Effects of Adhesives on the Physical and Mechanical Properties of Chip Block Pallets from Mixed Forest Group Wood Biomass

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The rapid development of the manufacturing industry has increased the demand for sustainable and efficient logistics solutions. Chip block pallets (CBPs) made from mixed forest group sawdust offer a promising alternative to traditional pallets due to their reliance on lower-cost, renewable materials. This study aims to evaluate the effects of different adhesives, phenol-formaldehyde (PF), urea-formaldehyde (UF), and poly-urea-formaldehyde (PUF), and varying pressing times on the physical and mechanical properties of CBPs. The CBPs were produced using 30, 60, and 90 min pressing times at 180 °C. The results showed that PF demonstrated the highest compressive strength (6.93 MPa) and screw-holding strength (343 N), making it suitable for applications requiring high mechanical performance. The PUF exhibited lower mechanical strength but provided significant environmental advantages with reduced formaldehyde emissions. Meanwhile, UF displayed adequate performance at shorter pressing durations but decreased efficiency with prolonged pressing. Optimal results were achieved at a pressing time of 60 min, which improved physical and mechanical properties while minimizing water absorption. These findings highlight the potential of CBPs as an eco-friendly and effective alternative, with adhesive and pressing parameters tailored to meet specific application requirements.

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INTRODUCTION

The rapid growth of the manufacturing industry has increased the demand for safe and efficient logistics solutions, particularly in the global packaging, storage, and distribution of products. Pallets are platforms or bases for goods. They are typically found in containers as a foundation for transporting items. Pallets play a key role in safely and efficiently transporting goods with the help of machinery such as forklifts (Bilbao *et al.* 2011; Handoko *et al.* 2021; Khan *et al.* 2021). The global market for pallets in 2023 was valued at US$ 632 billion and is projected to reach US$ 925 billion by 2032 (IMARC 2023). Therefore, pallets will consequently become higher in demand.

Pallets are manufactured from various materials, including solid wood, plastic, and metal. However, the use of solid wood is limited due to the shortage of natural forest wood and the low quality of plantation wood. Pallets made from plastic and metal also face significant challenges related to environmental impacts, such as the difficulty of recycling plastic and the high energy consumption in metal pallet production. As an alternative, wood waste, such as sawdust and residual wood particles from the furniture industry, has significant potential to be utilized in producing chip block pallets (CBP). Chip blocks are engineered wood components used as key structural parts in pallet assemblies, replacing traditional solid wood blocks while maintaining the necessary load-bearing capacity. Unlike oriented strand board (OSB) or particleboard, which primarily consist of thin strands or uniform particles, CBPs are made from a mixture of wood chips, particles, and sawdust, thereby achieving a balance of mechanical strength and cost efficiency (Morris 2017; Maryudi *et al.* 2020; Sambe *et al.* 2021).

Research has shown that CBPs made from teak wood waste can possess physical and mechanical properties that meet the standards of the National Wooden Pallet and Container Association (NWPCA) 2014, such as compressive strength of up to 11.2 MPa and screw holding strength of 337 N, with an optimal polyurethane adhesive content of 4.5% (Hermawan *et al.* 2024). In addition to their mechanical properties, CBPs made from teak wood have demonstrated good resistance to subterranean termite attack, although they remain susceptible to white-rot and brown-rot fungi (Damanik *et al.* 2023). In contrast, other wood waste materials, such as mixed forest wood produced in Indonesia, also offer significant potential as a raw material for CBPs. In 2023, mixed forest wood production accounted for 45.3% of total national output, or approximately 30.9 million m^3 ([BPS] Badan Pusat Statistik Indonesia 2024). With such abundant availability, mixed forest wood waste can serve as an alternative raw material that supports the development of more sustainable CBPs.

The development of CBPs faces challenges in selecting the appropriate adhesive. The industry has traditionally relied on formaldehyde-based adhesives, such as Urea Formaldehyde (UF) and Phenol-Formaldehyde (PF), which are known for their strength but release formaldehyde—a volatile organic compound harmful to human health and the environment (Böhm *et al.* 2012; Bekhta *et al.* 2014; Salthammer 2019; Kristak *et al.* 2023). In response to the growing awareness of the importance of sustainable and environmentally friendly industrial practices, developing adhesives with a lower formaldehyde-to-urea (F/U) molar ratio has emerged as a potential solution. Researchers have developed low-molar adhesives with F/U ratios ranging from 0.9 to 1.0 (de Jong and de Jonge 1952; Chiavarini *et al.* 1978; Yadav *et al.* 2021) and F/U 0.8 (Lubis *et al.* 2022). However, these low-molar adhesives have primarily been applied to plywood, necessitating further evaluation of their performance in CBP applications.

