

Evaluation of Porang Flour (*Amorphophallus muelleri*) as Natural Filler for Enhancing Urea Formaldehyde and Citric Acid Adhesives in Plywood Production

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This study explores the potential of porang flour (*Amorphophallus muelleri*) as a sustainable filler in urea formaldehyde (UF) and citric acid (CA) adhesives, highlighting its effect on enhancing plywood performance. The physical and mechanical properties of plywood bonded with varying compositions of porang flour (0%, 10%, 20%) were evaluated according to Japanese Agricultural Standard (JAS 233:2003) for plywood. Three-layer plywood panels were manufactured using sengon wood and both types of adhesives. The results showed that adding porang flour to UF and CA adhesives significantly increased the solids content and improved physical and mechanical properties. Plywood bonded with UF exhibited superior density, water absorption, thickness swelling, and shear strength properties. Conversely, plywood bonded with CA adhesive showed better results in moisture content, modulus of elasticity (MOE), and modulus of rupture (MOR). Overall, adding 10% porang flour was optimal for improving plywood's physical and mechanical properties. These findings suggest that porang flour is an eco-friendly additive that can enhance the performance of natural adhesives in plywood manufacturing, providing a greener alternative to conventional adhesives.

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INTRODUCTION

Over the past decade, the wood-based panel industry, including plywood, has experienced significant growth worldwide. However, the COVID-19 pandemic resulted in a decline in production in the panel industry. Especially in Indonesia, the production and export value of panel industry products has increased 18% following the COVID-19 pandemic (Ministry of Environment and Forestry 2023). The value is expected to continue rising to meet the demand for wood-based panel products. One prominent product of the wood-based panel industry is plywood, which has become a primary choice in construction and furniture manufacturing due to its strong, lightweight, and easy-to-work-with properties (Čehić *et al.* 2008; Sandberg 2016). The increasing demand drives innovation

in the production process to improve product quality and raw material efficiency. Furthermore, the most commonly used adhesive is urea-formaldehyde (UF) because it produces strong bonds, is fast drying, and has a relatively low cost (Dunky 1998; Zorba *et al.* 2008).

The UF adhesives are widely used in the wood industry due to their excellent wood bonding performance. The UF adhesives exhibit high reactivity, making them highly efficient in production. It provides strong bonding properties, which are essential for wood-based panels and is low in cost compared to other adhesives, making it economically viable for large-scale wood product manufacturing (Dunky 1998). The UF adhesives can be modified with components, such as melamine, and integrating additives, such as titanium dioxide nanoparticles, that can enhance their water resistance and shear strength properties. These modifications also improve adhesives' overall durability and performance (Zhao *et al.* 2018; Park *et al.* 2021). However, UF adhesives also have several disadvantages. First, UF adhesives are a major source of formaldehyde emissions, which have been linked to serious health impacts such as respiratory problems and potential carcinogenic effects, leading to its classification as a carcinogen and raising concerns about long-term exposure risks (Duan *et al.* 2015; Bilgin and Colakoglu 2021). This has led to stricter regulations and the push for safer alternatives (Solt *et al.* 2019). Increasing environmental regulations on formaldehyde emissions have limited the use of UF adhesives. This regulatory pressure necessitates continuous modifications to comply with the standards, which can increase costs and complexity (Solt *et al.* 2019). Second, UF adhesives have limited water resistance, making them unsuitable for applications exposed to moisture. This is due to the hydrolytic degradation of the adhesive under humid conditions (Dunky 1998). Due to its susceptibility to moisture and hydrolytic degradation, UF adhesive is generally recommended for indoor applications. Outdoor use is limited because exposure to these elements can significantly weaken the adhesive bond (Kim *et al.* 2006). Despite these improvements, UF adhesives still release free formaldehyde, which is toxic. Efforts have been made to reduce this toxicity, but eliminating formaldehyde emissions remains a challenge. Because of the drawbacks of UF resins, such as the emission of toxic formaldehyde, which can cause health and environmental problems (Hematabadi *et al.* 2012; Duan *et al.* 2015; Solt *et al.* 2019; Bilgin and Colakoglu 2021), it is necessary to research and develop different types of adhesives to ensure that the resulting products have optimal performance and are environmentally friendly.

In contrast, some alternative research on adhesives, such as citric acid (CA), is gaining traction, as they are derived from natural materials and have the potential to produce safer adhesives (Kusumah *et al.* 2017b). However, the main challenge in using CA is ensuring that the bond strength can compete with or exceed that of conventional adhesives, such as UF. Previous studies have reported that CA adhesives have several advantages over conventional adhesives. Citric acid is a natural, non-toxic substance derived from renewable resources, which makes it a highly sustainable alternative to traditional synthetic adhesives (Umemura *et al.* 2012b). The CA forms strong ester linkages with the hydroxyl groups in wood, resulting in high water resistance, resistance to hydrolysis, resistance to delamination, and excellent mechanical properties that can achieve modulus of rupture values comparable to those of synthetic adhesives (Umemura *et al.* 2012; Widyorini *et al.* 2016; Cahyono and Syahidah 2019; Ando and Umemura 2021). This makes them suitable for applications that are exposed to moisture. In addition, this adhesive performs well at high temperatures, with temperatures up to 200 °C without significant degradation, maintaining its bonding strength (Sutiawan *et al.* 2021). The CA

can be combined and modified with other natural substances, such as glucose and sucrose, to enhance adhesive properties, resulting in adhesives with improved mechanical properties and environmental benefits (Li *et al.* 2022). Overall, CA adhesives are nontoxic, making them safe for use in applications where human contact is possible, such as furniture and household items. They do not emit harmful chemicals such as formaldehyde and thereby contribute to a healthier indoor environment (Taguchi *et al.* 2004). However, CA adhesives have several disadvantages, including a high content of citric acid, which can cause the elution of substances and lead to brittleness in the bonded materials, affecting their thermal properties, stability of the adhesive bond, flexibility, and durability (Umemura *et al.* 2012; Syamani *et al.* 2020). Furthermore, CA can catalyze the degradation of carbohydrate polymers, thereby reducing the lifespan of adhesive and bonded materials under certain conditions (Choowang and Luengchavanon 2021). The curing process of CA adhesives can be complex and may require precise control over the temperature (200 °C) and pH (2.3) to achieve optimal bonding properties (Kusumah *et al.* 2017b; Zhao *et al.* 2019; Sutiawan *et al.* 2023). In addition, the optimal processing conditions for CA adhesives often require high temperatures and pressures, which can be energy-intensive and may limit their feasibility for certain applications (Wibowo *et al.* 2021). Although CA adhesives can exhibit good initial water resistance, their performance may degrade over time, particularly under prolonged exposure to moisture (Li *et al.* 2022). Therefore, the development of citric acid adhesives has gaps for future development and improvement.

One approach to improving these shortcomings and limitations is to modify the adhesive by adding flour. Previous studies showed that adding flour to wood adhesive can reduce formaldehyde emissions, enhance adhesive handling during application, lower curing temperature and activation energy, increase water resistance, and improve mechanical properties, especially the interfacial adhesion and shear strength, thus showing good performance in bonding wood products (Lee *et al.* 2006; Lei and Wu 2006; Frihart and Satori 2013; Moubarik *et al.* 2013; Zhu and Damodaran 2014; Hong and Park 2017; Ghahri and Pizzi 2018). This contributes to a lower environmental impact and aligns with the principles of green chemistry (Damodaran and Zhu 2016). However, a challenge in adding flour is that the optimal proportion must be carefully controlled to balance property improvements with potential drawbacks, such as increased brittleness or reduced flexibility (Hong and Park 2017). An excessive flour content can diminish adhesive properties (Lorenz *et al.* 1999). Therefore, development in flour utilization needs to be continued by exploring various types of flour. One type of flour that shows potential for development is porang flour (*Amorphophallus muelleri*).

The utilization of porang flour is pursued because porang belongs to the same family and genus of plants as Konjac (*Amorphophallus konjac*). Porang flour contains glucomannan, which has the potential to result in good binding properties, thus potentially increasing the adhesive bond strength and reducing formaldehyde emissions (Umemura *et al.* 2003; Kelleci *et al.* 2022; Budiastara and Noviyanti 2023). The main chemical component of porang flour is glucomannan (approximately 60 to 80%), along with minor components such as starch, proteins, and minerals (Umemura *et al.* 2003; Shi *et al.* 2020; Kapoor *et al.* 2024).

Adding porang flour to adhesive formulations is a promising innovation that results in a more environmentally friendly product, making it a sustainable and economical resource. In this study, the authors aimed to evaluate the effect of porang flour level on plywood's physical and mechanical properties using urea formaldehyde and citric acid adhesives. Furthermore, it is important to consider that improving the quality and

sustainability of plywood products can provide economic benefits and contribute to environmental conservation. Moreover, the results of this study are expected to provide alternative solutions for the plywood industry to reduce the use of hazardous chemicals and increase the use of safer natural materials.

EXPERIMENTAL

Materials

The materials used were sengon wood (*Falcataria moluccana*) veneers (3 mm of thickness) obtained from the Research Center for Biomass and Bioproducts, BRIN-Indonesia and porang (*Amorphophallus muelleri*) flour (PO) from the local shop in Bantul, Yogyakarta, Indonesia. The urea-formaldehyde (UF) resin was obtained from PT Dover Chemicals (Banten, Indonesia) and citric acid (CA) was obtained from CV Kurnia Rizki Abadi, Bogor, Indonesia.

Wood Adhesive Preparation

Urea formaldehyde adhesive, from PT Dover Chemicals, Cilegon, Banten, Indonesia, was directly used, while CA adhesive was made by dissolving CA in water at a concentration of 59 (w/w%) (Kusumah *et al.* 2017b). Both adhesives, UF and CA, were then modified by mixing with porang flour according to several composition ratios, as shown in Table 1.

