Manufacturing of oriented strand board from olive tree pruning residues

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(Received 14 September 2025)

Abstract: This study investigated the feasibility of manufacturing eco-friendly flakeboard from olive tree pruning residues using three concentrations of a tannin-formaldehyde adhesive, where the condensed tannin was extracted from pomegranate peels. The research evaluated the effects of adhesive concentration (11%, 12%, and 13%) on the physical and mechanical properties of panels to verify their compliance with European standards. Panels were tested for moisture content, density, water absorption, thickness swelling, modulus of rupture (MOR), internal bond (IB) strength, and screw withdrawal resistance. While moisture content and density were not significantly affected by adhesive ratio, water absorption and thickness swelling after 24 h decreased significantly with higher resin content. Mechanically, the 13% adhesive sample exhibited superior performance, achieving the highest values for MOR (18.8 MPa), IB strength (0.61 MPa), and screw withdrawal resistance (680 N), representing improvements of 7%–10%, 16%, and 10%, respectively, over panels with the lower resin content. All produced panels met the relevant European standard specifications. The results showed that olive tree pruning waste can be successfully valorized to produce sustainable oriented strand board (OSB) panels using a bio-based tannin-formaldehyde adhesive. The panels, which also feature an attractive natural appearance, are suitable for applications in furniture manufacturing, interior cladding, and structural uses, offering a promising solution to reduce reliance on synthetic adhesives and minimizing agricultural waste.

Keywords: Olive tree waste; Flakeboard; Tannin-formaldehyde adhesive; Pomegranate peels; Mechanical properties; European standards; Sustainable manufacturing.

Introduction

The manufacturing of composite panels relies on the use of industrial adhesives such as urea-formaldehyde (UF), phenol-formaldehyde (PF), or melamine-urea-formaldehyde (MUF) at rates ranging from 10% to 18%, relative to the dry wood material (Pizzi et al., 1994). The global production and consumption of engineered wood materials have seen a steady upward trend. For instance, global particleboard production reached 96 million cubic meters in 2020 (FAOSTAT 2022). However, this growth has been accompanied by the persistent problem of formaldehyde (HCHO) emissions from products bonded with synthetic adhesives, particularly those containing UF resin (Roffael 1982, 1993). The health risks associated with these emissions, which include irritation of mucous membranes and increased cancer risk, prompted significant regulatory action, most notably the California Air Resources Board's (CARB) Airborne Toxic Control Measure (ATCM) in 2009 (CARB 2009). This ruling established stringent formaldehyde emission limits for composite wood products, effectively setting a new, stricter standard that had a global impact on manufacturing practices.

At the industrial level, formaldehyde is emitted into the factory air during drying and pressing processes, exposing workers to harmful health effects, such as inflammation of the mucous membranes, eye irritation, an increased risk of cancer, and detrimental effects on the central nervous system (Tappler et al. 2008). These harmful effects occur at formaldehyde concentrations exceeding 0.1 parts per million (ppm), equivalent to 0.12 mg/m³ (Roffael 1982; Tappler et al. 2008; Rader, 1974).

At the domestic level, formaldehyde is emitted from furniture and building materials made from a variety of engineered wood products. These include particleboard, medium-density fiberboard (MDF), laminated veneer lumber (LVL), and oriented strand board (OSB). Emissions can be particularly pronounced during winter when colder temperatures reduce ventilation and

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Wood and Fiber Science, 58(2), 2026, pp. 82–90
https://doi.org/10.22382/wfs-2026-09

air-exchange rates in homes. Formaldehyde levels exceeding 0.1 ppm may be associated with acute health effects like eye inflammation, as well as chronic risks including cancer and adverse effects on the central nervous system (Roffael 1982; Tappler et al. 2008; Hameed et al. 2007; Rader 1974).