Previous studies have focused on CBPs made from single wood species. This study explores the potential of mixed forest wood biomass, which is more abundant and sustainable in Indonesia. Additionally, while prior research has evaluated the effects of adhesives on plywood or particleboard, limited studies have analyzed how different formaldehyde-based adhesives (UF, PF, and PUF) affect the physical and mechanical properties of CBPs. This work employed three kinds of adhesives to satisfy different application needs for pallets—both exterior and interior. As is well known, PF is used for exterior applications, whereas UF is used for interior ones. According to research trends, PUF is widely studied as a low formaldehyde emission adhesive that exhibits moderate properties between UF and PF. With each type of adhesive having unique properties, the

ideal conditions for producing CBPs from mixed forest wood biomass offer a variety of options based on requirements. This research also investigated the influence of pressing time (30, 60, and 90 min) on CBP quality, which has not been extensively studied in prior works. This study hypothesizes that PUF adhesive will provide optimal performance in CBPs due to its enhanced balance of mechanical strength and reduced formaldehyde emissions, making it a more sustainable alternative to UF and PF. Furthermore, increasing pressing time is expected to improve CBP performance, with longer pressing durations (90 minutes) enhancing mechanical properties and reducing void formation, leading to better bonding and water resistance. The findings aim to identify the optimal adhesive and processing parameters to enhance CBP performance, thereby contributing to the sustainable production of engineered wood pallets.

EXPERIMENTAL

Raw Material Preparation

Mixed forest group wood biomass, such as chips, particles, and sawdust, which was obtained from the sawmill of PT. Timber Dana (East Kalimantan, Indonesia), was used as the raw material. The method of material preparation refers to (Damanik *et al.* 2023; Hermawan *et al.* 2024). The materials were separated into two particle size categories: namely coarse (4 to 14 mesh) and powder (>60 mesh), then oven-dried at 80 °C until the moisture content (MC) was reduced to 5%. The adhesive resins used were poly-urea-formaldehyde (PUF) (Lubis *et al.* 2022), phenol-formaldehyde (PF), and urea-formaldehyde (UF) from PT Dover Chemical.

Adhesive Characterization

The adhesives' characteristics that were evaluated included solid content, gelation time, pH, and viscosity.

Solid content

The solids content of the adhesive indicates the amount of adhesive particles. The stronger the adhesive bond, the more particles will react with the wood in the bonding process. One gram of adhesive was added to aluminum foil and placed in an oven (Memmert, Germany) at 103 ± 3 °C for 3 h. After drying, the aluminum foil was moved to a desiccator and weighed. The solid content was calculated using the formula:

$$\text{Solid Content (\%)} = (\text{Oven-dry weight} / \text{Initial weight}) \times 100 \quad (1)$$

Gelation time

The gel time test method refers to Sutiawan *et al.* (2023) and SNI 06-4567-1998 (BSN 1998). The adhesive was placed in a test tube to evaluate the gelation time. A gelation timer (Techne GT-6, Coleparmer, Vernon, IL, USA) was positioned to immerse the needle into the sample. Dimethyl sulfoxide (DMSO) was used in a water bath, raising the temperature to 135 °C. The time required for the adhesive to become gelatinous was observed. The gelation time was recorded automatically when the timer stopped, showing the gelation time on the display.

Viscosity

Approximately 20 mL of adhesive sample was poured into a cup and placed on a rotational rheometer (RheolabQC, AntonPaar, Graz, Austria). Viscosity measurements were taken using a concentric cylinder spindle (cc) no. 27 at a rotational speed of 100/s. Testing was conducted at 25 °C to determine the viscosity, which was measured dynamically over 120 s.

pH Value

The pH value of the adhesive was determined using a pH meter (Laqua pH 1200, Horiba, Kyoto, Japan). The pH value was displayed shortly after the electrode probe was immersed in the adhesive sample in a container.

Production of Pallet Blocks

The production of CBP was divided into two stages (Table 1). The first stage evaluated the use of formaldehyde-based adhesives, while the second stage examined the effect of pressing time. In the first stage, PUF adhesive was compared to commercial adhesives (UF and PF). These materials were sifted into two types of particles, namely coarse (4–14 mesh) and powder (> 60 mesh), then dried in the oven at 80 °C until the moisture content (MC) reached 5%. Particle size composition in this study was set at 50% coarse and 50% powder according to the previous study (Hermawan *et al.* 2024). The adhesive was applied using a spray gun inside a mixer at 10% (Nuryawan and Rahmawaty 2018; Özlüsoylu and İstek 2018; Yalçın 2023).

The sawdust mixed with adhesive was molded into 9 x 9 x 9 cm^3 blocks. The weight of the sawdust was adjusted to achieve a density of 0.6 g/cm^3 and was pressed using a hot press at 180 °C under a specific pressure of 9.8 MPa (Hermawan *et al.* 2024). The selection of higher pressing pressure is intended to increase particle compaction and adhesive penetration, ensure increased interparticle bonding in the CBP, and prevent spring-back in the CBP.

Subsequently, the physical and mechanical properties of the CBP were evaluated to determine the optimal adhesive type for the second production stage. In the second stage, the best results from the first stage were then varied in the pressing time by three durations (30, 60, and 90 minutes), as shown in Table 1. Extended pressing times (30 to 90 minutes) were applied to ensure complete adhesive curing, moisture reduction, and enhanced dimensional stability. Before evaluation, the conditioned CBP was stored for 7 days at room temperature (25 ± 2 °C) (Kusumah *et al.* 2016).

