerization has garnered significant interest as a method to break down the large lignin polymer into smaller, more uniform oligomers or monomers [29,30]. These depolymerized lignin fractions typically exhibit lower viscosity, increased solubility, and a higher concentration of reactive functional groups, potentially leading to enhanced adhesive penetration and cross-linking efficiency [25,31].

In the development of formaldehyde-free adhesive systems, glyoxal ($C_2H_2O_2$), a less volatile and significantly less toxic dialdehyde, has emerged as a viable alternative cross-linker for phenolic compounds, including lignin [26,32,33]. The reaction between lignin and glyoxal can lead to the formation of a cross-linked network suitable for wood bonding, as demonstrated in studies on lignin-glyoxal (LG) adhesives [26,34]. While LG adhesives can achieve satisfactory dry bond strength, their performance under humid conditions or direct water exposure, a critical factor for many wood panel applications, often requires improvement [26,35-37].

To potentially enhance both mechanical performance and water resistance, while also managing costs, ternary systems incorporating phenol with lignin and glyoxal (PLG resins) have been investigated [36-38]. In these formulations, lignin acts as a partial substitute for petroleum-derived phenol, contributing to the bio-based content of the adhesive [6,39-41]. The specific use of depolymerized lignin within a PLG formulation, as explored in the present research, is hypothesized to offer advantages due to the increased reactivity and accessibility of the smaller lignin fragments, potentially leading to a more efficiently cured and robust adhesive network [35,42].

Complementing advancements in adhesive chemistry, the sustainable sourcing of lignocellulosic raw materials is paramount. The utilization of wood industry residues, such as veneer leftovers from plywood or Laminated Veneer Lumber production, aligns with circular economy principles by transforming low-value byproducts into valuable feedstock for panel manufacturing. However, the inherent variability in residue quality and geometry can pose challenges in achieving consistent panel properties [43].

For comparative purposes, tannin-based adhesives, another significant class of formaldehyde-free bio-adhesives, have also demonstrated considerable potential in wood panel production, often exhibiting excellent bonding properties [33,44-47].

Despite progress, critical gaps persist. First, most lignin adhesive studies focus on particleboard or fiberboard, with limited exploration of OSB-a panel requiring superior mechanical properties for structural applications [48,49]. Second, while tannin adhesives perform better in moisture resistance, their brittleness and low thermal stability hinder OSB performance [32,44]. Third, veneer-wood waste remains underexploited in OSB production, with prior research prioritizing virgin strands.

A comprehensive investigation into OSB-type panels produced from wood veneer leftovers using an adhesive system based specifically on depolymerized lignin, glyoxal, and phenol is still needed to fully evaluate its technical feasibility and performance characteristics. This study aims to address this gap by developing and evaluating OSB-type panels using adhesive formulations developed with a focus on environmental compatibility, mechanical strength, and moisture resistance, following procedures and compositions previously reported in scientific literature [26,47,50]. Thus, while the adhesive systems themselves are not novel, their application in the valorization of wood veneer residues for OSB manufacturing represents a significant advancement. This research proposes to contribute to the development of sustainable, high-performance building materials by valorizing industrial wood residues and advancing formaldehyde-free adhesive technology. The findings aim to inform adhesive manufacturers, wood panel producers, and policymakers about viable pathways to replace formaldehyde-based resins without compromising performance or increasing production costs. Moreover, this work addresses key research gaps identified in recent literature. While many studies have tested lignin or tannin adhesives in particleboard or plywood, few have extended these systems to OSB using industrial wood waste. The novelty of combining depolymerized lignin with glyoxal and phenol in OSB applications-and benchmarking it against a tannin-based system-represents a significant contribution to the field of green composites. Our research provides a scientific foundation for transitioning the wood panel industry toward circular, health-conscious manufacturing paradigms.

Materials And Methods

Methodology

Materials

The lignocellulosic raw material consisted of leftover pine (Pinus sp.) veneer strands (length 15-50mm, thickness 0.5-1.0mm), collected from plywood production waste of a commercial plywood mill in Michoacán, México. Strands were dried to 8% moisture content and stored at 20°C and 65% relative humidity until use. Kraft lignin, obtained as a byproduct from the pulp and paper industry, was used for the primary adhesive formulation. For comparative adhesive system, condensed tannins were also utilized. Phenol (99% purity), glyoxal (40%wt solution in H_2O), and sodium hydroxide (NaOH) pellets (98% purity) were purchased from Sigma-Aldrich and used without further purification.

Synthesis of Lignin- and Tannin-Based Adhesives

Two different formaldehyde-free adhesive formulations were prepared for this study: a phenol-lignin-glyoxal (PLG) resin and a phenol-tannin-glyoxal (PTG) resin. The synthesis procedure was adapted from methodologies established in previous studies [33,41,51]. For the PLG adhesive, depolymerized Kraft lignin was used to substitute 90% of the phenol on a weight basis. In a reaction vessel, the required amounts of phenol and lignin were dissolved in 50 g of deionized water. The pH of the solution was adjusted and maintained between 11.0 and 12.0 by the controlled addition of a 10 N NaOH solution to catalyze the reaction and ensure the dissolution of the phenolic components. Subsequently, glyoxal was added to the mixture as a cross-linking agent. The reaction was carried out at 100°C for 90 minutes under constant mechanical agitation to ensure homogeneity. The same procedure was followed for the PTG resin, with condensed tannins replacing the lignin. Figure *1* shows the synthesis process.