These risks have prompted researchers to develop formaldehyde scavengers, such as melamine and resorcinol, formaldehyde-free industrial adhesives, like polymerized diphenylmethane diisocyanate (pMDI) or natural adhesives derived from polyphenols, such as tannin-formaldehyde resin (TF-resin) (Roffael 1981). These risks have also prompted researchers to develop alternative adhesive systems. Among the most promising are bio-based adhesives, such as tannin-formaldehyde (TF) resins, which can be synthesized from condensed tannins extracted from renewable agricultural wastes like tree barks, prunings, and fruit peels (Pizzi 2006). While the potential of TF-resins is established in some engineered wood products like particleboard, their application in OSB remains relatively unexplored, particularly when using a combined system of non-wood strands and a non-conventional tannin source. Therefore, this study investigates the feasibility of manufacturing OSB panels from olive tree pruning residues using a novel TF-resin, where the condensed tannin is extracted from pomegranate peels. This approach directly addresses the dual challenge of reducing reliance on synthetic formaldehyde-based adhesives and valorizing agricultural waste streams.

The use of alternative raw materials, such as agricultural biomass and recycled wood waste, aligns with the principles of the circular economy and represents a promising avenue for diversifying the raw material base for wood-based panels (Lee et al. 2022). While much of the research in this area has focused on particleboard, the feasibility of applying these materials to OSB requires specific consideration. The production of high-quality, engineered flakes suitable for OSB is more challenging than producing particles for particleboard, as it demands longer strands with a specific geometry to ensure effective orientation and mechanical performance. Therefore, a key objective of this study was to evaluate whether olive tree pruning residues could be technically processed into viable flakes and successfully utilized in OSB production, thereby testing the boundaries of agricultural biomass for higher-value structural composites.

Several recent studies have established the viability of agricultural waste for wood panel manufacturing, demonstrating that various pruning residues can serve as effective raw materials. Wong et al. (2020) showed that incorporating 10% grapevine prunings with 90% pine produced hybrid panels with excellent mechanical properties and improved density, reducing dependence on natural wood while lowering carbon emissions. Complementing this, Şahin (2020) found that panels with 30% grapevine pruning residues met European standard specifications, and that increasing urea-formaldehyde resin content from 10% to 12% enhanced durability while maintaining suitable mechanical and physical properties. These findings collectively validate the approach of using woody, non-traditional biomass in panel production and directly support our hypothesis that olive tree prunings—a similar agricultural waste—possess suitable structural characteristics for engineered wood panels. Furthermore, these studies confirm the importance of resin content optimization, which informed our experimental design to test tannin-formaldehyde adhesive at 11%, 12%, and 13% concentrations for manufacturing panels from olive pruning residues.

In another study, Özlüsoylu (2023) successfully produced low-density wood panels from recycled wood bark using adhesive mixtures of varying densities. Subsequently, the panels were coated with three types of varnish (water-based, polyurethane, oil/wax) to study their effects on surface properties. Results showed that the oil/wax varnish yielded the highest roughness values and greatest color change, while water-based and polyurethane varnishes produced smoother and glossier surfaces, especially in high-density panels (420 kg/m^3). The study concluded that using a higher density (420 kg/m^3) with 4% adhesive content provides the best results in terms of smoothness and gloss, making it the optimal choice for applications requiring high surface quality.

Research by Ferrández-García et al. (2022) presents a method to transform olive tree pruning waste into adhesive-free eco-boards via hot pressing. The effects of leaf type (whole/shredded), temperature (130–150°C), and pressing time (4–12 min) on board properties were analyzed. The boards exhibited low water uptake, high thermal insulation, and enhanced mechanical performance with optimized processing conditions. This study is highly relevant to our work, as it confirms the fundamental suitability of olive tree pruning residues as a raw material for panel production. However, while Ferrández-García et al. (2022) focused on binderless boards for specific properties, our research explores a different pathway: utilizing these residues as a substitute for conventional wood flakes in structural OSB, which requires the addition of an adhesive to achieve the necessary mechanical strength for load-bearing applications. This comparison highlights the versatility of olive pruning waste and the novelty of our approach in targeting a different product segment.