Table 1. Manufacturing Condition of CBP

Stage	Adhesive	Pressing Time (min)	Pressing Temperature (°C)
1	PUF	60	180
	UF		
	PF		
2	PF	30	180
		60	
		90	

Determination of CBP Performance

The evaluation of CBP products was conducted following the NWPCA (2014) standards of the United States. The assessments included density, moisture content (MC), dimensional stability (DS), water absorption (WA), compressive strength (CS), and screw-holding strength (SHS). Test samples were prepared with dimensions of 5 × 5 × 5 cm^3. Samples for density and moisture content testing were initially weighed, dried at 105 ± 2 °C for 24 h until a constant weight was achieved, and then reweighed. Both DS and WA were tested by measuring the samples' weight and dimensions (width, length, and thickness) before immersing them in water for 24 h. After immersion, the weight and dimensions were measured again. Mechanical properties, including CS and SHS, were tested using a Universal Testing Machine (UTM) with a 50 kN load capacity (AG-IS, Shimadzu, Kyoto, Japan). Each evaluation was conducted in triplicate.

Fourier Transform Infrared Spectroscopy Analysis

Fourier Transform Infrared Spectroscopy (FTIR) was performed to identify the CBP's chemical structures and functional groups bonded with PUF, UF, and PF. The test samples were ground into fine particles using a mortar to ensure uniformity in the analysis. The samples were then analyzed using a Fourier Transform Infrared Spectrophotometer (FTIR 4000, PerkinElmer Inc., USA). The FTIR spectra were recorded over the 400 to 4000 cm^{-1} wavenumber range, with a resolution of 4 cm^{-1}.

X-ray Diffraction Analysis

The crystallinity of the CBP bonded with PUF, UF, and PF was determined using X-ray diffraction (XRD). The PerkinElmer XD-2 (4000, PerkinElmer, USA) was used to acquire the X-ray diffraction data for this study. At a scan rate of 2°/min, X-ray scattering data were collected over a 2θ range of 10° to 60° (Liao *et al.* 2016; Sutiawan *et al.* 2022).

Data Analysis

Data were analyzed using IBM Statistical Product and Service Solution software version 22 (Armonk, NY, USA) with analysis of variance (ANOVA) to evaluate the effects of variable variations and levels used. Mean comparisons were made with Duncan's Test, which determined whether groups had significantly different means at a 95% confidence level.

RESULTS AND DISCUSSION

Characteristic of Adhesive

The results of the adhesive characterization show that the PUF adhesive had higher solid content and gel time than UF and PF adhesives (Table 2). The PUF adhesive had the highest solid content (68.3%) compared to UF (51.2%) and PF (47.4%). Higher solid content is generally associated with better adhesive strength and more efficient usage, resulting in less volume loss during the drying process. According to Luo *et al.* (2017) and Zhang *et al.* (2017), increasing the solid content of the adhesive reduces water evaporation during drying, thus limiting damage to the mechanical properties of plywood. The PUF adhesive had a gel time of 5.35 min, which is longer than UF (2.25 min) and PF (4.28 min). According to Xing *et al.* (2007), longer gel time allows more flexible working time and

ensures a more uniform distribution of the adhesive before it hardens. The gel time of PUF is ideal for industrial applications that require a balance between flexibility and efficiency.

The PUF adhesive had a pH of 6.34 (slightly acidic, close to neutral), while UF had a pH of 7.96 (slightly alkaline), and PF has a pH of 12.81 (very alkaline). Adhesives with a pH close to neutral, like PUF, are more stable in various environmental conditions, making them more suitable for broad applications. According to Kotanen *et al.* (2021), neutral pH has better stability against water uptake and high temperatures, maintaining bonding strength and preventing bond failure in harsh environments. The PUF adhesive has a viscosity of 126 mPa.s, which was lower than UF (144 mPa.s) but higher than PF (92.6 mPa.s), thus providing a good balance between ease of spreading and penetration ability. Higher viscosity results in shallower adhesive penetration, while lower viscosity causes deeper penetration, which can reduce bonding strength (Cheng *et al.* 2006).

Table 2. Adhesive Characteristics

Type of Adhesive	Solid Content (%)	Gel-time (min)	pH	Viscosity (mPa.s)
PUF	68.27	5.35	6.34	126.00
UF	51.15	2.25	7.96	143.50
PF	47.35	4.28	12.81	92.61

Effect of Formaldehyde-Based Adhesive Type on Physical and Mechanical Properties of CBP

Density and moisture content (MC)

The CBPs showed a density range between 0.50 and 0.56 g/cm³, with the highest density achieved by CBPs utilizing phenol-formaldehyde (PF) adhesives (Table 3).

Table 3. Effect of Formaldehyde-Based Adhesive Type on Physical and Mechanical Properties of CBP

Physical and Mechanical Properties	Type of Adhesive			NWPCA (2014)
	PUF	UF	PF	
Density (g/cm^3)	0.51 (0.02)^a	0.50 (0.03)^a	0.56 (0.01)^b	-
Moisture content (%)	6.82 (0.29)^a	4.70 (0.11)^b	5.27 (0.14)^c	-
Dimensional stability (length; %)	1.80 (0.26)^a	1.55 (0.15)^{ab}	1.29 (0.10)^b	≤ 2
Dimensional stability (width; %)	1.69 (0.10)^a	1.29 (0.32)^a	1.17 (0.18)^a	≤ 2
Dimensional stability (thickness; %)	8.40 (1.33)^a	5.65 (0.84)^b	1.83 (1.25)^c	≤ 6
Water absorption (%)	92.29 (7.47)^a	81.08 (5.57)^a	33.58 (4.28)^b	≤ 25
Compressive strength (MPa)	2.38 (0.42)^a	5.13 (0.45)^b	6.93 (0.77)^c	≥ 9.65
Screw holding strength (N)	171.88 (43.41)^a	297.43 (45.38)^b	343.26 (31.89)^b	≥ 200