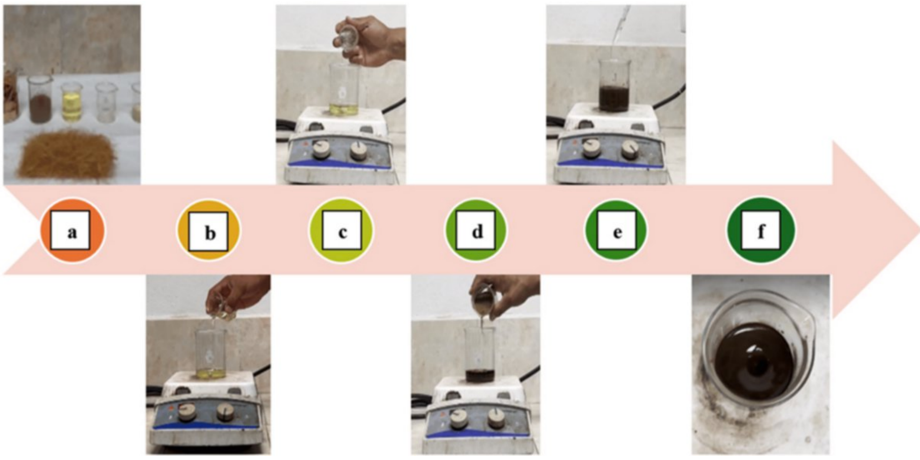

FIGURE 1: Flow chart of the synthesis process for the adhesive formulation

Schematic of adhesive synthesis process for PLG and PTG resins: (a) Reagents (phenol, lignin/tannins, glyoxal, NaOH); (b) Glyoxal addition as cross-linker; (c) Phenol dissolution; (d) Lignin/tannin incorporation; (e) Temperature-controlled reaction (100°C) under mechanical agitation; (f) Final formaldehyde-free adhesive product. Adapted from the methodologies detailed in references [33,41,51].

Preparation of Wood Strands from Veneer Leftovers

The Pinus sp. veneer leftovers were processed into strands with target dimensions suitable for OSB prototypes: length ranging from 15 mm to 50 mm, width of 15 mm, and thickness of 0.5-1 mm. The strands were then conditioned to a target moisture content of 8%. The conditioned strands were treated in an autoclave with steam vaporization at 125°C and 0.14 MPa for 4 hours before adhesive application to enhance surface activation and dimensional stability, as illustrated in Figure *2*.

FIGURE 2: Preparation of wood strands from veneer leftovers

(a) Pine veneer waste processed into OSB-compatible strands (15–50 mm length, 15 mm width, 0.5–1 mm thickness); (b) Autoclave steam treatment (125°C, 0.14 MPa, 4 h) for surface activation and dimensional stabilization prior to adhesive application.

OSB Panel Manufacturing

Three-layer OSB panels were prepared at laboratory scale with dimensions appropriate for laboratory testing, following the length/width/thickness ratios outlined in ASTM D1037-12 (15.5 cm × 8.3 cm × 0.9 cm). The target density was set to exceed 750 kg/m³. Wood strands were sprayed with FF, PLG, and PTG adhesives at a resin solids content of 10% relative to oven-dry weight. Adhesive-coated strands were arranged manually into a three-layer mat, positioning face layer strands parallel to the panel's length and core layer strands perpendicular, as illustrated in Figure *3*.

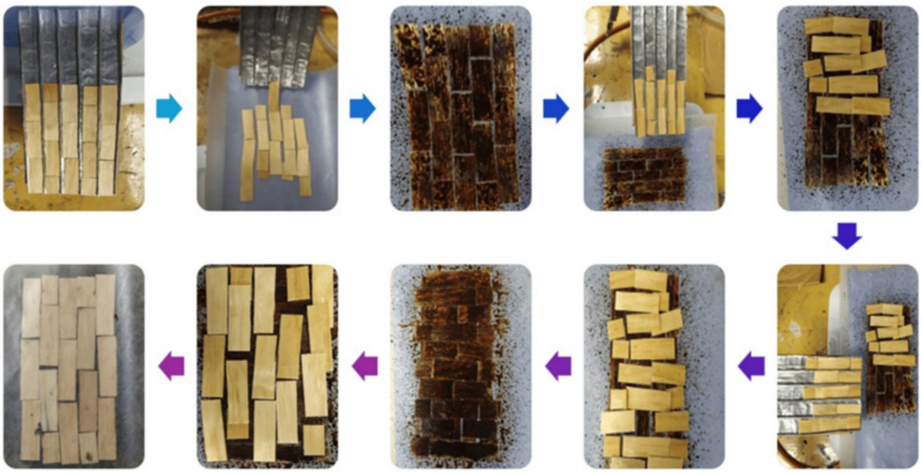

FIGURE 3: Manual assembly of the three-layer OSB mat

The diagram illustrates the process of assembling adhesive-coated wood strands to produce laboratory OSB prototypes using formaldehyde-free phenolic resin adhesives (PLG or PTG), with PF used as a control. The three-layer mat features face layer strands aligned with the panel length for strength, and core strands placed perpendicular for stability. This layout follows standard OSB methods, optimizing structural performance and using veneer waste as a sustainable resource. OSB, oriented strand board; PLG, phenol-lignin-glyoxal; PTG, phenol-tannin-glyoxal; PF, phenol-formaldehyde

The mat was subjected to hot pressing in a hydraulic press (EKA, 40-ton capacity) equipped with electrically heated platens. The pressing procedure was carried out at a constant pressure of 4.9 MPa (50 kg/cm²) and a platen temperature of 140°C over a period of 8 minutes (480 seconds), as displayed in Figure *4*. The cycle included a pre-heating ramp to ensure uniform heat distribution throughout the mat. Following the pressing process, panels were conditioned at 20°C ± 2°C and 65% ± 5% relative humidity for 48 hours until equilibrium moisture content was achieved prior to testing.