In the work by Chia-Ju Lee et al. (2021), a formaldehyde-free tannin-based adhesive (AcBTanGlu) for the production of oriented bamboo scrimber board (OBSB) is presented. The scientific novelty of their work lies in the demonstration that this adhesive not only eliminates harmful emissions but also surpasses traditional synthetic resins in key performance indicators: mechanical strength, dynamic modulus of elasticity (MOE), and dimensional stability.

Wenjing Hu et al. (2025) proposed a method of photocatalytic degradation to reduce the mean degree of polymerization (mDP) of larch tannins, which solves the problem of high viscosity and low strength of tannin-based adhesives. The resulting modified tannin, with a formaldehyde mass fraction of only 10%, enabled the creation of an adhesive that meets strength and water resistance standards while minimizing formaldehyde emission.

Collectively, the literature demonstrates a clear trend toward utilizing agricultural residues and developing bio-based adhesives to mitigate the environmental impact of wood-based panels. Building upon these insights, particularly the proven suitability of olive tree pruning residues as a raw material and the successful use of condensed tannins as a resinous component, this research aims to bridge a specific knowledge gap. Therefore, this study investigates the feasibility of manufacturing eco-friendly OSB by combining two underutilized waste streams: using strands from olive tree pruning residues bonded with a tannin-formaldehyde adhesive, where the condensed tannin is extracted from pomegranate peels.

The specific objectives of this study were to evaluate the potential of utilizing olive tree pruning residues in combination with a tannin-based adhesive for panel production by

- Quantifying the effect of three condensed tannin-adhesive concentrations (11%, 12%, and 13%) on the physical, mechanical, and hygroscopic properties of the manufactured panels.
- Verifying compliance of the panel properties with relevant European technical standards to assess their suitability for commercial applications.
- Providing a sustainable environmental solution based on the simultaneous valorization of agricultural waste streams—olive tree prunings and pomegranate peels—and reducing reliance on conventional synthetic adhesives.
- Contributing to the development of an environmentally conscious wood composite industry that aligns with circular economy principles without compromising product quality and performance.

Materials and methods

Dried pomegranate peels (*Punica granatum* L.) were obtained as agricultural waste from local fruit processing facilities in Alanya, Türkiye. The raw material was processed using a Fritsch Pulverisette 19 laboratory cutting mill (Fritsch GmbH, Türkiye) equipped with a 1.0 mm sieve to achieve consistent particle size distribution. For extraction, 1 kg of the resulting powder was mixed with 12 L of distilled water preheated to 87°C (±2°C) in a temperature-controlled reactor (Isılab ISI-90, Türkiye). The suspension was maintained under continuous mechanical stirring at 200 rpm for precisely 75 min using an Hei-TORQUE Precision 100 overhead stirrer (Heidolph, Türkiye)—with parameters previously optimized through response surface methodology to maximize tannin yield from this specific biomass source. Following extraction, the mixture was cooled to ambient temperature (23±2°C) and sequentially filtered through Whatman No. 1 filter paper, followed by a 0.45 μm membrane filter.

The clarified filtrate was immediately concentrated using an IKA RV 10 rotary evaporator (IKA, Türkiye) at 55°C (±5°C) under reduced pressure (100–150 mbar) until reaching a total solids content of 42.5% (±2.5%), as determined by gravimetric analysis using a Precisa XR 205SM-DR analytical balance (Precisa, Türkiye). The mild temperature conditions were specifically maintained to prevent thermal degradation of polyphenolic compounds, while ensuring efficient solvent removal. The concentrated tannin extract was stabilized with 0.1% sodium metabisulfite and stored at 4°C in amber glass containers with nitrogen headspace until resin synthesis.

Resin synthesis

The concentrated tannin extract (42.5% ± 2.5% solids content) was transferred into a three-necked round-bottom flask (Jsil Glasstek, China) equipped with a mechanical stirrer (IKA RW 20 digital, IKA China), reflux condenser, and digital thermometer. For resin formulation, 35 g of paraformaldehyde (95% purity, Merck China) and 80 g of urea (ACS reagent, Sigma-Aldrich China) were added sequentially to 200 g of tannin extract under continuous stirring at 300 rpm. The reaction mixture was gradually heated to 83°C (±2°C) using a programmable heating mantle (Heidolph, China) to ensure complete reagent dissolution and initiate the polycondensation reaction between tannin, urea, and formaldehyde components.