^{a} through ^{c} The results of the statistical tests denoted by the same letter indicate the absence of noticeable differences. CBP: chip block pallets, NWPCA: National Wooden Pallet and Container Association

These results closely resemble the density characteristics of commercial products. While the NWPCA (2014) does not define specific standards for density, the findings

indicate that CBPs with PF adhesives may offer improved structural integrity due to their greater density. Vick (1999) emphasized the critical role of adhesive type in influencing the density and structural performance of wood products. Additionally, statistical analysis (ANOVA) revealed a significant effect of adhesive type on density (Table 4).

The MC is a critical factor in determining the quality of composite materials, as it influences both dimensional stability and mechanical properties. In this study, the MC of CBPs varied significantly, with the lowest value of 4.70% recorded for CBPs using UF adhesives, while the highest value of 6.82% was observed for PUF adhesives. These findings align with Belleville *et al.* (2008), who demonstrated that adhesive layers significantly affect moisture diffusion. Furthermore, Mahapatra *et al.* (2022) highlighted that higher moisture content can degrade mechanical properties by reducing crack resistance. Statistical tests confirmed that adhesive type has a highly significant impact on MC (Table 4).

Table 4. Summary Variance Analysis of Formaldehyde-Based Adhesive Type

Physical and Mechanical Properties	ANOVA (p)
Density	0.014**
Moisture content (MC)	0.000**
Dimension stability (length)	0.037**
Dimension stability (width)	0.062ns
Dimension stability (thickness)	0.001**
Water absorption (WA)	0.000**
Compressive strength	0.000**
Screw holding strength (SHS)	0.005**

ns Not significant, ** Highly significant difference

Dimensional stability (DS)

The DS refers to a material's ability to maintain its dimensions when exposed to changes in MC, temperature, and humidity. The CBPs made with different adhesive types exhibited varying DS values. The CBPs with UF adhesives demonstrated superior dimensional stability in length and width, meeting the NWPCA (2014) standards (≤ 2%). Among the tested adhesives, only CBPs using PF adhesives were able to meet the standard for thickness stability (≤ 6%). This indicates the effectiveness of PF adhesives in enhancing thickness stability, whereas further optimization of adhesive formulations and application techniques may be required for PUF and UF adhesives to achieve similar performance. These findings are consistent with the study by Iswanto *et al.* (2019), which demonstrated that bamboo-based particleboards using PF adhesive exhibited the lowest thickness swelling compared to other adhesives.

Water absorption

Water absorption (WA) was identified as a critical property influenced by adhesive type. The CBPs bonded with PF adhesives exhibited the lowest WA value at 33.6%, which was significantly lower than those bonded with PUF or UF adhesives. However, none of the adhesives allowed the CBPs to meet the NWPCA (2014) standard of ≤ 25%. This limitation is likely due to voids within the composite structure, which facilitate water

infiltration and retention between particles, as highlighted in prior studies (Desiasni *et al.* 2021; Syahfitri *et al.* 2024). Stronger matrix bonding is essential to reduce void formation and improve water resistance. Voids and weak bonding can exacerbate WA and mechanical degradation in composites exposed to water (Fortini and Mazzanti 2018).

The high WA values observed in this study can be attributed to the high proportion of fine wood particles and sawdust in composite particleboards (CBPs), which enhance capillary action and moisture retention. Particle size in particleboards influences mechanical properties and WA, with smaller particles tending to increase moisture uptake due to their larger surface area (Jiang *et al.* 2021). Unlike oriented strand board (OSB) or plywood, which utilize larger wood fibers to improve water resistance, CBPs rely on smaller particles that are more susceptible to moisture penetration. Research by Aras *et al.* (2023) found that small particles in particleboards increase the void spaces between fibers, facilitating water penetration and increasing WA.

Additionally, the adhesives used in this study—urea-formaldehyde (UF), phenol-formaldehyde (PF), and polyurethane-formaldehyde (PUF)—did not contain hydrophobic additives, which are commonly used in engineered wood products to reduce WA. Raydan *et al.* (2024) stated that standard adhesives without hydrophobic additives result in higher *water absorption* values compared to adhesives modified with water-repellent agents. Many particleboard and fiberboard products in the commercial industry incorporate wax additives or hydrophobic resin formulations to limit WA. However, these treatments were intentionally omitted in this study to maintain a controlled evaluation of adhesive effects. Research has shown that without hydrophobic materials, particleboards exhibit a significant increase in water absorption (Hafezi and Hosseini 2014).