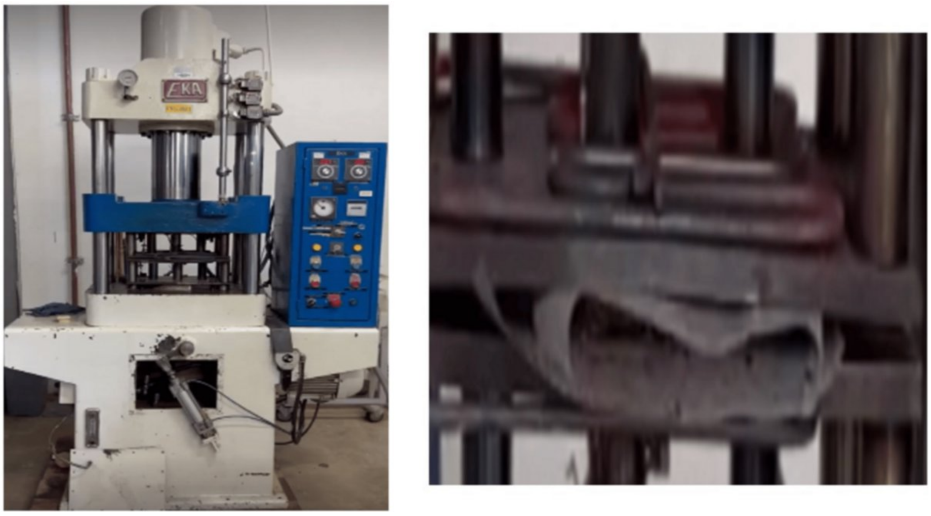

FIGURE 4: The hot-pressing process is used to consolidate OSB panels

This procedure involves a laboratory-scale hydraulic press, which compresses the adhesive-coated wood mat into a panel that is dense and uniform. The mat undergoes high pressure (4.9 MPa) and temperature (140°C) for 8 minutes. OSB, oriented strand board

Physical and Mechanical Characterization

The properties of the manufactured OSB panels were evaluated in accordance with the American Society for Testing and Materials (ASTM) D1037-12 standard: "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials", under controlled atmospheric conditions (20°C ± 2°C, 65% ± 5% RH).

Density: Panel density was assessed through weight and volume measurements employing a precision balance (±0.01 g) and digital calipers (±0.01 mm). For statistical analysis, five specimens of each panel type were evaluated.

Water Absorption and Thickness Swelling: Water resistance was evaluated by fully immersing test specimens (15.7 × 3.5 × 0.9 cm), prepared from laboratory-fabricated panels, in accordance with ASTM D1037 standards. The specimens were placed horizontally under 2.54 cm of distilled water at a temperature of 20°C ± 1°C. Measurements of specimen weight and thickness were taken prior to immersion and subsequently after 2 and 24 hours of submersion, utilizing a precision balance and digital calipers. Water Absorption (WA) and Thickness Swelling (TS) were determined as the percentage increase relative to the initial dry condition.

Flexural Properties: Static bending properties were determined using a universal testing machine (Instron 5582) with a three-point loading configuration. Test specimens with dimensions of 15.7 cm × 3.5 cm × 0.9 cm were loaded at a constant crosshead speed of 5 mm/min until failure. The span-to-depth ratio was maintained at 16:1 as specified in ASTM D1037-12. Both Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) were calculated from load-deflection curves recorded during testing (Figure *5*).

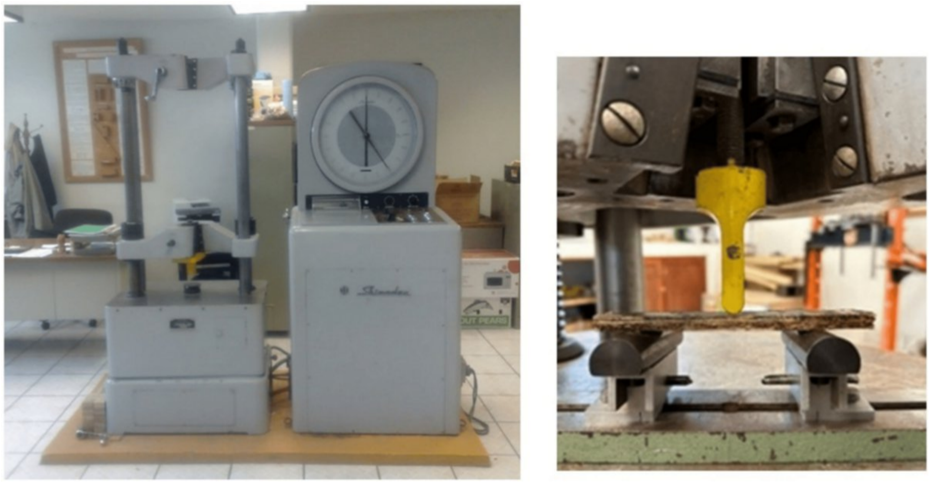

FIGURE 5: The MOR and MOE of the prototypes was determined by a universal machine

Three-point bending test setup in a universal testing machine used to determine both modulus of rupture (MOR) and modulus of elasticity (MOE). Specimen dimensions: 15.7 × 3.5 × 0.9 cm; support span = 12 cm; loading rate = 5 mm/min; tests performed at 20°C and 65% RH to comply with ASTM D1037.