The reaction was maintained at 82–85°C for 150 min (±15 min) under reflux conditions. Reaction progress was monitored through periodic viscosity measurements using a Brookfield DV2T viscometer (Brookfield China) with RV-06 spindle at 20 rpm. Polymerization was considered complete when the dynamic viscosity reached 450–550 mPa·s, corresponding to a homogeneous, viscous syrup-like consistency suitable for strand coating and subsequent hot-press curing. The resulting tannin-urea-formaldehyde (TUF) resin was immediately cooled to 25°C (±3°C) in a water bath and stored in sealed HDPE containers (Nalgene China) at 4°C for subsequent panel manufacturing within 24 hours.

Wood preparation

Olive tree branches (*Olea europaea*) were collected from agricultural pruning operations in the Mediterranean region of Turkey. Selected branches measuring 80–200 mm in length, with straight grain and minimal knots, were processed into strands using a laboratory-scale rotary lathe (Pallmann, China). The strands were precision-cut to dimensions of 70–120 mm in length and 1.0–2.0 mm in thickness, with a target width of approximately 15 mm. The resulting strands were then conditioned in a forced-air drying oven (Memmert, China) at 40°C for 24 h to achieve a uniform moisture content of 5.0% (±0.5%) as verified by a moisture analyzer (Sartorius, China). This strand geometry and moisture content were selected to optimize both resin adhesion and panel formation characteristics during panel manufacturing.

Panel manufacturing

The process of manufacturing prototype panels from olive tree pruning strands using a tannin-urea-formaldehyde (TUF) adhesive was conducted with reference to the German standard DIN-T 60 (1999) for wood-based panels. Strands were resinated using an industrial-scale pneumatic spray system (SATA, China) with a 1.3 mm nozzle diameter at 3.5 bar pressure, applying adhesive for 90 s with continuous mechanical mixing to ensure uniform distribution. The strands were sprayed with 11%, 12%, and 13% TUF resin content (based on dry wood weight), achieving consistent resin coverage without strand surface saturation.

The resinated strands (2.6 kg per panel) were manually formed into a single-layer mat within a forming frame (430 × 430 × 300 mm) placed on a caul plate. The mat was pre-pressed at 0.5 MPa for 30 s using a wooden platen to facilitate handling. Hot-pressing was conducted in a laboratory hydraulic press (Carver, China) at 170°C for 7 min under 3.5 MPa pressure, using 16-mm thick metal stops to control panel thickness. After 24-h conditioning at 20°C and 65% RH, panels were trimmed to final dimensions of 410 × 410 × 16 mm. Three replicate panels were manufactured for each resin concentration, totaling nine experimental panels (Figure 1).

The panels were cut into sections appropriate for assessing moisture content according to standard EN 322 (1993), density according to standard EN 323 (1993), water absorption capacity after 24 h according to standard DIN EN 322 (1993-08), and thickness swelling after 24 h of water immersion according to standard EN 317 (1993; Table 1, Figure 2).