Table 1. Composition Ratios of Porang Flour with Adhesive (w/w%)

Wood Adhesive	Addition Porang Flour
Citric acid (CA)	0%
	10%
	20%
Urea-formaldehyde (UF)	0%
	10%
	20%

Wood Adhesive Characterizations

Solids content

Adhesive solid content testing measures the amount of solid or solid components in an adhesive. Solids content measurement is important for understanding the adhesive composition (Zheng *et al.* 2024). The test was conducted by drying 2 g of adhesive sample in an oven (Mettler UN55, Berlin, Germany) at 105 ± 2 °C for 3 h.

Gelation time

Adhesive gelatinization testing was used to understand adhesive characteristics during heating or activation. Gelatinization changes the adhesive to cure or melt when exposed to a certain temperature (Hao *et al.* 2022) using a gel time meter (Techne GT6, Coleparmer, Washington, D.C., USA).

Viscosity

Adhesive viscosity testing measures the viscosity or fluid of an adhesive at various temperatures or deformation rates. Viscosity measurements are critical for understanding adhesive flow properties and consistency (Cai *et al.* 2024). The adhesive viscosity was analyzed using a Rotational Rheometer (RheolabQC, AntonPaar, Austria) at 27 ± 2 °C with a shear rate of 500/s.

pH value

Adhesive pH testing is important for measuring an adhesive's acidity or alkalinity level (He *et al.* 2021). A pH paper of 0 to 14 was used for the test.

Plywood Manufacture

Plywood was made from Sengon wood veneers. Before production, the Sengon wood veneers were cut to a width, length, and thickness of $30 \times 30 \times 0.3$ cm³ of width, length, and thickness, respectively. The veneers were then dried in an oven at 60 °C for 48 h to obtain a moisture content of less than 8%. The veneers were then assembled into 3-layers with perpendicular fiber directions, and their tight and loose positions were respected. The assembled veneers were then bonded to adhesives. The amount of glue spread was 140 g/m² for plywood with 3 layers size 30 cm x 30 cm x 0.9 cm using sengon veneers. The plywood was hot-pressed at 190 °C and 15 kg/cm² for 10 min (Sutiawan *et al.* 2023). Finally, the plywood was then conditioned at room temperature of 20 ± 3 °C and humidity of 70 to 80% for 14 days.

Evaluation of Physical-Mechanical Properties of The Plywood

The physical properties tested consisted of density, moisture content (MC), water absorption (WA), and thickness swelling (TS). In contrast, the modulus of elasticity (MOE), modulus of rupture (MOR), and shear strength were measured for the mechanical properties. Plywood performance was assessed according to the JAS 233 (2003) standard. A completely randomized block design with two factors: wood adhesive type (block) and additional porang flour (treatment). Each stage was then evaluated using an analysis of variance (ANOVA). Tukey's test was subsequently performed to statistically analyze the differences in the plywood properties at $\alpha < 0.05$.

Functional Group Analysis

To determine possible changes in the functional groups of the plywood and adhesive chemical structures, each wood adhesive was analyzed using a Fourier transform infrared (FTIR) instrument (Spectrum Two, PerkinElmer, USA) in the spectral region of 4000 to 400 cm⁻¹.

RESULTS AND DISCUSSION

Effect of Additional Porang Flour on Solids Content and pH

The solid content and pH of the UF and CA adhesive formulations with porang flour are presented in Table 2. In UF-based adhesives, adding porang flour significantly increased the solids content. The UF adhesive exhibited a solids content of 50.99%, which increased to 57.99% and 58.95%, with the addition of 10% and 20% porang flour, respectively. This increase indicates that porang flour introduces more non-volatile

components into the adhesive system. However, the pH of the UF-based adhesives remained stable at 7, regardless of the amount of porang flour added. This suggests that the porang flour did not affect the acidity or alkalinity of the UF adhesive. Adding 10 to 20% porang flour to CA adhesives increased pH due to the buffering effect of glucomannan, a slightly basic component in porang flour, which reduces free hydrogen ions in the acidic citric acid environment (Widyorini *et al.* 2017). In contrast, porang flour had little effect on UF adhesives' pH, as their curing relies on a strongly acidic environment (pH 4.8 to 5.1), which neutralizes the mild alkalinity of the flour (Chen *et al.* 2012).

For CA-based adhesives, adding porang flour led to a significant increase in solids content. The pure CA adhesive had a solids content of 58.43%, which increased to 70.93% and 79.53% with 10% and 20% porang flour, respectively. This substantial increase suggests that the porang flour acted as a filler, enhancing the overall mass of the adhesive. Unlike the UF adhesive, the pH of the CA-based adhesives shifted when the porang flour was added. The pH of the pure CA adhesive was 1, indicating a highly acidic nature. However, with the addition of porang flour, the pH increased to 4 for both 10% and 20% formulations. This pH increase suggests that porang flour neutralized some of the acidity of citric acid, creating a less acidic but still effective adhesive. These results indicate that adding porang flour to both UF and CA adhesives enhanced the solid content, potentially improving the mechanical performance of the adhesives. However, the pH behavior differed between the two systems. While the UF adhesives maintained a neutral pH, the CA adhesives became less acidic, which may affect their performance in specific applications. The ability of CA adhesives to retain a relatively low pH even after adding porang flour could improve bonding in applications where acidity plays a critical role in adhesion. These findings suggest that the combination of CA and porang flour has potential in applications requiring higher solid content and moderate acidity. In contrast, UF with porang flour is more suitable for applications where stable pH and improved mechanical properties are critical. The ability of citric acid (CA) adhesives to maintain a relatively low pH even after the addition of porang flour plays a critical role in enhancing adhesion. The acidic environment promotes esterification reactions between citric acid and hydroxyl groups on the substrate surface, leading to stronger chemical bonding and resulting neutral pH condition (Ando and Umemura 2021). Kusumah *et al.* (2017a) found that acidic compounds easily degrade amorphous polysaccharides in lignocellulose, which contributes to wood brittleness. Reducing the acidity of citric acid can decrease brittleness and enhance the performance of composite panels.

Table 2. Characteristic of UF and CA Adhesive Formulation with Porang Flour

Adhesive	Solid Content (%)	pH Value
UF + Po 0%	50.99	7
UF + Po 10%	57.99	7
UF + Po 20%	58.95	7
CA + Po 0%	58.43	1
CA + Po 10%	70.93	4
CA + Po 20%	79.53	4

Additionally, flour-based fillers can interact with UF resin, forming cross-links that help increase the density and solid content of the adhesive while maintaining adequate bonding properties. This filler effect has been observed with other flour fillers, such as soy

and corn, which enhance adhesive properties and reduce formaldehyde emissions (Moubarik *et al.* 2013; Bacigalupe *et al.* 2020).

Porang flour contains a high amount of starch, a solid component that significantly increases the solids content when added to UF adhesives. Porang flour also contains polysaccharides such as glucomannan, which are highly hydrocolloid and can form gels. This gel formation increases the viscosity and solids content of the adhesive, contributing to enhanced cross-linking reactions between the UF resin and the adhesive matrix. This cross-linking process densifies the adhesive mixture, making it thicker and increasing its overall solids content (Derkyi *et al.* 2008). For CA adhesives, the increase in the solids content due to adding porang flour can be attributed to the incorporation of non-volatile filler materials from the porang flour. The glucomannan in the porang flour interacts with citric acid, contributing to the overall mass of the adhesive without being lost during the curing process. This interaction enhances the solid matrix by forming stable ester linkages between the carboxyl citric acid groups and the porang flour hydroxyl groups. This effect has been observed in other natural adhesives, where starch or carbohydrate fillers improved the adhesive properties and increased the solid content (Widyorini *et al.* 2017).

Density of Plywood

The density of plywood is shown in Fig. 1. The density values of plywood bonded with CA and UF adhesives remained generally stable across different levels of porang flour addition, ranging from 0.35 to 0.40 g/cm³, with the average density of plywood with CA and UF adhesive being 0.36 and 0.39 g/cm³, respectively. The results of the variance analysis in Table 3 show that the density of plywood was affected by the type of wood adhesive used, with plywood using the UF adhesive having a higher density than plywood using the CA adhesive. Adding porang flour into the adhesive resulted in an average plywood density of 0.38 g/cm³, indicating no differences in plywood density were observed between the adhesives with or without porang flour addition. Specifically, using UF adhesive, plywood bonded with 10% porang flour had the highest density at 0.40 g/cm³, while the lowest density, 0.35 g/cm³, was observed in CA-bonded plywood with 10% porang flour. These slight variations suggest that porang flour did not significantly alter the plywood structure's compaction or fiber-to-adhesive bonding density. Furthermore, increasing the level of porang flour showed no significant differences, which is consistent with the Tukey analysis presented in Table 4. However, adding 20% porang flour resulted in different responses between the two types of plywood adhesives.

The results were similar to previous research on other starch-based fillers, such as wood flour and chestnut starch, which showed that higher concentrations of filler tend to reduce density due to the lower mass of the filler compared to the base material. Dasiewicz and Wronka (2023) observed that chestnut starch enhanced mechanical properties when used as a filler in plywood, but it also affected density, depending on the percentage of flour added. Moreover, optimizing the filler proportions is crucial, as demonstrated by Huang *et al.* (2011), who found that increasing the filler content to 40% led to modifications in density while maintaining adequate mechanical properties. In the current study, the relatively consistent density values across all treatments indicated that porang flour, even at higher concentrations, did not drastically reduce the overall density of plywood. This suggests that the filler was well integrated into the plywood structure without significantly compromising its compactness.