Compressive strength (CS)

The CS values ranged from 2.38 to 6.93 MPa, with CBP utilizing PF adhesives achieving the highest CS value of 6.93 MPa (Table 3). However, none of the adhesives used in this study enabled the CBPs to meet the NWPCA (2014) standard for CS, which requires a minimum value of 9.65 MPa. Statistical analysis confirmed that the type of adhesive had a significant impact on CS, with PF adhesives demonstrating the best performance among the tested adhesives (Table 4). The relatively higher CS observed in CBP bonded with PF adhesives is attributed to their ability to penetrate deeply and establish strong bonds with wood particles. The PF adhesives offer excellent thermal and chemical resistance, enabling more effective interaction with the hydrophilic surfaces of wood particles (Zaia *et al.* 2015). During the pressing process, the adhesive matrix interacts effectively with particle surfaces, facilitating even load distribution and enhancing the structural integrity of the composite. This efficient bonding reduces the presence of voids within the material, which are commonly associated with stress concentration and eventual failure of the composite (Mirindi *et al.* 2021).

Screw holding strength (SHS)

The SHS values of the CBPs varied significantly among adhesive types, ranging from 172 N for PUF to 343 N for PF adhesives. The SHS of CBPs with PF adhesives exceeded the NWPCA (2014) standard of ≥ 200 N, demonstrating the superior bonding performance of PF adhesives. This strength can be attributed to the deeper penetration of PF adhesives into particle voids, which increases the bonding surface and reinforces the connections between particles (Aprillia *et al.* 2019). Conversely, PUF adhesives resulted in the lowest SHS value, which is likely due to weaker bonding and insufficient matrix

coverage, leading to inadequate stress transfer between particles. The high SHS of CBPs bonded with PF adhesives suggests their effectiveness in minimizing void formation and enhancing the material's resistance to shear forces. Additionally, the chemical composition of PF adhesives enhances their ability to withstand stress, making them highly suitable for applications requiring superior mechanical strength.

Effect of Pressing Time

Density and moisture content

Pressing time significantly influenced the physical properties of CBPs, particularly in terms of density and MC. As shown in Table 5, CBPs pressed for 30 min exhibited the lowest density of 0.52 g/cm³, while samples pressed for 60 and 90 min recorded higher and nearly identical densities of 0.56 g/cm³. This suggests that prolonged pressing times promote better compaction of particles and adhesive, enhancing the overall material density. Sutrisno *et al.* (2024) found that pressing time significantly affects the density and physical properties of wood-polymer composites, supporting the importance of optimizing pressing parameters. Similarly, Kúdela *et al.* (2018) observed that longer pressing times improve dimensional stability and density in compressed wood products, emphasizing the critical role of pressing duration. Statistical analysis (ANOVA) confirmed that pressing time had a significant effect on density ($p < 0.05$) (Table 6). The increased density observed with extended pressing time highlights the importance of proper pressing duration in achieving optimal particle-packing and matrix interactions.

Table 5. Effect of Pressing Time on Physical and Mechanical Properties of CBP

Physical and Mechanical Properties	Pressing Time (min)			NWPCA (2014)
	30	60	90	
Density (g/cm³)	0.52 (0.01)[a]	0.56 (0.01)[b]	0.56 (0.02)[b]	-
Moisture content (%)	6.44 (0.11)[a]	5.27 (0.14)[b]	5.54 (0.29)[b]	-
Dimensional stability (length; %)	3.66 (1.78)[a]	1.29 (0.10)[a]	2.50 (1.90)[a]	≤ 2
Dimensional stability (width; %)	1.36 (0.09)[a]	1.17 (0.18)[a]	1.31 (0.14)[a]	≤ 2
Dimensional stability (thickness; %)	2.87 (2.15)[a]	1.83 (1.25)[a]	1.18 (0.13)[a]	≤ 6
Water absorption (%)	92.22 (13.02)[a]	33.58 (4.28)[b]	91.75 (7.56)[a]	≤ 25
Compressive strength (Mpa)	4.56 (0.80)[a]	6.93 (0.77)[b]	6.77 (0.27)[b]	≥ 9.65
Screw holding strength (N)	300.37 (30.76)[a]	343.46 (31.89)[a]	318.76 (58.88)[a]	≥ 200

[a] through [c] The results of the statistical tests denoted by the same letter indicate the absence of noticeable differences. CBP: chip block pallets, NWPCA: National Wooden Pallet and Container Association.

The MC was also affected by pressing time, with values ranging from 5.27% to 6.44%. The lowest MC was recorded for CBPs pressed for 60 min, followed by 90 min (5.54%) and 30 min (6.44%). Extended pressing times and heat generated during the process facilitate moisture evaporation, leading to lower MC values. Candan *et al.* (2013) demonstrated that thermal modifications during hot pressing significantly reduce moisture content and enhance dimensional stability in wood composites. Rofii *et al.* (2016) also observed that adjusting pressing parameters, such as temperature and mat density,

significantly influences moisture evaporation and panel properties. Statistical tests confirmed that pressing time is critical in reducing moisture levels ($p < 0.05$). These findings indicate that pressing time affects density and plays a critical role in reducing moisture levels, essential for improving dimensional stability and mechanical performance.

Table 6. Summary Variance Analysis of Pressing Time

Physical and Mechanical Properties	ANOVA (p)
Density	0.006**
Moisture content (MC)	0.001**
Dimension stability (length)	0.235ns
Dimension stability (width)	0.314ns
Dimension stability (thickness)	0.404ns
Water absorption (WA)	0.000**
Compressive strength	0.008**
Screw holding strength (SHS)	0.503ns

ns Not significant, ** Highly significant difference

Dimensional stability

The DS is an essential property that determines the ability of CBPs to maintain their dimensions under varying environmental conditions, such as changes in moisture content, temperature, and humidity. The pressing time had varying effects on DS values for length, width, and thickness (Table 5). Statistical analysis showed that pressing time did not significantly affect dimensional stability for length, width, or thickness (Table 6).