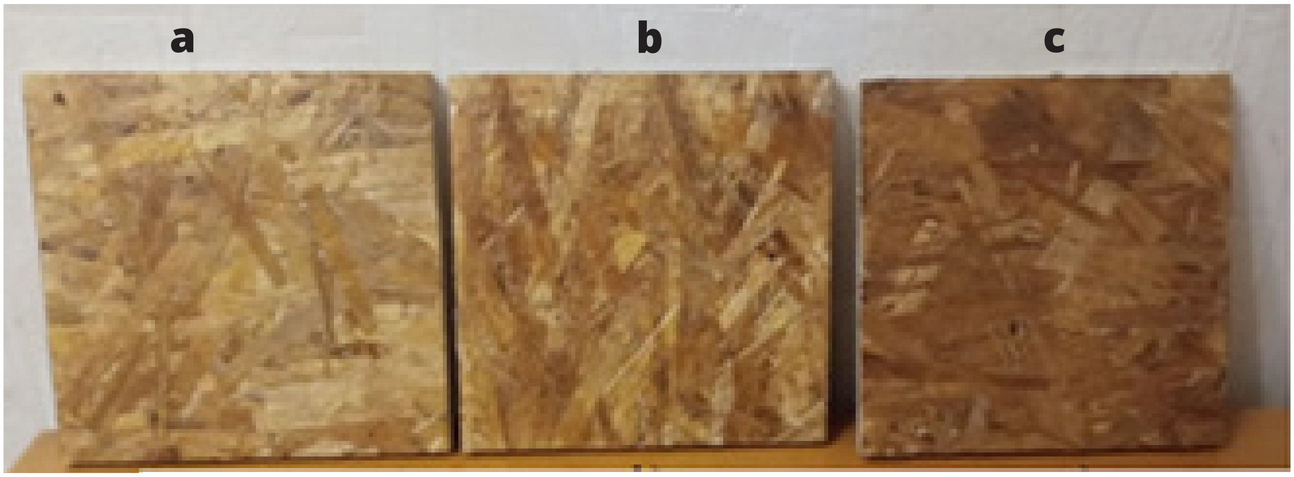

Figure 1. Examples of wood panels constructed using (a) 11%, (b), 12%, and (c) 13% condensed tannin adhesive.

Table 1. Dimensions and replicates used to evaluate various panel properties.

Property measured	Specimen dimensions	Replicates	Test method
Moisture content	50 × 50 × 16	3/panel	EN 322 (1993)
Density	50 × 50 × 16	3/panel	EN 323 (1993)
24 h water absorption	50 × 50 × 16	3/panel	EN 317 (1993)
24 h Swelling	50 × 50 × 16	3/panel	EN 317 (1993)
Flexural properties	250 × 50 × 16	3/panel	EN 310 (1993)
Internal bond strength	50 × 50 × 16	3/panel	EN319 (1993)
Screw withdrawal capacity	150 × 50 × 16	3/panel	EN 319 (1993)