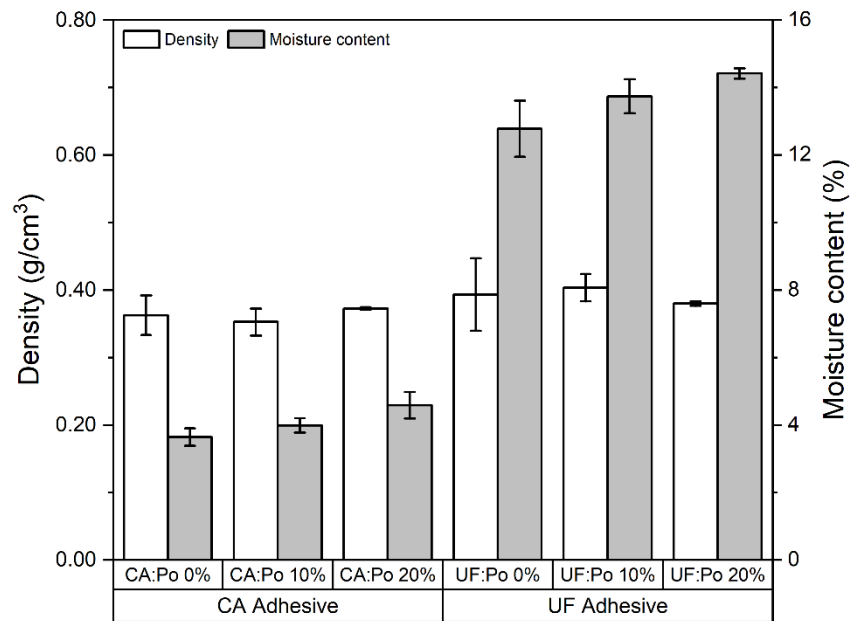


Fig. 1. The density and moisture content of plywood with different adhesives and porang flour level

The type of adhesive also affects the density of the plywood, although its influence is often indirect. Mansouri *et al.* (2006) reported that UF adhesives can affect the local density near the glue line due to adhesive diffusion into the wood layers, leading to localized densification. According to Hong and Park (2017), the viscosity of UF resin affects adhesion, which in turn can influence the density near the glue lines. In contrast, biomass-based adhesives, such as CA, can offer comparable or superior mechanical properties but may alter the density depending on the formulation and application technique (Li *et al.* 2022). However, in this study, the overall effect of adhesive type on density appeared to be minimal, as both CA- and UF-bonded plywood demonstrated similar density ranges. In addition, research has shown a positive correlation between density and mechanical properties, such as bending strength and modulus of elasticity (MOE), with higher density typically leading to better strength (Kūliņš *et al.* 2021). However, Kowaluk and Ježo (2021) suggested that, in some cases, higher density does not strictly correlate with improved compression strength, emphasizing the role of adhesive quality and particle bonding. Furthermore, Miao *et al.* (2022) demonstrated that small variations in density between 0.51 and 0.59 g/cm³ do not lead to significant differences in mechanical properties such as withdrawal or lateral holding strength. The relatively small range in density suggests that factors, such as adhesive distribution and veneer thickness, may play more significant roles in determining the mechanical performance of plywood than the density alone.

The Moisture Content of Plywood

The moisture content of the plywood is shown in Fig. 1. The moisture content ranged from 3.64 to 14.41%. According to JAS 233:2003, the moisture content for plywood should be below 12%, and all value with CA adhesive in this study met this standard bond. Analysis of variance in Table 3 revealed that the type of wood adhesive and additional

porang flour significantly affected the moisture content. The moisture content exhibited significant differences between the CA and UF adhesive treatment groups. Plywood bonded with CA demonstrated much lower moisture content values, ranging from 3.64% to 4.58%, than those bonded with UF adhesive, ranging from 12.78% to 14.41%. Tukey analysis in Table 4 revealed that adding up to 10% porang flour did not differ from the other.

Table 3. Variance Analysis Resume of Plywood Properties

Parameter	Wood Adhesive (A)	Filler (B)
Density	*	NS
Moisture content	**	**
Water absorption	NS	NS
Thickness swelling	NS	**
MOE	NS	NS
MOR	NS	NS
Shear strength	**	**

** Highly significant difference ($p < 0.01$); * Significant difference ($p < 0.05$); NS: not significant difference

Table 4. Result of Tukey Test of Plywood Properties

Response	Wood Adhesive		Filler		
	CA	UF	PO 0%	PO 10%	PO 20%
Density	0.36a	0.39b	0.37c	0.37c	0.38c
Moisture content	4.07a	13.64b	8.21c	8.86cd	9.50d
Water absorption	64.74a	63.33a	54.30b	67.19b	70.59b
Thickness swelling	8.31a	7.54a	5.96b	7.03b	10.78c
MOE	4.98a	4.30a	4.47b	4.56b	4.87b
MOR	39.36a	38.28a	35.63b	39.67b	41.17b
Shear strength	0.45a	1.04b	0.52c	0.97e	0.75d

Note: A through e values followed by the same letter within row are not statistically different based on Tukey's multiple comparison test.

This substantial difference can be attributed to the hygroscopic nature of urea-formaldehyde, which is known to absorb moisture from the environment. The UF adhesives tend to absorb moisture, negatively affecting the mechanical properties of wood-based products. Increased moisture content in UF-bonded plywood can reduce bonding strength and mechanical performance, as studies have shown that plywood manufactured with high-moisture veneers exhibits reduced shear and bending strengths (Aydin *et al.* 2006). Adding porang flour, a hydrophilic material primarily composed of glucomannan, contributed to a slight increase in the moisture content as its concentration increased from 0% to 20% in both adhesive systems. The hydrophilic nature of the porang flour, which attracts and holds water, explains this trend. For instance, the moisture-retaining properties of porang flour are evident in food applications, and their addition can significantly increase moisture content (Aryawan and Fitriana 2022). When used in wood composites,

hydrophilic fillers, such as porang flour, can lead to higher moisture absorption, which may affect the material's dimensional stability and mechanical properties (Aggarwal *et al.* 2015).

In contrast, citric acid-based adhesives exhibit lower moisture content than synthetic adhesives such as UF. This is primarily due to the hydrophobic ester linkages formed between citric acid and wood fibers during bonding, which enhance moisture resistance (Umemura *et al.* 2012b). Citric acid adhesives have shown better moisture resistance under challenging conditions, such as boiling water, than UF adhesives, which tend to degrade and absorb more water (Sutiawan *et al.* 2021). Furthermore, when exposed to moisture, UF adhesives are susceptible to hydrolytic degradation, weakening adhesive bonds over time, particularly in humid environments, making them less suitable for moisture-prone applications without modification (Kim *et al.* 2006). The presence of porang flour slightly increased the moisture retention in both adhesive systems, which may affect the overall performance of the plywood, particularly in terms of dimensional stability and mechanical strength in moisture-laden environments.

Water Absorption of Plywood

Water absorption is shown in Fig. 2. The results revealed a clear trend in which plywood-containing porang flour exhibited significantly higher water absorption than those without it. Specifically, plywood with 20% porang flour exhibited the highest water absorption, ranging from 69.74% (UF) to 71.45% (CA). According to the analysis variance results in Table 3, the type of wood adhesive and porang level did not affect the water absorption. Tukey analysis in Table 4 shows that both the wood adhesive and all porang flour levels did not differ significantly. This increase in water absorption can be attributed to the hydrophilic nature of porang flour, which tends to attract and retain moisture. Additionally, plywood bonded with CA generally showed slightly higher water absorption than that bonded with UF at all porang levels, suggesting that the CA-bonded plywood had lower density and provided less water resistance compared to UF adhesive.

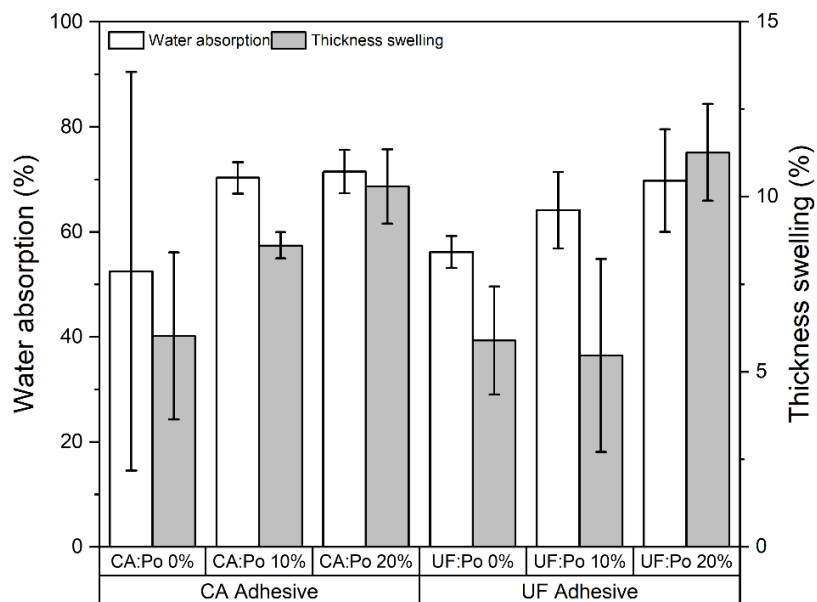


Fig. 2. Water absorption and thickness swelling of plywood with different adhesives and porang flour level

The increased water absorption observed in plywood-containing porang flour aligns with the findings of studies on hydrophilic fillers in wood composites. Hydrophilic fillers, such as porang flour, increase water absorption due to their ability to attract moisture, similar to other lignocellulosic fillers, such as wood flour and bio-based materials. These fillers, rich in cellulose and hemicellulose, exhibit high water retention properties, leading to increased water absorption in the composite (Aggarwal *et al.* 2015). Furthermore, this increased moisture absorption can negatively impact the mechanical properties of the composite, as the absorbed water disrupts the bonding between the filler and adhesive matrix, leading to decreased tensile strength and overall performance (Kiryakova *et al.* 2023). Moreover, the water absorption rate tended to increase with increasing filler content. A previous study on composites showed that filling with materials, such as rice husk and wood flour, demonstrated that higher filler content results in significantly higher water absorption, depending on the filler size and concentration (Lai *et al.* 2008). This trend was also observed in plywood with increasing porang flour content, where the material's porosity increased, providing more pathways for water to penetrate and be retained.