The DS for length ranged from 1.29% to 3.66%, with the lowest value observed at 60 min of pressing time (1.29%), meeting the NWPCA (2014) standard of ≤ 2%. However, samples pressed for 30 min exhibited the highest DS value (3.66%), failing to meet the required standard. Prolonged pressing times reduce dimensional changes due to better particle bonding and matrix coverage, resulting in greater dimensional stability. Increased pressing temperatures and durations improved dimensional stability in compressed wood, primarily through enhanced particle bonding and reduced internal stresses (Kúdela *et al.* 2018).

The DS for width showed a similar trend, with the lowest value of 1.17% recorded at 60 min of pressing, which meets the NWPCA (2014) standard of ≤ 2%. Conversely, CBPs pressed for 30 min showed a higher DS value of 1.36%, still within the acceptable range but slightly less stable than samples pressed for longer durations. The reduced DS values with extended pressing times can be attributed to improved compaction and adhesive penetration. Hot-pressing conditions improve the dimensional stability of layered wood materials by reducing swelling coefficients and enhancing bonding strength (Chen *et al.* 2023).

For thickness, only samples pressed for 60 min (1.83%) and 90 min (1.18%) satisfied the NWPCA (2014) standard of ≤ 6%. Samples pressed for 30 min exhibited a higher DS value of 2.87%, indicating that shorter pressing durations result in less effective matrix bonding and increased dimensional changes. The improvement in DS at longer pressing times reflects enhanced interparticle bonding and reduced voids within the composite structure. Supporting this, Gao and Huang (2022) noted that pressurized steam

treatment during hot pressing significantly reduces dimensional instability by modifying wood microstructures and reducing hygroscopic hydroxyl groups.

Water absorption

Water absorption (WA) is a critical property that influences the durability and performance of CBPs, particularly in environments exposed to moisture. The WA values of CBPs varied significantly with pressing time, ranging from 33.6% to 92.2% (Table 5). CBPs pressed for 30 minutes exhibited the highest WA value of 92.2%, significantly exceeding the NWPCA (2014) standard of ≤ 25%. This high absorption amount indicates insufficient adhesive coverage and poor matrix bonding, likely due to inadequate pressing duration, which prevents full polymerization and results in voids and micrographs that facilitate water penetration. In contrast, CBPs pressed for 60 minutes showed the lowest WA value of 33.6%, indicating improved water resistance. The reduction in WA at this pressing duration is attributed to optimized adhesive distribution and reduced porosity, as the combination of heat and pressure at 60 minutes allows for complete adhesive polymerization, minimizing voids within the material. However, despite the improvement, this value still did not comply with the NWPCA (2014) standard, suggesting that further optimization in adhesive formulation or pressing parameters is necessary.

CBPs pressed for 90 minutes exhibited a WA increase of 91.8%, suggesting that excessively long pressing times may negatively affect adhesive performance. This phenomenon can be explained by over-curing or thermal degradation of the adhesive, which reduces its bonding strength and creates microcracks that facilitate moisture infiltration. Kallbofm *et al.* (2020) observed that severe water exposure and prolonged thermal conditions could lead to microstructural changes in thermally modified wood-plastic composites, emphasizing the delicate balance between processing time and moisture resistance. Additionally, the presence of voids within the composite structure significantly influences WA. Voids allow water to penetrate and be retained within the material, particularly in CBPs pressed for shorter durations (30 minutes), where insufficient adhesive polymerization leads to poor filler-matrix interactions. Conversely, pressing for excessive durations (90 minutes) may cause over-compaction, which alters the material's microstructure and further facilitates water uptake. Fortini and Mazzanti (2018) reported that minimizing void formation in composite materials enhances filler-matrix interactions, leading to better water resistance.

Statistical analysis confirmed that pressing time significantly affected WA, highlighting the importance of optimizing pressing parameters to reduce WA while maintaining the mechanical and dimensional stability of CBPs. Furthermore, Križan *et al.* (2020) noted that adjustments in particle size and matrix compatibility during production can significantly influence water absorption behavior in wood composites. These findings suggest that future research should explore adhesive modifications, particle size distribution adjustments, or hydrophobic treatments to reduce WA further and enhance CBP performance.

Compressive strength

The CS is a key mechanical property of CBPs, indicating the material can withstand compressive loads without failure. In this study, CS values ranged from 4.56 to 6.93 MPa, with pressing time significantly affecting the results (Tables 5 and 6). The CBPs pressed for 30 min exhibited the lowest CS value of 4.56 MPa, indicating insufficient adhesive bonding and poor particle compaction under shorter pressing durations. Conversely, the

highest CS value of 6.93 MPa was observed in CBP pressed for 60 min. This demonstrates that optimal pressing time enhances adhesive penetration, particle bonding, and overall matrix strength, allowing the material to resist compressive loads better. It is worth mentioning that CBPs pressed for 90 min showed a slight decrease in CS to 6.77 MPa, suggesting that excessively long pressing times may lead to over-compaction or thermal degradation of the adhesive, which can weaken the composite structure.