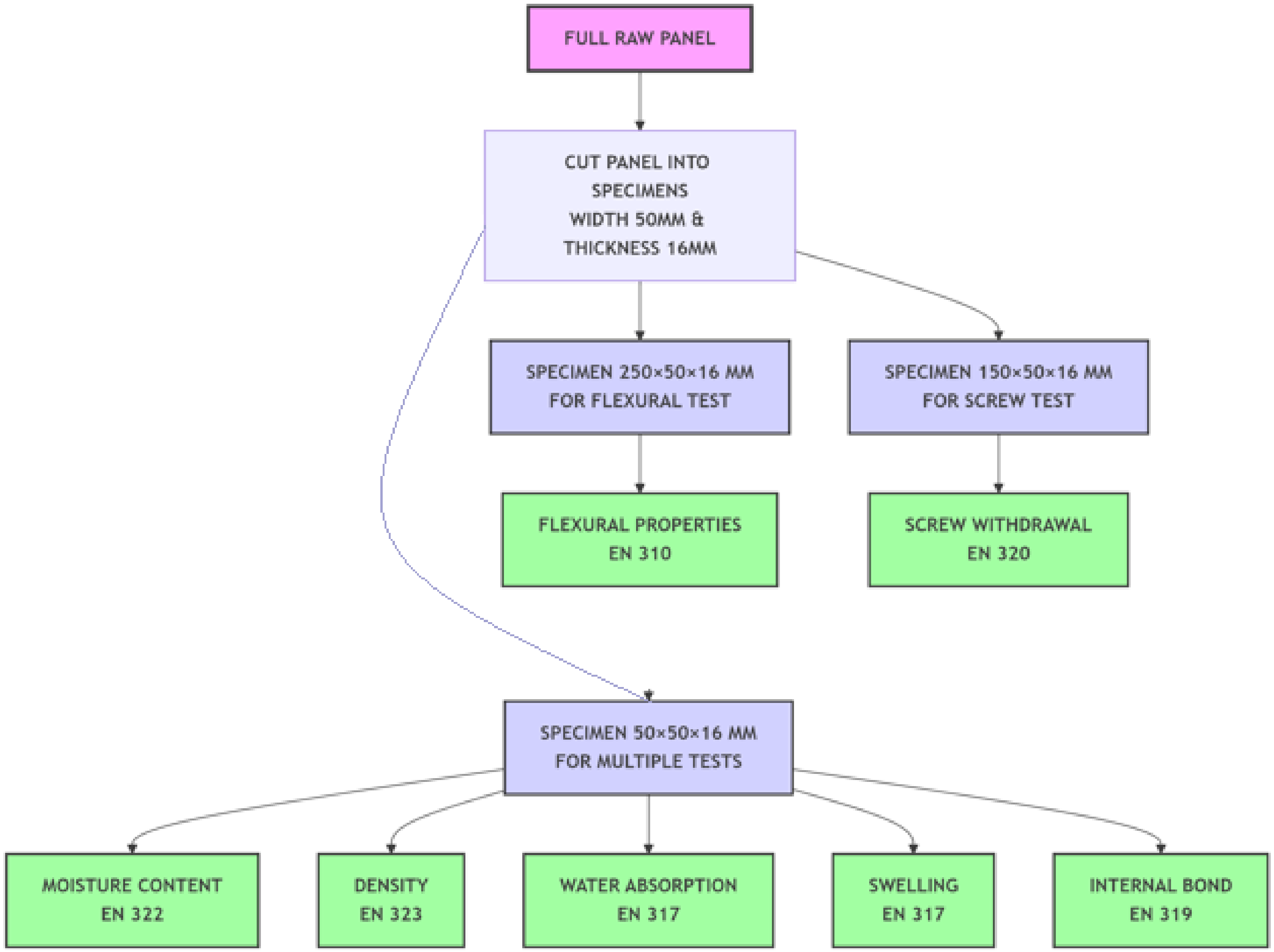

Figure 2. Cutting scheme and testing protocol for wood-based panels according to European standards (EN).

Flexural properties testing

Panel flexural properties were evaluated using a Universal Testing Machine (Jinan Testing Equipment IE-5020, China) equipped with a 10 kN load cell. Testing was performed according to EN 310 (1993) standard employing a three-point bending configuration with a 200-mm span length. Specimens were loaded to failure at a constant crosshead speed of 5 mm/min.

Load-deflection data were continuously recorded at 10 Hz sampling frequency through the machine's integrated data acquisition system. The modulus of rupture (MOR) was calculated from the maximum load at failure, while the MOE was determined from the slope of the initial linear portion of the load-deflection curve (specifically between 10% and 40% of maximum load). Three replicate specimens were tested from each of the three panels for every resin concentration, yielding a total of nine measurements per resin treatment for both MOR and MOE.

The MOR and MOE values were calculated using the following equations from the standard EN 310 (1993):

$$MOR = (3 \times F_{max} \times L)/(2 \times b \times h^2) \quad [1]$$

$$MOE = (L^3 \times \Delta F)/(4 \times b \times h^3 \times \Delta y) \quad [2]$$

Where: F_{max} = maximum load (N); L = span length (mm); b = specimen width (mm); h = specimen thickness (mm); ΔF = load increment in the elastic region (N); and Δy = deflection increment corresponding to ΔF (mm).

Internal bond strength (IB) was assessed by gluing blocks to the face of each panel and pulling the section apart at a rate of 0.5 mm/min. Maximum load at failure was recorded as IB. Three samples were tested from each of the three panels for each resin concentration.

Screw withdrawal tests were performed by inserting a 3.5 mm diameter by 40 mm long screw to a depth of 15 mm into the panel. The screw was then inserted into a specially designed apparatus that applied the load while constraining the panel. The load at failure was recorded. Three samples were tested from each of the three panels for each resin concentration.