When comparing the water resistance of CA and UF adhesives, it is important to note that CA adhesives, while eco-friendly, may not always provide the same level of water resistance as the modified UF adhesives. Citric acid-based adhesives have shown potential for good water resistance due to ester linkages formed during the esterification reaction between citric acid and wood components. For specific formulations, such as when combined with glucose, CA adhesives can outperform UF adhesives regarding water resistance (Li *et al.* 2022). However, in the case of the pure CA adhesives used in this study, the water absorption was slightly higher than that of the UF-bonded plywood. Despite their modifications, such as the addition of melamine, such adhesive formulations remain prone to water absorption and hydrolytic degradation. Although certain additives can improve the water-resistance of UF adhesives, their inherent structure makes them susceptible to moisture, particularly when used in environments with high humidity (Dunky 1998). Therefore, while UF adhesives can offer reasonable water resistance when properly modified, they still absorb more water over time than citric acid-based adhesives when formulated for moisture resistance (Dunky 2021). In addition, the increase in material porosity caused by adding hydrophilic fillers, such as porang flour, plays a significant role in increasing water absorption. Hydrophilic fillers often introduce more voids and pores into the composite structure, creating additional water penetration and trapping pathways. Studies have shown that higher porosity leads to increased water absorption because void spaces act as reservoirs for moisture (Lavrinenko 2019). Furthermore, poor bonding between the filler and adhesive matrix can create gaps that allow for greater water retention, further contributing to the higher water absorption in composites with porang flour (Tajvidi and Ebrahimi 2003). The increased water absorption in the plywood-containing porang flour can be attributed to the hydrophilic nature of the filler and the resulting increase in material porosity. Although CA adhesives offer certain advantages in terms of sustainability, they may not provide the same level of water resistance as UF adhesives, especially when used with hydrophilic fillers. This suggests that further formulation adjustments may be necessary to optimize the water resistance of plywood composites using CA adhesives.

Thickness Swelling of Plywood

The thickness of the plywood, which is shown in Fig. 2, is a critical parameter for evaluating the dimensional stability of plywood when exposed to moisture. In this study,

the thickness swelling increased with the addition of porang flour, with plywood containing 20% porang flour showing the highest swelling values of 10.3% for CA and 11.3% for UF. Variance analysis in Table 3 also revealed that the filler porang level affected thickness swelling compared to the type of wood adhesive. Furthermore, Tukey analysis in Table 4 shows that an additional 20% porang flour differed from the other levels. This result suggests that the addition of porang flour compromises the dimensional stability of the plywood, primarily due to the hydrophilic nature of the flour, which absorbs water and leads to expansion. Furthermore, plywood bonded with UF adhesive showed slightly higher swelling with 20% porang flour compared to CA-bonded plywood, which was likely due to the weaker moisture resistance of the UF adhesive compared to the citric acid adhesive. Adding starch or flour-based fillers, such as porang flour, significantly influences wood composites, swelling behavior due to their moisture-absorbing properties. Kord *et al.* (2022) reported that a higher hydrophilic filler content, such as wood or rice husk flour, generally leads to increased water absorption and thickness swelling in the composite. This is largely due to the porosity introduced by the fillers, which creates more pathways for moisture to penetrate and be retained, contributing to dimensional changes, such as thickness swelling (Hosseinzadeh 2017; Matseevich *et al.* 2019).

A comparison of the dimensional stability of plywood bonded with CA and UF adhesives showed that CA-based adhesives tend to exhibit better water resistance, in which CA forms hydrophobic ester bonds *via* esterification (Kusumah *et al.* 2017b). Furthermore, CA-glucose adhesives outperform UF in water resistance due to esterification between citric acid and glucose, also forming stable bonds. This crosslinked structure enhances dimensional stability under wet conditions, unlike UF adhesives, which degrade more easily in moisture (Sun *et al.* 2019; Li *et al.* 2022). In contrast, UF adhesives are known to have poor water resistance and susceptibility to hydrolytic degradation. They tend to absorb moisture more readily in humid environments, which weakens the adhesive bonds and causes significant dimensional instability, often requiring modifications, such as melamine, to improve their performance (Park and Jeong 2011). Moreover, the relationship between thickness swelling and water absorption has been confirmed, such that wood-based panels experience greater swelling as their water absorption rate increases under various moisture conditions (Mohebbi *et al.* 2010). Consequently, it is necessary to reduce wood composites' water absorption and swelling to mitigate these effects. Moreover, optimizing adhesive formulations and possibly treating the filler could help improve dimensional stability and reduce swelling in such composites.

Modulus of Elasticity of Plywood

The modulus of elasticity (MOE) of plywood is presented in Fig. 3. The average MOE of plywood was 4.64 GPa, in which plywood with CA adhesive was higher than UF adhesive. Plywood bonded with the CA adhesive exhibited higher MOE values than plywood bonded with the UF adhesive, particularly at 0% porang flour content. The highest MOE, 5.29 GPa, was recorded for CA-bonded plywood without porang flour, whereas the lowest MOE, 4.16 GPa, was observed in UF-bonded plywood with 10% porang flour. According to the analysis of variance in Table 3, both types of wood adhesive and the percentage of porang flour level did not affect the MOE value. In addition, the Tukey analysis in Table 4 showed that the type of wood adhesive and porang flour level were not significantly different. As the percentage of porang flour increased, the MOE values showed a slightly decreasing trend for both adhesives, suggesting that including porang flour slightly reduced the stiffness of the plywood. This reduction may be due to the impact

of porang flour on fiber bonding and the overall rigidity of the adhesive matrix. On average, plywood bonded with CA adhesive displayed superior stiffness, which could be attributed to the stronger fiber adhesion provided by citric acid.

The CA adhesives demonstrated strong performance in terms of the modulus of elasticity. Li *et al.* (2022) found that plywood bonded with a fully bio-based citric acid-glucose adhesive achieved MOE values that outperformed those bonded with UF resin, highlighting the potential of citric acid as a green alternative to UF adhesives. The CA adhesives form ester bonds with wood fibers, which enhances the bonding strength and contributes to the stiffness of the plywood. In contrast, UF adhesives, which are widely used due to their fast-curing times and strong bonding capabilities, can exhibit lower performance in terms of long-term durability and water resistance. A comparison of the two adhesives revealed that citric acid-modified starch adhesives can achieve competitive MOE values relative to UF adhesives. For instance, Mohamad Amini *et al.* (2020) reported that plywood bonded with citric acid-modified corn starch achieved an MOE of 4.02 GPa, which increased to 5.19 GPa when 2% UF was added, indicating that combining citric acid and UF adhesives can enhance the mechanical properties. Fillers, such as porang flour, play a critical role in influencing the MOE of composite materials. In general, the inclusion of natural fillers, such as wood flour or cellulose, has been shown to increase stiffness due to the high rigidity of these materials, which must consider the size, shape, and dispersion of filler particles as crucial factors (Chauhan *et al.* 2006). Smaller and more uniformly dispersed particles enhance stiffness more effectively, whereas larger or poorly dispersed particles can reduce the reinforcing effect (Takarini *et al.* 2012).

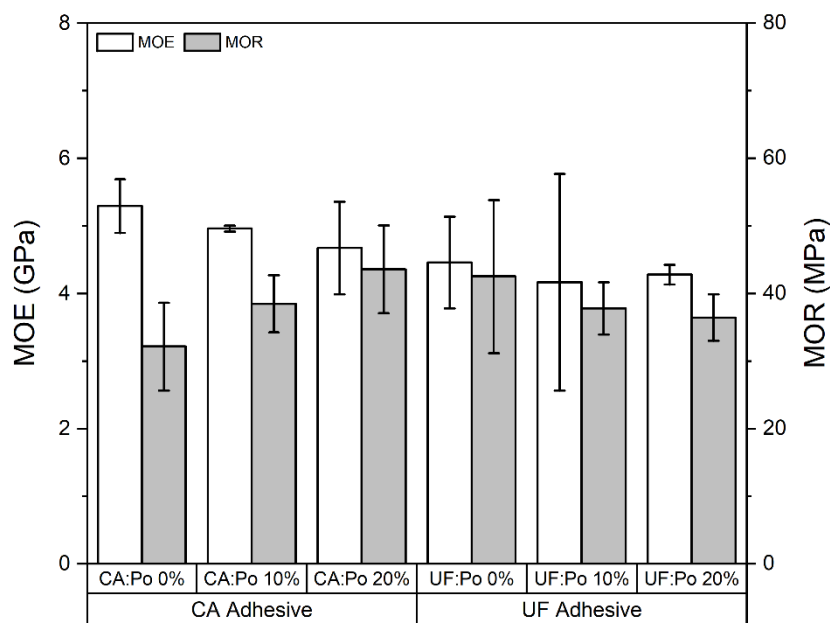


Fig. 3. MOE and MOR of plywood with different adhesives and porang flour level

Although porang flour, like other starch-based fillers, is hydrophilic, it can affect the internal bonding and moisture resistance. The ability of porang flour to absorb water may negatively affect the mechanical performance of plywood if the filler is not properly treated. However, at certain concentrations, porang flour can contribute to increased stiffness and MOE, depending on its interaction with the adhesive matrix (Osman and

Zakaria 2012). Additional factors, such as plywood thickness, adhesive distribution, and veneer configuration, also influence the stiffness and MOE of plywood. Thicker plywood generally exhibits higher stiffness because more layers of veneer distribute loads more effectively, increasing the resistance to bending forces. Beer *et al.* (2022) found that plywood made from Scots pine veneers exhibited a higher MOE as veneer thickness increased, indicating a direct correlation between thickness and stiffness. In addition, the distribution of adhesive across the layers and crosswise veneer arrangements of plywood is another important factor that ensures strong bonding between the layers, as better penetration of the adhesive affects the configuration and load distribution (Hrázský and Král 2004; Makowski 2019).

Modulus of Rupture of Plywood

The modulus of rupture (MOR) is shown in Fig. 3. In this study, plywood bonded with both CA and UF adhesives showed increased MOR values as the amount of porang flour increased. The highest MOR was observed in plywood containing 20% porang flour bonded with CA adhesive, reaching 45.7 MPa. This finding suggests that porang flour positively influences the bending strength of plywood when used at moderate to high concentrations, particularly in combination with the CA adhesive. According to the variance analysis in Table 3, the type of wood adhesive and porang filler level did not affect the MOR value. Tukey analysis in Table 4 revealed that the wood adhesive and porang filler levels were not different. It is worth mentioning that the UF-bonded plywood with 0% porang flour exhibited a higher MOR than CA-bonded plywood, which indicates that the UF adhesive initially provided stronger bonding. However, as the percentage of porang flour increased, plywood bonded with the CA adhesive outperformed UF-bonded plywood in MOR. This phenomenon is related to the neutralization of the adhesive's pH. The addition of porang flour increases the pH of CA adhesives, making them less acidic, while the pH of UF adhesives remains unchanged. Porang flour enhances bonding strength in CA adhesives, but may reduce mechanical properties in UF adhesives (Dewi *et al.* 2022).