Characterization tests were conducted using five samples from each prototype (n = 5) to ensure statistical reliability of the results.

Statistical Analysis: Characterization tests used five replicates per panel type for statistical reliability, following similar studies [52,53]. Data were analyzed with one-way ANOVA and Tukey's HSD post-hoc test ($\alpha = 0.05$). Results are reported as mean ± standard deviation.

Results And Discussion

Results and discussion

The physical and mechanical properties of OSB panels made from Pinus sp. veneer residues and bonded with formaldehyde-free PLG and PTG adhesives were evaluated and compared to those produced with conventional phenol-formaldehyde (PF) adhesives. A one-way ANOVA was conducted to assess statistical differences between the adhesive types. The OSB prototypes are displayed in Figure 6.

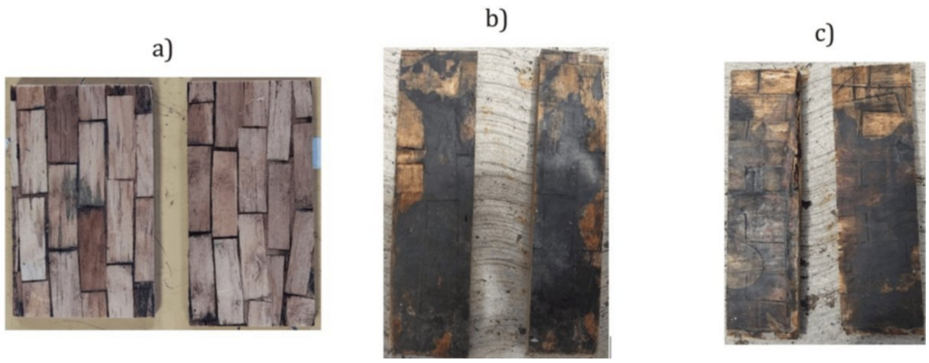

FIGURE 6: OSB-type samples

Visual differences among the three OSB panel prototypes: (a) OSB/PF, the control with PF adhesive, appears light brown; (b) OSB/PLG, using PLG adhesive, is dark brown to nearly black due to Kraft lignin; and (c) OSB/PTG, bonded with PTG adhesive, features a reddish-brown color from condensed tannins. OSB, oriented strand board; PLG, phenol-lignin-glyoxal; PTG, phenol-tannin-glyoxal; PF, phenol-formaldehyde

Physical Properties: Density and Water Resistance

The experimental results demonstrate that all panel formulations achieved consistent densities within acceptable ranges for structural OSB applications. Mean densities were 1040 ± 80 kg/m³ for OSB/PLG, 1060

± 60 kg/m³ for OSB/PTG, and 1100 ± 120 kg/m³ for OSB/PF controls. The slightly higher density of conventional panels reflects the different curing characteristics and penetration behavior of formaldehyde-based resins compared to glyoxal-cross-linked systems. The lack of significant density differences (ANOVA p = 0.217) validates the experimental design and ensures that subsequent property comparisons reflect true adhesive performance rather than density effects.

Water resistance properties, quantified through Water Absorption (WA) and Thickness Swelling (TS) measurements, revealed significant performance differences between adhesive formulations. The comprehensive results are presented in Table *1*, showing measurements at both 2-hour and 24-hour immersion periods to assess initial and prolonged moisture exposure effects. The results are summarized in Table *1*.

Adhesive Type	Density (g/cm³)	WA 2 h (%)	WA 24 h (%)	TS 2 h (%)	TS 24 h (%)
PF (Control)	1.100 ± 0.12	21.96 ± 2.64	28.53 ± 3.24	36.87 ± 5.56	45.67 ± 1.97
PLG (Lignin)	1.040 ± 0.08	21.10 ± 1.55	42.94 ± 3.39	23.38 ± 1.73	39.11 ± 0.92
PTG (Tannin)	1.060 ± 0.06	12.06 ± 0.92	27.56 ± 1.01	8.21 ± 0.91	17.80 ± 3.63

TABLE 1: Density, water absorption and thickness swelling of OSB type panels. Data presented as Mean ± Standard Deviation (SD)

ANOVA p-values: Density = 0.217; Water Absorption 2 h = 0.696; Water Absorption 24 h = 0.742; Thickness Swelling 2 h = 0.662; Thickness Swelling 24 h = 0.317. OSB, oriented strand board; PLG, phenol-lignin-glyoxal; PTG, phenol-tannin-glyoxal; PF, phenol-formaldehyde

All p-values exceed 0.05, suggesting that the formaldehyde-free adhesives (PLG and PTG) produce panels with physical properties comparable to the PF control, without significant deviations. This is positive for sustainability, as it implies bio-based alternatives can match conventional performance. No post-hoc tests (e.g., Tukey's HSD) were needed due to non-significance, but if trends persist in future studies, they could be explored. The results indicate that the OSB/PTG panels exhibited higher water resistance compared to both the OSB/PLG and the conventional OSB/PF panels. After 24 hours, the OSB/PTG panels showed a TS of only 17.80%, which is less than half that of the OSB/PLG (39.11%) and OSB/PF (45.67%) panels. Similarly, the WA for OSB/PTG panels (27.56%) was significantly lower than that for OSB/PLG (42.94%) and comparable to the PF control (28.53%). This superior performance is attributed to the inherent characteristics of tannins. Tannins, as polyphenolic compounds, possess high reactivity with glyoxal and can form a highly cross-linked, hydrophobic adhesive network [44], which effectively limits water penetration and subsequent swelling. Conversely, the OSB/PLG panels, while showing good initial water resistance after 2 hours (21.10%), demonstrated significantly higher WA and TS after 24 hours (42.94%). This suggests that the lignin-glyoxal bond is more susceptible to hydrolysis over prolonged water exposure compared to the tannin-glyoxal bond [46]. This finding is consistent with literature that highlights the need to improve the water resistance of lignin-based adhesives for certain applications [34].