The improved matrix-particle interaction with extended pressing durations can explain the relationship between pressing time and CS. During pressing, the adhesive distributes more evenly and penetrates deeper into the voids between particles, reducing stress concentration points and enhancing load distribution. Hot-pressing significantly improves compressive strength in bamboo fiber-based composites, particularly at optimal pressing times and densities, highlighting the importance of balancing pressing conditions (Zhang *et al.* 2018). Despite the improvements with longer pressing times, none of the tested CBPs met the NWPCA (2014) standard for CS, which requires a minimum value of 9.65 MPa. This indicates that while pressing time is crucial in improving CS, additional factors, such as adhesive type, formulation, or pressing pressure, might need optimization to meet the required standards.

Screw holding strength

The SHS is a crucial mechanical property of CBPs, reflecting the material's ability to retain screws under applied loads. In this study, SHS values ranged from 300 to 343 N (Table 5). Statistical analysis (ANOVA) revealed that pressing time did not have a statistically significant effect on SHS ($p > 0.05$) (Table 6). The CBPs pressed for 30 min exhibited the lowest SHS value of 300 N, meeting the NWPCA (2014) standard of ≥ 200 N but indicating weaker interparticle bonding and inadequate adhesive penetration. In contrast, CBPs pressed for 60 min showed the highest SHS value of 343 N, demonstrating the optimal pressing duration for achieving superior screw retention strength. For CBP pressed for 90 min, the SHS value slightly decreased to 319 N, although it remained above the NWPCA (2014) standard. The slight reduction in SHS at 90 min could be attributed to over-compaction or thermal degradation of the adhesive, which might weaken the overall matrix integrity.

The improvement in SHS with longer pressing times (up to 60 min) can be attributed to better particle bonding, enhanced adhesive penetration, and reduced void formation within the composite. These factors contribute to stronger interparticle connections, allowing the material to resist higher screw withdrawal forces. The type and composition of fillers in wood-plastic composites significantly affect SHS, emphasizing the importance of matrix-filler interactions and adhesive performance in improving mechanical properties (Borysiuk *et al.* 2021). However, excessively long pressing durations, such as 90 min, may result in microstructural changes, such as adhesive degradation or reduced flexibility, which can slightly compromise the SHS. Esen and Yapici (2013) found that extended press times and high pressures can reduce screw withdrawal strength due to adhesive brittleness and over-compaction in oriented strand boards.

FTIR Analysis

The FTIR spectra CBP bonded with PUF, UF, and PF adhesives highlight distinct chemical compositions and structural characteristics (Fig. 1). In this study, the presence of the wood natural wood polymer as functional groups of cellulose and lignin was found in

the regions within 4000 to 2500 cm^{-1} and 2000 to 500 cm^{-1}. The absorbance peak of 3340 cm^{-1} assigned for O-H stretching from hydroxyl groups in holocellulose. The band at 2923 cm^{-1} represented C-H stretching of methyl and methylene groups in cellulose/lignin, while C=C aromatic stretching of lignin was found at 1605 cm^{-1}. Furthermore, the band at 1735 cm^{-1} was assigned for C=O stretching from carboxyl groups in hemicellulose. The broad peak at 3340 cm^{-1}, associated with O-H stretching vibrations, was most prominent in PF, reflecting its higher hydroxyl group content due to its phenolic structure. This indicates that PF may exhibit greater hydrophilicity, which could influence its behavior in humid environments. Meanwhile, UF and PUF showed relatively lower intensities in this region, indicating reduced hydroxyl content.

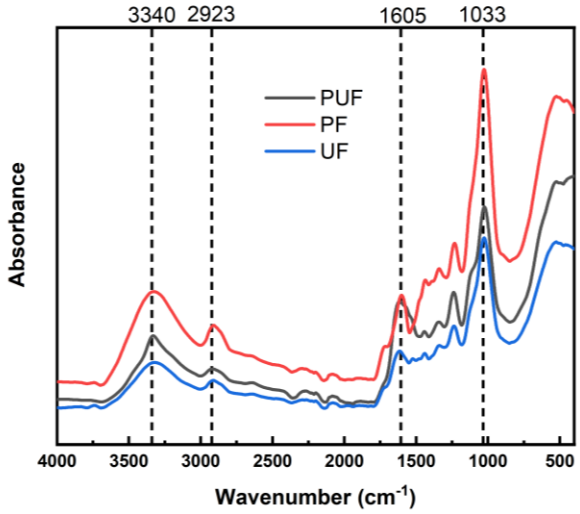

Fig. 1. FTIR spectrum of CBP at various adhesive

The peak at 2923 cm^{-1} corresponds to C-H stretching vibrations, which were present in all three adhesives but are most intense in PF, suggesting a higher concentration of aliphatic hydrocarbon chains. The strong peak at 1605 cm^{-1}, attributed to C=C aromatic ring stretching, is particularly prominent in PF, highlighting its rich aromatic structure. This aromatic content contributes to PF's superior mechanical strength and thermal stability, distinguishing it from UF and PUF. In contrast, UF showed a weaker response in this region, which is consistent with its lack of significant aromatic components.