Adding organic fillers, such as porang flour, as a natural filler, such as wood flour or plant-based fillers, can enhance certain mechanical properties, often leading to a reduction in flexural strength due to weaker filler-matrix bonding. Mirmehdi *et al.* (2014) found that high levels of date palm wood flour in polyethylene composites decreased flexural strength because of weak bonding between the filler and the matrix material. Similarly, organic fillers can introduce more porous structures into composites, which weaken the material under flexural loads (Mirmehdi *et al.* 2017). Furthermore, Stark (2001) noted that organic fillers increase moisture absorption, leading to swelling and mechanical degradation under bending stress. This moisture sensitivity could explain the performance differences between the CA and UF adhesives when combined with porang flour. The UF adhesives are more prone to hydrolytic degradation under moisture exposure, reducing their long-term MOR performance (Li *et al.* 2022). The CA adhesives form strong ester linkages between the carboxyl groups in citric acid and hydroxyl groups in wood, resulting in robust adhesive bonds. Studies on citric acid-modified starch adhesives have demonstrated competitive MOR values in plywood applications, with MOR values reaching 16.8 MPa and slightly improving when 2% UF was added (Mohamad Amini *et al.* 2020). This suggests that citric acid adhesives, when used with fillers, such as porang flour, can provide strong flexural performance, potentially improving the overall bending strength of the plywood.

While UF adhesives provide a higher initial MOR, citric acid adhesives, especially with porang flour, offer more stable long-term performance due to their improved moisture resistance. Umemura *et al.* (2012b) demonstrated that citric acid-bonded plywood can achieve an MOR of 18.1 MPa, with mechanical properties comparable to conventional UF adhesives. Optimal pressing conditions, such as high temperatures and long pressing times, have improved the mechanical performance of CA-bonded plywood, including its MOR and shear strength (Sutiawan *et al.* 2021). Moreover, Li *et al.* (2022) reported that fully bio-based citric acid-glucose adhesives surpassed UF adhesives regarding bonding strength and water resistance and achieved higher MOR values in moisture-exposed conditions. While UF adhesives offer strong initial bonding and flexural strength, CA adhesives combined with porang flour provide superior long-term stability and moisture resistance, making them a promising alternative for applications where environmental exposure is a concern.

Shear Strength of Plywood

The shear strength of plywood is shown in Fig. 4. The results from this study showed a significant increase in shear strength with the addition of porang flour, particularly in plywood bonded with UF adhesive. The highest shear strength was recorded in plywood with 10% porang flour using UF adhesive (1.44 MPa), compared to 0.50 MPa for plywood bonded with CA adhesive at the same filler content. These phenomena were different for MOE and shear strength.

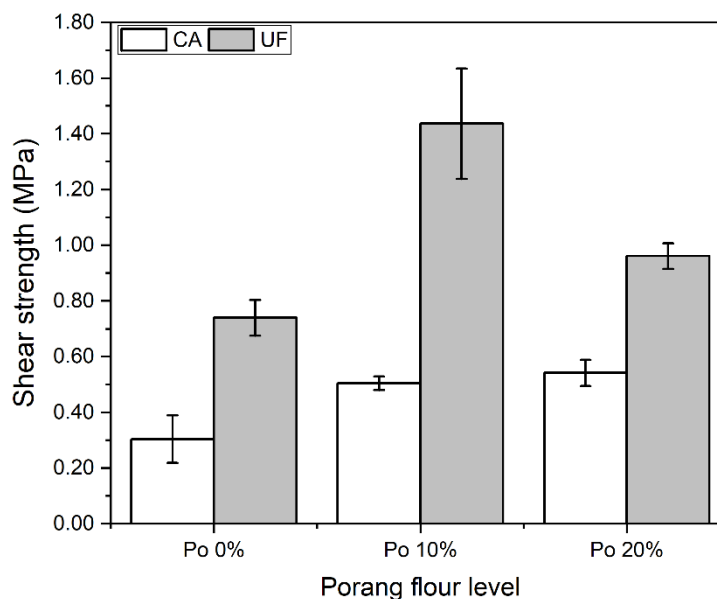


Fig. 4. Shear strength of plywood with different adhesives and porang flour level

According to the variance analysis in Table 3, the type of wood adhesive and porang flour levels affected the shear strength of plywood. Tukey analysis in Table 4 reveals that additional porang flour levels of 10% differed. Furthermore, this suggests that the UF adhesive interacted more effectively with porang flour, enhancing the resistance of the plywood to shear forces. However, when the porang flour content was increased to 20%, the shear strength of the UF-bonded plywood decreased slightly, implying that an excessive

amount of porang flour may weaken the internal bonding structure of the adhesive matrix. The increased shear strength with higher porang flour concentration is primarily due to better adhesive viscosity and stronger mechanical interlocking between adhesive, filler, and veneer layers (Ong *et al.* 2018). In contrast, plywood bonded with the CA adhesive demonstrated a more consistent and linear increase in shear strength as porang flour content increased, indicating that the CA adhesive may provide a more stable bonding structure when porang flour is used as an additive.

The effects of the CA and UF adhesives on the shear strength of plywood have been explored in several studies. Citric acid-based adhesives have been shown to provide excellent shear strength, particularly under wet conditions. Li *et al.* (2022) found that fully biobased citric acid-glucose adhesives achieved shear strength values exceeding 0.7 MPa, outperforming UF adhesives under water-resistant conditions. The ability of CA adhesives to form ester bonds with wood fibers improves moisture resistance and enhances shear strength even in humid environments (Sutiawan *et al.* 2021). In contrast, while UF adhesives are known for their strong initial bonding and cost-effectiveness, their shear strength may deteriorate over time, particularly under moisture-exposed conditions (Sahoo *et al.* 2020). The cited authors reported that although UF adhesives perform satisfactorily in dry and wet conditions, they outperform bio-based alternatives like CA adhesives in water-exposed environments. Fillers, such as porang flour, also play a significant role in influencing the shear strength of plywood composites. A previous study using similar organic fillers with palm kernel meal, showed that the optimal filler content could enhance shear strength while reducing formaldehyde emissions (Ong *et al.* 2018). The interaction between the porang flour and the UF adhesive matrix strengthens the bond, which is likely due to improved mechanical interlocking and increased adhesive viscosity (Heon Kwhciwon *et al.* 2015). However, an excessive filler content can lead to agglomeration and porosity, weakening the adhesive bond and reducing the overall shear strength (Schulze *et al.* 2003). Regarding the relationship between filler content and mechanical performance, Ong *et al.* (2018) reported that shear strength improves with increased organic filler content, but only up to an optimal concentration of 13 to 18%. Beyond this point, further increases in filler concentration resulted in a decline in shear strength due to poor filler dispersion and weaker interaction with the adhesive matrix (Ikejima *et al.* 2003). These findings align with the results of this study, where the addition of porang flour improved the shear strength by up to 10%, after which a slight reduction was observed at 20% filler content. According to JAS 233:2003, the standard value for shear strength is at least 0.70 MPa. Based on this standard, only the plywood using UF adhesive meets the requirement.

Functional Group Analysis

The results of the FTIR analysis are shown in Fig. 5. The FTIR spectra of plywood bonded with UF and CA adhesives exhibited different characteristics. Previous studies have shown that plywood bonded with UF polymers exhibits characteristic absorbance bands due to their amide groups (C=O stretching) around 1650 cm^{-1} and methylene bridges (C-H stretching) around 2940 cm^{-1} , which are indicative of the urea and formaldehyde reactions (Jiang *et al.* 2010). The strong absorbance at 1650 cm^{-1} primarily results from carbonyl (C=O) stretching vibrations due to the reaction of formaldehyde with urea (Wang *et al.* 2019). Additionally, methylene bridges formed during UF polymerization show bands around 1400 to 1450 cm^{-1} from -CH₂- bending vibrations (Antunes *et al.* 2018). Hydroxymethyl (-CH₂OH) groups, formed during the reaction of urea with formaldehyde,

exhibit absorbances at 3450 cm^{-1} (O-H stretching) and 1080 cm^{-1} (C-O stretching) (Song *et al.* 2021). Amine groups (N-H stretching) appear around 3300 to 3500 cm^{-1} , indicating unreacted or partially reacted urea in UF adhesives (Khorramabadi *et al.* 2023).

Plywood bonded with citric acid adhesives was characterized by key features observable in their FTIR spectra. The formation of ester linkages, a hallmark of these adhesives, is indicated by strong absorbance bands around 1720 cm^{-1} , corresponding to C=O stretching vibrations, signifying esterification between the carboxyl groups of citric acid and the hydroxyl groups of cellulose or starch (Lin *et al.* 2022; Sutiawan *et al.* 2021). Hydroxyl groups exhibit absorbance bands around 3400 cm^{-1} , which decrease in intensity upon esterification as they react with citric acid (Choowang and Luengchavanon 2021). The carboxyl groups show characteristic peaks around 1700 cm^{-1} (C=O stretching) and 1200 cm^{-1} (C-O stretching), with shifts or changes in intensity when esters are formed (Li *et al.* 2022). In formulations such as sucrose-citric acid adhesives, furan ring formation is indicated by absorbance bands around 1600 cm^{-1} , suggesting dehydration and condensation reactions during curing (Sun *et al.* 2019). Citric acid also forms strong hydrogen bonds with components such as starch, demonstrated by broad peaks around 3200 to 3500 cm^{-1} due to O-H stretching vibrations (Yu *et al.* 2005). Furthermore, FTIR analysis combined with thermal methods, such as TGA, shows that forming stable ester linkages enhances the thermal stability of citric acid adhesives, resulting in improved performance under heat (Ando and Umemura 2021). However, in the current study, Ding *et al.* (2013) showed that UF mixing with wheat flour indicated no clear evidence of a reaction between wheat flour and UF-glue around room temperature in the IR spectra.