Mechanical Performance: Flexural Strength

Table *2* summarizes the mechanical properties of three categories of OSB panels produced with distinct adhesive formulations: OSB/PF (the control group, utilizing conventional PF adhesive), OSB/PLG (phenol-lignin-glyoxal, a formaldehyde-free lignin-based alternative), and OSB/PTG (phenol-tannin-glyoxal, a formaldehyde-free tannin-based alternative). Each value represents the mean ± standard deviation calculated from five samples per prototype (n = 5). These mechanical parameters are essential for evaluating the structural performance and application potential of OSB panels in construction, particularly as bending strength (MOR) and stiffness (MOE) are key indicators of load-bearing capacity and resistance to deformation.

Adhesive Type	MOR (MPa)	MOE (MPa)
PF (Control)	27.66 ± 3.24	1942.86 ± 416.12
PLG (Lignin)	25.86 ± 9.05	2717.25 ± 960.69
PTG (Tannin)	24.55 ± 2.44	2323.46 ± 208.19

TABLE 2: Mechanical properties (MOR and MOE) of OSB type panels. Data presented as Mean ± Standard Deviation

ANOVA p-values: MOR = 0.460; MOE = 0.181. MOR, Modulus of Rupture; MOE, Modulus of Elasticity; OSB, oriented strand board; PLG, phenol-lignin-glyoxal; PTG, phenol-tannin-glyoxal; PF, phenol-formaldehyde

Statistical analysis (ANOVA) indicates that adhesive type does not have a significant effect on either MOR or MOE, suggesting that panels manufactured with formaldehyde-free adhesives retain their structural integrity even when produced from waste feedstocks. The high standard deviations observed reflect sample variability, which may be attributed to the heterogeneity of residual veneer material, highlighting the need for further process optimization. Among formulations, PLG displays the highest average strength (MOR) but also exhibits considerable variability (~35%), compared to PF (~12%) and PTG (~12%). The increased variability in PLG panels is primarily related to the intrinsic properties of lignin-based adhesives. Depolymerized lignin contains fragments with diverse molecular weights and reactive site densities, resulting in inconsistent curing across the panel matrix. This molecular heterogeneity influences bond formation uniformity between wood strands, as smaller lignin fragments penetrate wood tissue at varying depths, leading to irregular adhesive distribution and mechanical performance within panels. Furthermore, the lignin-glyoxal cross-linking reaction is characterized by more complex kinetic behavior than the tannin-glyoxal system, contributing to spatial variation in cure completeness.

While variability exists, all formulations show mean MOR values above 20 MPa and MOE around 2000 MPa, meeting or exceeding EN 300 OSB/2 standards (minimum 18 MPa) and demonstrating industrial feasibility [54].

Overall Discussion and Implications

In summary, the use of adhesives did not markedly impact mechanical strength: both MOR and MOE ANOVA results were non-significant, indicating comparable flexural properties among PLG, PTG, and PF panels. Conversely, adhesive type influenced water resistance: PTG panels exhibited substantially lower water absorption than PF panels, with PLG showing intermediate performance. Additionally, all panel types experienced significantly greater thickness swelling after 24 hours compared to 2 hours, regardless of the adhesive employed.

This study effectively demonstrates that industrial veneer-wood residues can be repurposed into high-performance OSB panels using sustainable, formaldehyde-free adhesives. The findings highlight a noteworthy trade-off between two bio-based adhesive systems: the PLG formulation provides superior mechanical strength, while the PTG formulation excels in water resistance. This differentiation supports targeted applications-OSB/PLG panels are recommended for dry, interior structural uses requiring enhanced load-bearing capacity, whereas OSB/PTG panels are preferable for environments susceptible to moisture or elevated humidity [55,56].

The research makes a significant contribution by validating the application of depolymerized Kraft lignin at a high substitution rate (90%) for phenol in OSB production. This approach substantially reduces dependence on petroleum-derived phenol and transforms lignin, an industrial byproduct of low economic value, into a high-performance binder, thereby advancing the principles of circular bioeconomy. Moreover, the complete replacement of carcinogenic formaldehyde with non-toxic glyoxal addresses key health and environmental concerns, enabling manufacturers to comply with rigorous international air quality standards.

By integrating veneer waste, this work presents an environmentally favorable pathway to lower raw wood consumption and foster circular resource utilization within the forest products sector. The demonstrated technical viability provides a robust scientific basis for guiding the wood panel industry toward more sustainable, circular, and health-conscious manufacturing practices. Future research should prioritize optimizing the PLG formulation to improve moisture durability without compromising mechanical integrity, potentially through coupling agents or further chemical modification of lignin.