All statistical analyses were conducted using R software version 4.3.1 (Beijing R Foundation for Statistical Computing, China) with the following packages: tidyverse (version 2.0.0) for data manipulation and visualization, car (version 3.1-2) for ANOVA assumptions testing, and agricolae (version 1.3-7) for post-hoc comparisons. The data were subjected to a one-way analysis of variance (ANOVA) at $\alpha = 0.05$ significance level to determine the effects of tannin-adhesive concentration (11%, 12%, 13%) on all measured panel properties.

Prior to ANOVA, data normality was verified using Shapiro-Wilk tests ($p > 0.05$) and homogeneity of variances was confirmed with Levene's tests ($p > 0.05$). When ANOVA indicated significant main effects, means were separated using Tukey's Honest Significant Difference (HSD) test at $\alpha = 0.05$. All results are presented as mean ± standard deviation based on nine replicates per treatment group (three specimens from each of three panels per resin concentration).

Results and discussion

Panels were increasingly darker with increased resin content, but appeared similar otherwise (Figure 1).

Physical properties

Moisture content

The moisture content of all panels after pressing ranged from 6.76% to 6.77%, meeting the requirement of the European Standard DIN-T-60 (1999), which specifies a maximum moisture content of 12% for wood-based panels. Statistical analysis confirmed that adhesive concentration had no significant effect on moisture content ($F = 0.011$, $p = 0.989$), which reflects the consistent initial moisture content of the resinated strands (11%) and the standardized pressing conditions applied to all panels. (Tables 2, 3).

Density

Densities were slightly below the EN 323 (1993) standard (0.80 g/cm^3), but there was no significant effect of resin concentration (Tables 1, 2). The slightly lower density may reflect the characteristics of the pruned material, which contained more internal voids. Branch wood in olives is typically denser than stem wood, owing to slower growth rates. Higher pressing pressure might have improved this property, although this would have resulted in a thinner panel. The use of a thicker mat coupled with higher pressing pressures would likely be necessary to utilize these materials.

Water absorption

Resin concentration demonstrated a highly significant effect on both 24-h water absorption ($F(2, 33) = 50713$, $p < 0.0001$) and thickness swelling ($F(2, 33) = 10962$, $p < 0.0001$). Increased resin content from 11% to 13% resulted in a progressive decrease in both properties, with water absorption declining

Table 2. Effect of different levels of a tannin-formaldehyde resin on physical properties of oriented strand board panels[a].

Adhesive concentration	Moisture content (%)	Density (g/cm³)	Water absorption 24h (%)	Thickness swelling 24h (%)
11%	6.760 ± 0.15	0.7558 ± 0.008	68.93 ± 0.52	15.88 ±0.41
12%	6.764 ± 0.14	0.7561 ± 0.007	67.90 ± 0.48	15.05 ±0.36
13%	6.766 ± 0.13	0.7563 ± 0.006	66.36 ± 0.44	14.46 ±0.39

[a] Values represent means of nine replicates per adhesive concentration plus or minus one standard deviation

Table 3. Analyses of variance examining the effects of adhesive concentration on panel moisture content, density, 24-h water absorption, and thickness swell.

	Effect	SS	Df	MS	F	P
Moisture content	Type	0.000	2	0.000	0	0.457
	Error	0.012	33	0.000		
Density	Type	0.000	2	0.000	0	0.875
	Error	0.00019	33	0.00001		
24-h water absorption	Type	40.1	3	20.0	50713	<0.0001
	Error	0	33	0		
Thickness swell	Type	12.213	2	6.107	10962	<0.0001

from 68.93% to 66.36% and thickness swelling reducing from 15.88% to 14.46%. These improved hygroscopic properties reflect enhanced strand coating and more complete coverage at higher resin levels, which creates a more effective barrier against water penetration and improves interfacial bonding between strands. The results align with established principles of composite wood panel behavior, where increased resin content typically enhances dimensional stability through improved matrix formation and reduced capillary water uptake (Lelis 1992).

Mechanical properties

The mechanical properties demonstrated significant improvement with increasing resin content. The MOR increased from 17.10 MPa to 18.80 MPa, while the MOE rose from 3750 MPa to 4180 MPa as the resin concentration increased from 11% to 13%. One-way ANOVA confirmed that resin content had a statistically significant effect on both MOR ($F(2, 24) = 22.85$, $p < 0.001$) and MOE ($F(2, 24) = 15.12$, $p = 0.0003$).