The FTIR analysis of the CA and UF adhesives, both with and without adding porang flour, revealed significant alterations in their chemical structure and bonding environments. The spectrum of the CA adhesive displayed distinct peaks corresponding to functional groups, such as hydroxyl (O-H), carboxyl (C=O), and ester (C-O) groups. Upon the incorporation of porang flour, noticeable shifts in these peaks were observed, particularly in the O-H stretching region around 3200 to 3600 cm^{-1} and the C=O stretching region around 1700 to 1750 cm^{-1} . These shifts suggest the formation of new hydrogen bonds and potential interactions between the hydroxyl groups of porang flour and carboxyl groups of CA. Additionally, the C-O stretching region (1000 to 1300 cm^{-1}) exhibited variations, indicating possible changes in ester linkages due to the introduction of polysaccharides from porang flour.

In the case of UF adhesive, the FTIR spectrum typically featured peaks associated with urea and formaldehyde reactions, such as N-H stretching (3300 to 3500 cm^{-1}) and C=O stretching (1650 to 1700 cm^{-1}). The addition of porang flour led to shifts in these peaks, particularly in the N-H stretching region, implying enhanced hydrogen bonding or alterations in the environment of the amine group. The C-N stretching region (1200 to 1350 cm^{-1}) also showed changes, suggesting modifications in the amide linkages within the UF matrix. These spectral shifts underscore the interaction between the urea-formaldehyde network and porang flour, possibly affecting the cross-linking density of the polymer matrix and the overall bonding properties.

Comparative analysis of the FTIR spectra of CA and UF adhesives with varying concentrations of porang flour (10% and 20%) highlighted the impact of polysaccharides on the chemical structure of the adhesive. The hydroxyl region exhibited broadening in both adhesive systems, reflecting increased hydrogen bonding due to the additional hydroxyl groups from the porang flour. The carbonyl stretching region exhibited shifts in the peak positions, indicating changes in the cross-linking density and interactions within

the adhesive matrix. Notably, the C-O-C stretching region around 1000 to 1100 cm^{-1} , characteristic of glycosidic linkages in polysaccharides, became more pronounced with porang flour addition, confirming its integration into the adhesive matrix.

These findings align with previous studies on UF and CA adhesives, which emphasize the role of functional groups such as amides, esters, and hydroxyl groups in determining the adhesive properties. The observed changes in the FTIR spectra suggest that porang flour introduces new interactions within the adhesive matrix and enhances the overall bonding and stability. This analysis provides valuable insights into the chemical modifications in CA and UF adhesives upon adding porang flour, paving the way for developing improved adhesive formulations with potential applications in various industries.

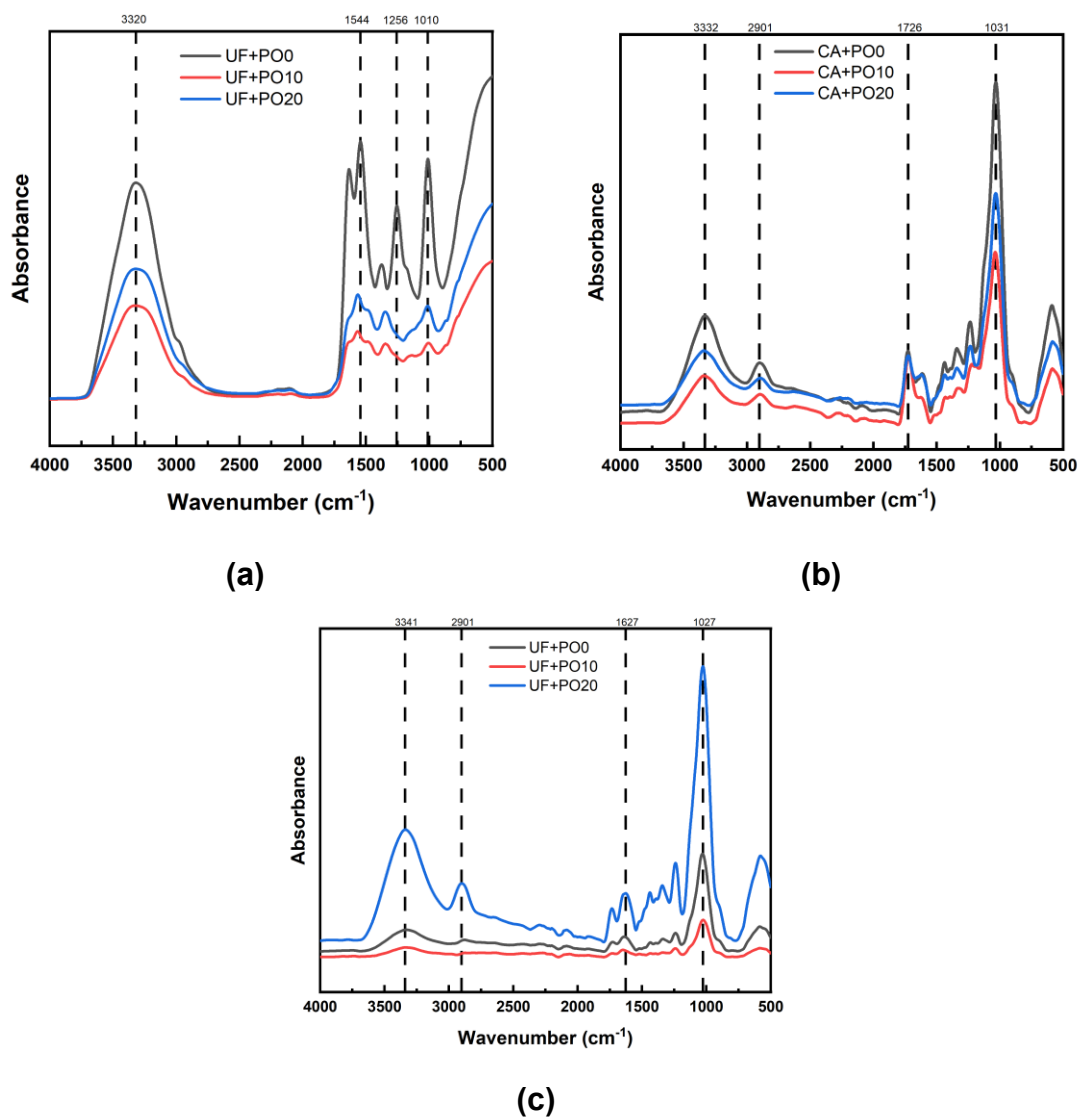


Fig. 5. FTIR spectra of urea formaldehyde adhesive (a), plywood with citric acid adhesive (b), and plywood with urea formaldehyde adhesive (c) with different porang flour additions

CONCLUSIONS

1. The addition of porang flour significantly impacted the performance of plywood, particularly in enhancing the physical and mechanical properties when used in both urea formaldehyde (UF) and citric acid (CA) adhesives. Plywood bonded with UF adhesive demonstrated superior performance in density, water absorption, thickness swelling, and shear strength compared to plywood bonded with CA adhesive.
2. In accordance with JAS 233:2003, the moisture content of plywood should be below 12%. All plywood samples bonded with CA adhesive in this study complied with this requirement. However, regarding shear strength, which must be at least 0.70 MPa as specified by the standard, only the plywood bonded with UF adhesive met the standard.
3. Porang flour effectively increased the solids content of both adhesives, contributing to enhanced bonding properties without compromising performance. Overall, adding 10% porang flour was optimal for improving plywood's physical and mechanical properties.
4. These findings suggest that porang flour is a sustainable and eco-friendly additive that can reduce synthetic adhesives while maintaining high-quality plywood production. Using porang flour as a filler can also help reduce the total adhesive content needed, offering a cost-effective and greener alternative.
5. Further research is necessary to optimize the balance between porang flour content and adhesive performance to ensure industrial feasibility and to determine the ideal amount of porang flour for different adhesive formulations. This includes exploring its potential in other adhesive systems to realize its full benefits in plywood manufacturing.

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REFERENCES CITED

- Aggarwal, P. K., Raghu, N., Kale, A., Vani, C. N., and Chauhan, S. (2015). "Moisture adsorption and absorption behaviour of bio-fiber filled thermoplastic composites," *Journal of the Indian Academy of Wood Science* 12(2), 104-109. DOI: 10.1007/s13196-015-0151-5