Conclusions

The development of OSB panels from industrial veneer-wood residues using high-substitution, formaldehyde-free PLG and PTG adhesives has been demonstrated to yield technically viable composites with distinct performance advantages. The PLG formulation achieved flexural strengths nearly equivalent to conventional phenol-formaldehyde panels while valorizing depolymerized lignin as a renewable phenol substitute, thereby maintaining load-bearing capacity without reliance on petrochemicals. Conversely, the PTG panels exhibited superior moisture resistance, evidenced by markedly lower water absorption and thickness swelling, highlighting the capacity of condensed tannins to form a robust, hydrophobic network suited to humid environments. The statistical analysis of the panels' performance validates the development of distinct composites with tailored properties, offering a significant contribution to sustainable manufacturing. A key finding is the clear performance trade-off between the two bio-adhesive systems. The PLG panels exhibited mechanical properties (MOR and MOE) that were statistically comparable to the conventional PF control panels. However, the high-performance variability observed in the PLG formulation suggests that while promising, further optimization is needed to ensure consistent reliability for structural applications. Together, these findings confirm that veneer-waste feedstocks can be transformed into structural OSB products through tailored, non-toxic adhesive systems that meet or exceed established performance benchmarks.

The broader implications of this research offer a clear roadmap for a paradigm shift within the wood panel industry toward more sustainable and health-conscious manufacturing. By demonstrating the potential for application-specific material design, this work moves beyond the search for a single, universal replacement for formaldehyde resins. OSB/PLG panels are ideally suited for dry, load-bearing structural applications such as interior framing, I-joist components, and furniture, where mechanical performance is paramount. In contrast, OSB/PTG panels are suitable for applications demanding durability in humid environments, including wall and roof sheathing, subflooring, and cabinetry in kitchens and bathrooms.

This research provides a prototypical model of the circular bioeconomy in action, establishing a waste-to-value pathway that transforms low-value byproducts into durable goods, thereby reducing landfill pressure, mitigating the consumption of raw timber, and decreasing the industry's reliance on finite petrochemical feedstocks like phenol. Furthermore, the complete replacement of carcinogenic formaldehyde with non-toxic glyoxal directly addresses critical regulatory and market demands, enabling manufacturers to comply with stringent international indoor air quality standards and meet growing consumer preference for healthier building materials.

Beyond validating a sustainable route to OSB manufacture, this work advances circular-economy and indoor-air-quality objectives by replacing carcinogenic formaldehyde with glyoxal while upcycling wood-processing byproducts. The dual-adhesive strategy affords manufacturers the flexibility to match panel properties to end-use requirements-prioritizing mechanical strength or water durability as needed-without sacrificing environmental or health considerations. Future efforts should focus on optimizing the hydrolytic stability of PLG panels, potentially via coupling agents or further lignin modification, and on enhancing the toughness of PTG systems to broaden their structural applicability. By integrating chemical innovation with residue valorization, this research lays a foundation for transitioning wood-panel production toward more sustainable, health-conscious paradigms.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Pablo Lopez-Albarran, Joel A. Sánchez-Badillo, Luis E. Chávez-García, Raúl Espinoza-Herrera

Acquisition, analysis, or interpretation of data: Pablo Lopez-Albarran, Joel A. Sánchez-Badillo, Luis E. Chávez-García, Raúl Espinoza-Herrera

Drafting of the manuscript: Pablo Lopez-Albarran, Joel A. Sánchez-Badillo, Luis E. Chávez-García, Raúl Espinoza-Herrera

Critical review of the manuscript for important intellectual content: Pablo Lopez-Albarran, Joel A. Sánchez-Badillo, Raúl Espinoza-Herrera