At 1033 cm^{-1}, a sharp peak corresponding to C-O stretching vibrations was evident, with PF again exhibiting the highest intensity, followed by PUF and UF. This indicates a higher presence of oxygenated functional groups in PF, which is linked to its phenolic resin composition. In contrast, PUF displayed balanced intensities across all functional groups, reflecting its hybrid composition of aliphatic and aromatic structures and ester linkages, contributing to its versatility and reduced formaldehyde emissions compared to PF and UF. These observations align with Borysiuk *et al.* (2021), who highlighted the role of aromatic content and ester linkages in enhancing adhesive bonding strength and stability.

These findings underscore the unique advantages of each adhesive. With its high hydroxyl and aromatic content, the PF provides exceptional mechanical strength and durability but may pose environmental concerns due to formaldehyde emissions. The PUF emerges as a more environmentally friendly alternative, offering balanced mechanical

properties and reduced emissions, while UF is a cost-effective option with moderate performance. These distinct chemical profiles suggest that the choice of adhesive can be tailored to specific applications and sustainability requirements.

XRD Analysis

X-ray diffraction (XRD) analysis investigated the crystallinity and structural changes in CBPs bonded with PUF, UF, and PF adhesives. This analysis was conducted on bonded wood particles, rather than the adhesives alone, to evaluate the influence of adhesive interaction and curing on the crystalline structure of the wood matrix. There were two primary peaks in the cellulose diffraction pattern, located at 2θ around 15° and 22°. The results indicate that the primary diffraction peak at 22.39° (2θ), characteristic of cellulose I, confirms the presence of the natural crystalline structure of wood across all formulations (Fig. 2). However, a reduction in crystallinity was observed in some samples, particularly in UF-bonded CBPs, suggesting that adhesive infiltration modified the structural arrangement of the wood matrix. This aligns with the findings by Li and Zhang (2021), who reported that curing conditions and adhesive composition significantly influence crystallinity, impacting mechanical properties and stability.

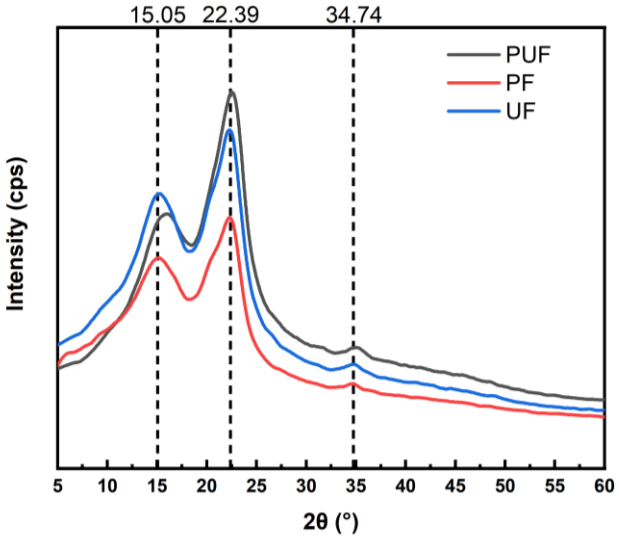

Fig. 2. XRD graph of CBP at various adhesive

Further analysis revealed distinct crystallinity patterns among the adhesives. At 15.05° (2θ), the diffraction peak was most pronounced in PUF-bonded CBPs, indicating a higher degree of microcrystallinity than PF and UF. This suggests that PUF facilitated a more ordered polymer arrangement, potentially enhancing bonding strength and material stability. Similar observations were made by Lubis and Park (2021), who found that modifications to UF adhesives could enhance crystallinity, improve mechanical properties, and reduce emissions.

The 34.74° (2θ) peak, associated with interchain interactions and crosslinking, was also most intense in PUF, followed by PF, while UF exhibited the weakest intensity. The lower crystallinity observed in UF-bonded CBPs may be due to its highly amorphous nature, whereas PF, with its rigid phenolic backbone, shows a moderate level of crystallinity. These findings suggest that the bonding process influences the internal organization of the wood matrix, potentially enhancing mechanical properties by

modifying its crystalline structure. This aligns with studies by Khorramabadi *et al.* (2023), who demonstrated that nano clay modifications could enhance molecular interactions and thermal stability in UF adhesives, further reinforcing the role of crystallinity in overall composite performance.

CONCLUSIONS

1. The production of high-quality chip board pallets (CBPs) has not been possible with PUF adhesive. The PF demonstrated the best mechanical strength performance, including compressive strength and screw-holding strength, making it the superior choice for applications requiring high durability.
2. A pressing time of 60 min yielded the best physical and mechanical properties for CBPs, such as compressive strength and dimensional stability. However, longer duration of pressing time, around 90 min may cause thermal degradation of the adhesive.
3. None of the adhesives met the NWPCA (2014) standard for water absorption (≤ 25%). However, phenol formaldehyde (PF) demonstrated the lowest water absorption compared to phenol urea formaldehyde (PUF) and urea formaldehyde (UF), indicating better resistance to water absorption.
4. The PF is recommended for applications requiring high mechanical strength, while PUF is more suited for applications prioritizing sustainability and environmental aspects.
5. To meet global standards, such as NWPCA (2014), future research related to hydrophobic treatments should be conducted to enhance the water resistance of CBPs without compromising their mechanical properties. is necessary to enhance CBP performance.

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