- Ando, D., and Umemura, K. (2021). "Bond structures between wood components and citric acid in wood-based molding," *Polymers* 13(1), article 58. DOI: 10.3390/polym13010058
- Antunes, A., Paiva, N., Ferra, J., Martins, J., Carvalho, L., Barros-Timmons, A., and Magalhães, F. D. (2018). "Highly flexible glycol-urea-formaldehyde resins," *European Polymer Journal* 105, 167-176. DOI: 10.1016/j.eurpolymj.2018.05.037
- Aryawan, C. W., and Fitriana, I. (2022). "Supplemental porang glucomannan flour (*Amorphophallus muelleri* Blume) on green grass jelly (*Cyclea barbata* L. Miers) texture, syneresis, and moisture content," *Indonesian Journal of Food Technology* 1(2), 180-193. DOI: 10.20884/1.ijft.2022.1.2.7547
- Aydin, I., Colakoglu, G., Colak, S., and Demirkir, C. (2006). "Effects of moisture content on formaldehyde emission and mechanical properties of plywood," *Building and Environment* 41(10), 1311-1316. DOI: 10.1016/j.buildenv.2005.05.011
- Bacigalupe, A., Molinari, F., Eisenberg, P., and Escobar, M. M. (2020). "Adhesive properties of urea-formaldehyde resins blended with soy protein concentrate," *Advanced Composites and Hybrid Materials* 3(2), 213-221. DOI: 10.1007/s42114-020-00151-7
- Beer, P., Pacek, P., and Burawska-Kupniewska, I. (2022). "Influence of the thickness of Scots pine (*Pinus sylvestris* L.) veneers on selected properties of flooring," *Forests* 13(2), article175. DOI: 10.3390/f13020175
- Bilgin, U., and Colakoglu, G. (2021). "Effect of using urea formaldehyde modified with extracts in plywood on formaldehyde emission," *Drvna Industrija* 72(3), 237-244. DOI: 10.5552/drvind.2021.2005
- Budiastra, I. W., and Noviyanti, A. A. (2023). "Determination of chemical content of Porang flour (*Amorphophallus muelleri* Blume) by near infrared spectroscopy," *IOP Conference Series: Earth and Environmental Science* 1187(1), article 012027. DOI: 10.1088/1755-1315/1187/1/012027
- Cahyono, T. D., and Syahidah. (2019). "Citric acid, an environmentally friendly adhesive and wood impregnation material-review of research," *IOP Conference Series: Materials Science and Engineering* 593(1), article 012009. DOI: 10.1088/1757-899X/593/1/012009
- Cai, L., Chen, Y., Lu, Z., Wei, M., Zhao, X., Xie, Y., Li, J., and Xiao, S. (2024). "Citric acid/chitosan adhesive with viscosity-controlled for wood bonding through supramolecular self-assembly," *Carbohydrate Polymers* 329, article 121765. DOI: 10.1016/j.carbpol.2023.121765
- Ćehić, M., Omer, S.-E., and Hodžić, A. (2008). "Influence construction and properties of plywood on areas of their application in wooden constructions," *TMT, Trends in the Development of Machinery and Associated Technology*, Istanbul, Turkey.
- Chauhan, S. S., Karmarkar, A., and Aggarwal, P. (2006). "Evaluation of dynamic elastic properties of wood-filled polypropylene composites," *Journal of Applied Polymer Science* 102(2), 1706-1711. DOI: 10.1002/app.24285
- Chen, M. C.-M., Chao, P.-Y., Huang, M.-Y., Yang, J.-H., Yang, Z.-W., Lin, K.-H., and Yang, C.-M. (2012). "Chlorophyllase activity in green and non-green tissues of variegated plants," *South African Journal of Botany* 81, 44-49. DOI: 10.1016/j.sajb.2012.04.004
- Choowang, R., and Luengchavanon, M. (2021). "Oil palm trunk powder blended with citric acid directly used as wood adhesive by one step liquefaction reaction,"

- Industrial Crops and Products* 170, article 113809. DOI: 10.1016/j.indcrop.2021.113809
- Damodaran, S., and Zhu, D. (2016). "A formaldehyde-free water-resistant soy flour-based adhesive for plywood," *Journal of the American Oil Chemists' Society* 93(9), 1311-1318. DOI: 10.1007/s11746-016-2866-x
- Dasiewicz, J., and Wronka, A. (2023). "Influence of the use of chestnut starch as a binder filler in plywood technology," *Annals of WULS, Forestry and Wood Technology* 122, 137-148. DOI: 10.5604/01.3001.0053.9126
- Derkyi, N. S. A., Seliyere, D., Darliwa, N. A., and Yartey, J. G. (2008). "Effect of cassava flour as urea formaldehyde adhesive extender on the bonding strength of plywood," *Ghana Journal of Forestry* 23, 25-34.
- Dewi, G. K., Widyorini, R., and Lukmandaru, G. (2021). "Application of maltodextrin-based adhesive on particleboard made from *Salacca frond*," *BioResources* 17(1), 190-206. DOI: 10.15376/biores.17.1.190-206
- Ding, R., Su, C., Yang, Y., Li, C., and Liu, J. (2013). "Effect of wheat flour on the viscosity of urea-formaldehyde adhesive," *International Journal of Adhesion and Adhesives* 41, 1-5. DOI: 10.1016/j.ijadhadh.2012.08.003
- Duan, H., Qiu, T., Guo, L., Ye, J., and Li, X. (2015). "The microcapsule-type formaldehyde scavenger: The preparation and the application in urea-formaldehyde adhesives," *Journal of Hazardous Materials* 293, 46-53. DOI: 10.1016/j.jhazmat.2015.03.037
- Dunky, M. (1998). "Urea-formaldehyde (UF) adhesive resins for wood," *International Journal of Adhesion and Adhesives* 18(2), 95-107. DOI: 10.1016/S0143-7496(97)00054-7
- Dunky, M. (2021). "Wood adhesives based on natural resources: A critical review: Part II. Carbohydrate-based adhesives," in: *Progress in Adhesion and Adhesives*, Wiley, 337-382. DOI: 10.1002/9781119846703.ch9
- Frihart, C. R., and Satori, H. (2013). "Soy flour dispersibility and performance as wood adhesive," *Journal of Adhesion Science and Technology* 27(18-19), 2043-2052. DOI: 10.1080/01694243.2012.696948
- Ghahri, S., and Pizzi, A. (2018). "Improving soy-based adhesives for wood particleboard by tannins addition," *Wood Science and Technology* 52(1), 261-279. DOI: 10.1007/s00226-017-0957-y
- Hao, Y., Yuan, C., Deng, J., Zheng, W., Ji, Y., and Zhou, Q. (2022). "Injectable self-healing first-aid tissue adhesives with outstanding hemostatic and antibacterial performances for trauma emergency care," *ACS Applied Materials and Interfaces* 14(14), article 877. DOI: 10.1021/acsami.2c00877
- He, J., Zhang, Z., Yang, Y., Ren, F., Li, J., Zhu, S., Ma, F., Wu, R., Lv, Y., He, G., et al. (2021). "Injectable self-healing adhesive pH-responsive hydrogels accelerate gastric hemostasis and wound healing," *Nano-Micro Letters* 13(1), article 80. DOI: 10.1007/s40820-020-00585-0
- Hematabadi, H., Behrooz, R., Shakibi, A., and Arabi, M. (2012). "The reduction of indoor air formaldehyde from wood based composites using urea treatment for building materials," *Construction and Building Materials* 28(1), 743-746. DOI: 10.1016/j.conbuildmat.2011.09.018
- Heon Kwon, J., Lee, S.-H., Ayrilmis, N., and Hyung Han, T. (2015). "Tensile shear strength of wood bonded with urea-formaldehyde with different amounts of

- microfibrillated cellulose,” *International Journal of Adhesion and Adhesives* 60, 88-91. DOI: 10.1016/j.ijadhadh.2015.04.002
- Hong, M.-K., and Park, B.-D. (2017). “Effect of urea-formaldehyde resin adhesive viscosity on plywood adhesion,” *Journal of the Korean Wood Science and Technology* 45(2), 223-231. DOI: 10.5658/WOOD.2017.45.2.223
- Hosseinzadeh, A. (2017). “The effect of using the flour of kiwi (*Actinidia* sp.) twigs and refined fibers in the production of polypropylene/wood plastic composites,” *BioResources* 12(1), 1369-1381. DOI: 10.15376/biores.12.1.1369-1381
- Hrázský, J., and Král, P. (2004). “Analysis of properties of boards for concrete formwork,” *Journal of Forest Science* 50(8), 382-398. DOI: 10.17221/4665-JFS
- Huang, H. B., Du, H. H., Wang, W. H., and Wang, H. G. (2011). “Effects of the size of wood flour on mechanical properties of wood-plastic composites,” *Advanced Materials Research* 393–395, 76-79. DOI: 10.4028/www.scientific.net/AMR.393-395.76
- Ikejima, I., Nomoto, R., and McCabe, J. F. (2003). “Shear punch strength and flexural strength of model composites with varying filler volume fraction, particle size and silanation,” *Dental Materials* 19(3), 206–211. DOI: 10.1016/S0109-5641(02)00031-3
- JAS 233 (2003). “Japanese agricultural standard for plywood,” Japanese Agricultural Standard Association, Tokyo, Japan.
- Jiang, X., Li, C., Chi, Y., and Yan, J. (2010). “TG-FTIR study on urea-formaldehyde resin residue during pyrolysis and combustion,” *Journal of Hazardous Materials* 173(1–3), 205-210. DOI: 10.1016/j.jhazmat.2009.08.070
- Kapoor, D. U., Sharma, H., Maheshwari, R., Pareek, A., Gaur, M., Prajapati, B. G., Castro, G. R., Thanawuth, K., Suttiruengwong, S., and Sriamornsak, P. (2024). “Konjac glucomannan: A comprehensive review of its extraction, health benefits, and pharmaceutical applications,” *Carbohydrate Polymers* 339, article 122266. DOI: 10.1016/j.carbpol.2024.122266
- Kelleci, O., Koksall, S. E., Aydemir, D., and Sancar, S. (2022). “Eco-friendly particleboards with low formaldehyde emission and enhanced mechanical properties produced with foamed urea-formaldehyde resins,” *Journal of Cleaner Production* 379, article 134785. DOI: 10.1016/j.jclepro.2022.134785
- Khorramabadi, L. A., Behrooz, R., and Kazemi, S. (2023). “Effects of nanoclay modification with aminopropyltriethoxysilane (APTES) on the performance of urea-formaldehyde resin adhesives,” *BioResources* 18(3), 5417-5434. DOI: 10.15376/biores.18.3.5417-5434
- Kim, J., Carlborn, K., Matuana, L. M., and Heiden, P. A. (2006). “Thermoplastic modification of urea-formaldehyde wood adhesives to improve moisture resistance,” *Journal of Applied Polymer Science* 101(6), 4222-4229. DOI: 10.1002/app.23654
- Kiryakova, D. S., Ilieva, A. S., and Simeonova, N. A. (2023). “Effect of water absorption on the mechanical properties of silane-treated wood flour polypropylene composites,” *Wood Research* 68(3), 477-487. DOI: 10.37763/wr.1336-4561/68.3.477487
- Kord, B., Ghalehno, M. D., and Movahedi, F. (2022). “Effect of imidazolium-based green solvents on the moisture absorption and thickness swelling behavior of wood flour/polyethylene composites,” *Journal of Thermoplastic Composite Materials* 35(11), 2162-2176. DOI: 10.1177/0892705720962170
- Kowaluk, G., and Ježo, A. (2021). “Compression strength-focused properties of wood composites induced by structure,” *Annals of WULS, Forestry and Wood Technology* 116, 131-140. DOI: 10.5604/01.3001.0015.6879