Supervision: Pablo Lopez-Albarran, Raúl Espinoza-Herrera

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

References

1. UNEP - UN Environment Programme. Building Materials and the Climate: Constructing a New Future. (2023). Accessed: September 12, 2023: https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future.
2. Lima L, Trindade E, Alencar L, Alencar M, Silva L: Sustainability in the construction industry: A systematic review of the literature. Journal of Cleaner Production. 2021, 289:125730. 10.1016/j.jclepro.2020.125730
3. Pacheco-Torgal F: An introductory overview of bio-based construction materials. Advances in Bio-Based Materials for Construction and Energy Efficiency. 2025, 1-14. 10.1016/B978-0-443-32800-8.00008-1
4. He S, Zhao X, Wang EQ, Chen GS, Chen PY, Hu L: Engineered wood: sustainable technologies and applications. Annual Review of Materials Research. 2023, 53:195-223. 10.1146/annurev-matsci-010622-105440
5. Pizzi A: Advanced Wood Adhesives Technology. Pizzi A (ed): CRC Press, Boca Raton; 1994. 10.1201/9781482293548
6. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 100D. (2025). Accessed: November 14, 2012: https://www.who.int/publications/m/item/iarc-monographs-on-the-evaluation-of-carcinogenic-risks-to-humans-volume-100d.
7. Khoshakhlagh AH, Mohammadzadeh M, Sicard P, Bamel U: Human exposure to formaldehyde and health risk assessment: a 46-year systematic literature review. Environmental Geochemistry and Health. 2024, 46:1-22. 10.1007/s10653-024-02004-4
8. Khoshakhlagh AH, Mohammadzadeh M, Ghobakhloo S, Cheng H, Gruszecka-Kosowska A, Knight J: Health risk assessment from inhalation exposure to indoor formaldehyde: A systematic review and meta-analysis. Journal of Hazardous Materials. 2024, 471:134307. 10.1016/j.jhazmat.2024.134307
9. Salthammer T, Mentese S, Marutzky R: Formaldehyde in the indoor environment. Chemical Reviews. 2010, 110:2536-572. 10.1021/cr800399g
10. Swenberg JA, Moeller BC, Lu K, Rager JE, Fry RC, Starr TB: Formaldehyde carcinogenicity research: 30 years and counting for mode of action, epidemiology, and cancer risk assessment. Toxicologic Pathology. 2013, 41:181-89. 10.1177/0192623312466459
11. Salem MZM, Böhm M: Understanding of formaldehyde emissions from solid wood: an overview. BioResources. 2013, 8:4775-790.
12. Yang Y, Zhang Z, Zhang L, et al.: Recent advances in the control of volatile organic compounds emissions from indoor wood-based panels: A comprehensive review. The Science of The Total Environment. 2023, 884:163741. 10.1016/j.scitotenv.2023.163741
13. Kunič R: Forest-based bioproducts used for construction and its impact on the environmental performance of a building in the whole life cycle. Environmental Footprints and Eco-Design of Products and Processes. Singapore; 2016. 173-204. 10.1007/978-981-10-0655-5_5
14. Arias A, Feijoo G, Moreira MT: New environmental approach based on a combination of planetary boundaries and life cycle assessment in the wood-based bioadhesive market. ACS Sustainable Chemistry & Engineering. 2022, 10:11257-1272. 10.1021/acssuschemeng.2c03058
15. Stewart D: Lignin as a base material for materials applications: Chemistry, application and economics. Industrial Crops and Products. 2008, 27:202. 10.1016/j.indcrop.2007.07.008
16. Mahajan JS, Gottlieb ER, Kim JM, Epps TH: Toward sustainable materials: from lignocellulosic biomass to high-performance polymers. Accounts of Materials Research. 2025, 6:316-26. 10.1021/accountsmr.4c00359
17. Bajwa DS, Pourhashem G, Ullah AH, Bajwa SG: A concise review of current lignin production, applications, products and their environmental impact. Industrial Crops and Products. 2019, 139:111526. 10.1016/j.indcrop.2019.111526
18. Calvo-Flores FG, Dobado JA: Lignin as renewable raw material. ChemSusChem. 2010, 3:1227-235. 10.1002/cssc.201000157
19. Musl O, Galler S, Wurzer G, et al.: High-resolution profiling of the functional heterogeneity of technical lignins. Biomacromolecules. 2022, 23:1413-422. 10.1021/acs.biomac.1c01630
20. Sapouna I, Lawoko M: Deciphering lignin heterogeneity in ball milled softwood: unravelling the synergy between the supramolecular cell wall structure and molecular events. Green Chemistry. 2021, 23:3348-364. 10.1039/d0gc04319b
21. Guo H, Zhao Y, Chang JS, Lee DJ: Lignin to value-added products: Research updates and prospects. Bioresource Technology. 2023, 384:129294. 10.1016/j.biortech.2023.129294
22. Garlapati VK, Chandel AK, Kumar SPJ, Sharma S, Sevda S, Ingle AP, Pant D: Circular economy aspects of lignin: Towards a lignocellulose biorefinery. Renewable and Sustainable Energy Reviews. 2020, 130:109977. 10.1016/j.rser.2020.109977
23. Xu C, Ferdosian F: Conversion of lignin into bio-based chemicals and materials. Springer Berlin, Heidelberg; 2017. 10.1007/978-3-662-54959-9
24. Tian W, Wang X, Ye Y, et al.: Recent progress of biomass in conventional wood adhesives: a review. Green Chemistry. 2023, 25:10304-337. 10.1039/d3gc03441k
25. Mansouri NEE, Yuan Q, Huang F: Study of chemical modification of alkaline lignin by the glyoxylation reaction. BioResources. 2011, 6:4523-536. 10.15376/biores.6.4.4523-4536
26. Sazanov YN, Gribanov A: Thermochemistry of lignin. Russian Journal of Applied Chemistry. 2010, 83:175-94.
27. Němec M, Prokůpek L, Obst V, Pipíška T, Král P, Hýsek Š: Novel kraft-lignin-based adhesives for the