Similarly, IB strength significantly improved with increased resin content ($F(2, 24) = 18.90$, $p < 0.001$), rising from 0.52 MPa to 0.61 MPa, reflecting enhanced inter-strand bonding through more complete surface coverage and improved adhesive bridging.

Screw withdrawal resistance also showed statistically significant improvement with higher resin content ($F(2, 24) = 25.45$, $p < 0.001$), increasing from 615 N to 680 N. This improvement occurred despite the absence of significant density variation among panels, indicating that enhanced resin-strand interactions and improved matrix cohesive strength—rather than bulk density—contributed to better resistance against lateral forces during screw insertion and withdrawal.

Table 4. Effect of resin concentration on modulus of rupture (MOR), internal bond strength (IB) and screw withdrawal resistance of oriented strand board.[a]

Resin concentration	Modulus of rupture (MPa)	Internal bond strength (MPa)	Screw withdrawal resistance (N)
11%	17.10 ±0.45	0.52 ±0.03	615 ± 12
12%	17.60 ±0.38	0.55 ±0.02	635 ± 10
13%	18.80 ±0.42	0.61 ±0.03	680 ± 14

[a] Values represent means of nine samples per resin concentration plus or minus one standard deviation.

Detailed statistical results

Tukey's multiple comparisons test

Tukey's test revealed that differences between all resin content levels (11%, 12%, 13%) were statistically significant ($p < 0.05$) for all tested mechanical properties, confirming a gradual and continuous performance improvement with each increase in resin content.

These results confirm that increasing the tannin-formaldehyde resin content leads to statistically significant improvements in all mechanical properties of panels manufactured from olive tree pruning residues.

Table 5. Analysis of variance and mean values of mechanical properties of experimental panels manufactured with different tannin-formaldehyde resin concentrations.

Property	F-value	Degrees of freedom	P-value	Statistical significance
MOR	22.85	(2, 24)	<0.001	Significant
MOE	15.12	(2, 24)	0.0003	Significant
IB	18.90	(2, 24)	<0.001	Significant
Screw withdrawal	25.45	(2, 24)	<0.001	Significant

Conclusions

Oriented strand board panels produced from olive branch prunings were fully compliant with relevant European standards. Increased resin content produced significant improvements in water absorption, swelling, IB, and screw withdrawal resistance. Panel appearance, coupled with panel properties would make these materials highly suitable for a variety of applications, including furniture manufacturing, interior wall cladding for halls and auditoriums, and interior structural applications.

Single-layer panels manufactured from olive tree pruning strands using a tannin-urea-formaldehyde adhesive derived from pomegranate peels demonstrated compliance with key European standard requirements for wood-based panels. Statistically significant improvements ($p < 0.05$) were observed in critical performance properties with increasing resin content from 11% to 13%: 24-h thickness swelling decreased by 9.0%, IB strength increased by 17.3%, and screw withdrawal resistance improved by 10.6%.

The enhanced mechanical performance, coupled with the aesthetically pleasing natural appearance of the panels, suggests strong potential for commercial applications in furniture manufacturing, interior wall cladding for architectural spaces, and non-structural interior applications. The successful valorization of two agricultural waste streams—olive tree prunings and pomegranate peels—provides a sustainable manufacturing pathway that reduces dependence on conventional wood resources and synthetic formaldehyde-based adhesives, supporting circular economy principles in the composite panel industry.

Recommendations

Based on the findings of this study, it is recommended to adopt the 13% tannin-formaldehyde resin concentration for manufacturing panels from olive tree pruning residues, as it demonstrated superior mechanical performance and dimensional stability. Future research should focus on developing multi-layer panel structures to meet standard OSB specifications and exploring formaldehyde-free cross-linkers to enhance the environmental profile. Further investigation into the long-term durability and economic feasibility of this approach is essential for commercial implementation.

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