production of particleboards. Composite Structures. 2024, 344:118344. 10.1016/j.compstruct.2024.118344
28. Toledano A, Serrano L, Garcia A, Mondragon I, Labidi J: Comparative study of lignin fractionation by ultrafiltration and selective precipitation. Chemical Engineering Journal. 2010, 157:93-99. 10.1016/j.cej.2009.10.056
29. Azadi P, Inderwildi OR, Farnood R, King DA: Liquid fuels, hydrogen and chemicals from lignin: A critical review. Renewable and Sustainable Energy Reviews. 2013, 21:506-23. 10.1016/j.rser.2012.12.022
30. Yan L, Huertas-Alonso AJ, Liu H, Dai L, Si C, Sipponen MH: Lignin polymerization: towards high-performance materials. Chemical Society Reviews. 2025, 54:6634-651. 10.1039/d4cs01044b
31. Younesi-Kordkheili H, Pizzi A: Properties of plywood panels bonded with ionic liquid-modified lignin-phenol-formaldehyde resin. The Journal of Adhesion. 2017, 94:143-54. 10.1080/00218464.2016.1263945
32. Navarrete P, Mansouri HR, Pizzi A, Tapin-Lingua S, Benjelloun-Mlayah B, Pasch H, Rigolet S: Wood panel adhesives from low molecular mass lignin and tannin without synthetic resins. Journal of Adhesion Science and Technology. 2010, 24:1597-610. 10.1163/016942410x500972
33. Siahkamari M, Debnath D, Wang T, Nejad M: A fundamental study of lignin reactions with formaldehyde and glyoxal. Green Chemistry. 2025, 27:2342-358. 10.1039/d4gc05695g
34. Fazeli M, Mukherjee S, Baniasadi H, et al.: Lignin beyond the status quo: recent and emerging composite applications. Green Chemistry. 2024, 26:593-630. 10.1039/d3gc03154c
35. Dunky M: Natural crosslinkers for naturally-based adhesives. Biobased Adhesives: Sources, Characteristics, and Applications. 2023, 207-54. 10.1002/9781394175406.CH6
36. Hemmilä V, Adamopoulos S, Karlsson O, Kumar A: Development of sustainable bio-adhesives for engineered wood panels - A Review. RSC Advances. 2017, 7:38604-8630. 10.1039/c7ra06598a
37. Younesi-Kordkheili H, Pizzi A: Improving the properties of urea-lignin-glyoxal resin as a wood adhesive by small addition of epoxy. International Journal of Adhesion and Adhesives. 2020, 102:102681. 10.1016/j.ijadhadh.2020.102681
38. Pizzi A: Bioadhesives for wood and fibres. Reviews of Adhesion and Adhesives. 2013, 1:88-113.
39. Pizzi A: Recent developments in eco-efficient bio-based adhesives for wood bonding: opportunities and issues. Journal of Adhesion Science and Technology. 2006, 20:829-46. 10.1163/156856106777638635
40. Sedano-Mendoza M, Lopez-Albarran P, Pizzi A: Natural lignans as adhesives for cellulose: Computational interaction energy vs experimental results. Journal of Adhesion Science and Technology. 2010, 24:1769-786.
41. Li H, Guo X, He Y, Zheng R: A green steam-modified delignification method to prepare low-lignin delignified wood for thick, large highly transparent wood composites. Journal of Materials Research. 2019, 34:932-40.
42. Comath S, Chirakkal A, Shaji A: Lignin-based adhesive bonded veneer composites: a sustainable approach. Green Lignocellulosic-Based Panels. Engineering Materials. Osman Al Edrus SS, Lee SH, Abdul Halip J, Kamaruddin N, Nabilah Haris NI, Md Tahir P (ed): Springer, Singapore; 2025. 89-110. 10.1007/978-981-96-3404-0_4
43. Gonzalez J, Pizzi A: Influence of preparation procedure on pine tannin-based cold-set glulam adhesives. Holz als Roh- und Werkstoff. 1996, 54:389-92. 10.1007/s001070050207
44. Li K, Geng X, Simonsen J, Karchesy J: Novel wood adhesives from condensed tannins and polyethylenimine. International Journal of Adhesion and Adhesives. 2004, 24:327-33. 10.1016/j.ijadhadh.2003.11.004
45. Kumar A, Patil PB, Pinjari D: Eco-friendly adhesives for wood panels: advances in lignin, tannin, protein, and rubber-based solutions. Journal of Adhesion Science and Technology. 2025, 1-42. 10.1080/01694243.2025.2514151
46. Mansouri HR, Navarrete P, Pizzi A, Tapin-Lingua S, Benjelloun-Mlayah B, Pasch H, Rigolet S: Synthetic-resin-free wood panel adhesives from mixed low molecular mass lignin and tannin. European Journal of Wood and Wood Products. 2011, 69:221-29. 10.1007/s00107-010-0423-0
47. Amusant N, Arnould O, Pizzi A, Depres A, Mansouris RH, Bardet S, Baudassé C: Biological properties of an OSB eco-product manufactured from a mixture of durable and non durable species and natural resins. European Journal of Wood and Wood Products. 2009, 67:439-47. 10.1007/s00107-009-0335-z
48. Yu O, Kim KH: Lignin to materials: a focused review on recent novel lignin applications. Applied Sciences. 2020, 10:4626. 10.3390/app10134626
49. Tondi G, Pizzi A: Tannin-based rigid foams: Characterization and modification. Industrial Crops and Products. 2009, 29:356-63. 10.1016/j.indcrop.2008.07.003
50. López-Albarrán P, Pizzi A, Navarro-Santos P, Hernández-Esparza R, Garza J: Oligolignols within lignin-adhesive formulations drive their Young's modulus: A ReaxFF-MD study. International Journal of Adhesion and Adhesives. 2017, 78:227-33. 10.1016/j.ijadhadh.2017.08.003
51. Mansouri NEE, Pizzi A, Salvadó J: Lignin-based wood panel adhesives without formaldehyde. European Journal of Wood and Wood Products. 2007, 65:65-70. 10.1007/s00107-006-0130-z
52. Núñez-Decap M, Friz-Sánchez C, Opazo-Carlsson C, Moya-Rojas B, Vidal-Vega M: A potential replacement to phenol-formaldehyde-based adhesives: a study of plywood panels manufactured with bio-based wood protein and nanolignin adhesives. Forests. 2024, 15:1345. 10.3390/f15081345
53. Shi SQ, Cui Z, Jin Y, Smith L, Wu HF, Neogi A: Fiberboard made from scrap denim: Characterization of its properties by effective bulk modulus elastography. BioResources. 2023, 18:3279-294. 10.15376/biores.18.2.3279-3294
54. CEN (European Committee for Standardization): EN 300:2006 - Oriented Strand Boards (OSB) - Definitions, classification and specifications. CEN, Brussels, Belgium; 2006.
55. Zhen X, Li H, Xu Z, Wang Q, Zhu S, Wang Z, Yuan Z: Facile synthesis of lignin-based epoxy resins with excellent thermal-mechanical performance. International Journal of Biological Macromolecules. 2021, 182:276-85. 10.1016/j.ijbiomac.2021.03.203
56. Ralph J, Lapierre C, Boerjan W: Lignin structure and its engineering. Current Opinion in Biotechnology. 2019, 56:240-49. 10.1016/j.copbio.2019.02.019