- Kūliņš, L., Meija, A., Roziņš, R., Liepa, K. H., and Spulle, U. (2021). "Influence of veneer density on plywood thickness and some mechanical properties," *Rural Sustainability Research* 46(341), 66-74. DOI: 10.2478/plua-2021-0018
- Kusumah, S. S., Arinana, A., Hadi, Y. S., Guswenrivo, I., Yoshimura, T., Umemura, K., Tanaka, S., and Kanayama, K. (2017a). "Utilization of sweet sorghum bagasse and citric acid in the manufacturing of particleboard. III: Influence of adding sucrose on the properties of particleboard," *BioResources* 12(4), 7498-7514. DOI: 10.15376/biores.12.4.7498-7514
- Kusumah, S. S., Umemura, K., Guswenrivo, I., Yoshimura, T., and Kanayama, K. (2017b). "Utilization of sweet sorghum bagasse and citric acid for manufacturing of particleboard II: Influences of pressing temperature and time on particleboard properties," *Journal of Wood Science* 63(2), 161-172. DOI: 10.1007/s10086-016-1605-0
- Lai, J. C., Ani, F. N., and Hassan, A. (2008). "Water absorption of lignocellulosic phenolic composites," *Polymers and Polymer Composites* 16(6), 379-387. DOI: 10.1177/096739110801600605
- Lavrinenko, V. I. (2019). "Porosity and water absorbability of tool composite materials as factors of improving wear resistance of superabrasive grinding wheels. Part 1. Superabrasive composites," *Journal of Superhard Materials* 41(2), 126-132. DOI: 10.3103/S1063457619020084
- Lee, Y., Lee, H., Kim, H., Yun, D., and Kim, S. (2006). "Comparison of formaldehyde emission rate and formaldehyde content from rice husk flour filled particleboard bonded with urea-formaldehyde resin," *Journal of the Korean Wood Science and Technology* 34(5), 42-51.
- Lei, Y., and Wu, Q. (2006). "Cure kinetics of aqueous phenol-formaldehyde resins used for oriented strandboard manufacturing: Effect of wood flour," *Journal of Applied Polymer Science* 102(4), 3774-3781. DOI: 10.1002/app.24739
- Li, C., Lei, H., Wu, Z., Xi, X., Du, G., and Pizzi, A. (2022). "Fully biobased adhesive from glucose and citric acid for plywood with high performance," *ACS Applied Materials & Interfaces* 14(20), 23859-23867. DOI: 10.1021/acsami.2c02859
- Lin, C.-F., Karlsson, O., Jones, D., and Sandberg, D. (2022). "Bio-based adhesive derived from citric acid and sorbitol for wood-composite manufacture," *Wood Material Science & Engineering* 17(5), 397-399. DOI: 10.1080/17480272.2022.2090278
- Lorenz, L., Conner, A., and Christiansen, A. (1999). "The effect of soy protein additions on the reactivity and formaldehyde emissions of urea-formaldehyde adhesive resins," *Forest Products Journal* 49(3), 73-78.
- Makowski, A. (2019). "Analytical analysis of distribution of bending stresses in layers of plywood with numerical verification," *Drvna industrija* 70(1), 77-88. DOI: 10.5552/drwind.2019.1823
- Mansouri, H. R., Pizzi, A., and Leban, J.-M. (2006). "Improved water resistance of UF adhesives for plywood by small pMDI additions," *Holz als Roh- und Werkstoff* 64(3), 218-220. DOI: 10.1007/s00107-005-0046-z
- Matseevich, T., Matseevich, A., and Askadskii, A. (2019). "Water absorption of wood-polymer composites of sawewood," *E3S Web of Conferences* 97, article 02043. DOI: 10.1051/e3sconf/20199702043

- Miao, Y., Pan, S., and Xu, W. (2022). "Staple holding strength of furniture frame joints constructed of plywood and solid wood," *Forests* 13(12), article 2006. DOI: 10.3390/f13122006
- Ministry of Environment and Forestry (2023). Statistics Indonesian Forestry 2022, Ministry of Environment and Forestry, Jakarta, Indonesia.
- Mirmehdi, S. M., Henrique, G., Tonoli, D., and Dabbagh, F. (2017). "Lignocellulose-polyethylene composite: Influence of delignification, filler content and filler type," *Cellulose Chemistry and Technology* 51(3–4), 341–346.
- Mirmehdi, S. M., Zeinaly, F., and Dabbagh, F. (2014). "Date palm wood flour as filler of linear low-density polyethylene," *Composites Part B: Engineering* 56, 137–141. DOI: 10.1016/j.compositesb.2013.08.008
- Mohamad Amini, M. H., Hashim, R., Sulaiman, N. S., Mohamed, M., and Sulaiman, O. (2020). "Citric acid-modified starch as an environmentally friendly binder for wood composite making," *BioResources* 15(2), 4234–4248. DOI: 10.15376/biores.15.2.4234-4248
- Mohebbi, B., Younesi, H., Ghotbifar, A., and Kazemi-Najafi, S. (2010). "Water and moisture absorption and thickness swelling behavior in polypropylene/wood flour/glass fiber hybrid composites," *Journal of Reinforced Plastics and Composites* 29(6), 830–839. DOI: 10.1177/0731684408100702
- Moubarik, A., Mansouri, H. R., Pizzi, A., Allal, A., Charrier, F., Badia, M. A., and Charrier, B. (2013). "Evaluation of mechanical and physical properties of industrial particleboard bonded with a corn flour–urea formaldehyde adhesive," *Composites Part B: Engineering* 44(1), 48–51. DOI: 10.1016/j.compositesb.2012.07.041
- Ong, H. R., Khan, Md. M. R., Prasad, D. M. R., Yousuf, A., and Chowdhury, M. N. K. (2018). "Palm kernel meal as a melamine urea formaldehyde adhesive filler for plywood applications," *International Journal of Adhesion and Adhesives* 85, 8–14. DOI: 10.1016/j.ijadhadh.2018.05.014
- Osman, H., and Zakaria, M. H. (2012). "Effects of durian seed flour on processing torque, tensile, thermal and biodegradation properties of polypropylene and high density polyethylene composites," *Polymer-Plastics Technology and Engineering* 51(3), 243–250. DOI: 10.1080/03602559.2011.625379
- Park, B.-D., and Jeong, H.-W. (2011). "Hydrolytic stability and crystallinity of cured urea–formaldehyde resin adhesives with different formaldehyde/urea mole ratios," *International Journal of Adhesion and Adhesives* 31(6), 524–529. DOI: 10.1016/j.ijadhadh.2011.05.001
- Park, S., Jeong, B., and Park, B.-D. (2021). "Comparison of adhesion behavior of urea-formaldehyde resins with melamine-urea-formaldehyde resins in bonding wood," *Forests* 12(8), article 1037. DOI: 10.3390/f12081037
- Sahoo, S. C., Sil, A., and Solanki, R. T. (2020). "Effect of adhesive performance of liquid urea formaldehyde (UF) resin when used by mixing with solid UF resin for manufacturing of wood based panels," *International Journal of Scientific and Research Publications (IJSRP)* 10(4), 562–567. DOI: 10.29322/IJSRP.10.04.2020.p10065
- Sandberg, D. (2016). "Additives in wood products—Today and future development," in: *Environmental Impacts of Traditional and Innovative Forest-based Bioproducts*. Environmental Footprints and Eco-design of Products and Processes, A. Kutnar and S.S. Muthu (eds.), Springer, Singapore, pp. 105–172. DOI: 10.1007/978-981-10-0655-5_4

- Schulze, K. A., Zaman, A. A., and Söderholm, K.-J. M. (2003). "Effect of filler fraction on strength, viscosity and porosity of experimental compomer materials," *Journal of Dentistry* 31(6), 373-382. DOI: 10.1016/S0300-5712(03)00091-5
- Shi, X.-D., Yin, J.-Y., Cui, S. W., Wang, Q., Wang, S.-Y., and Nie, S.-P. (2020). "Plant-derived glucomannans: Sources, preparation methods, structural features, and biological properties," *Trends in Food Science & Technology* 99, 101-116. DOI: 10.1016/j.tifs.2020.02.016
- Solt, P., Konnerth, J., Gindl-Altmutter, W., Kantner, W., Moser, J., Mitter, R., and van Herwijnen, H. W. G. (2019). "Technological performance of formaldehyde-free adhesive alternatives for particleboard industry," *International Journal of Adhesion and Adhesives* 94, 99-131. DOI: 10.1016/j.ijadhadh.2019.04.007
- Song, J., Chen, S., Yi, X., Zhao, X., Zhang, J., Liu, X., and Liu, B. (2021). "Preparation and properties of the urea-formaldehyde res-in/reactive halloysite nanocomposites adhesive with low-formaldehyde emission and good water resistance," *Polymers* 13(14), article 2224. DOI: 10.3390/polym13142224
- Stark, N. (2001). "Influence of moisture absorption on mechanical properties of wood flour-polypropylene composites," *Journal of Thermoplastic Composite Materials* 14(5), 421-432. DOI: 10.1106/UDKY-0403-626E-1H4P
- Sun, S., Zhao, Z., and Umemura, K. (2019). "Further exploration of sucrose-citric acid adhesive: Synthesis and application on plywood," *Polymers* 11(11), article 1875. DOI: 10.3390/polym11111875
- Sutiawan, J., Hermawan, D., Massijaya, M. Y., Kusumah, S. S., Lubis, M. A. R., Marlina, R., Purnomo, D., and Sulastiningsih, I. M. (2021). "Influence of different hot-pressing conditions on the performance of eco-friendly jabon plywood bonded with citric acid adhesive," *Wood Material Science and Engineering* 17(6), 400-409. DOI: 10.1080/17480272.2021.1884898
- Sutiawan, J., Syahfitri, A., Purnomo, D., Sudarmanto, Narto, Akbar, F., Triwibowo, D., Ismadi, Amanda, P., Kusumah, S. S., et al. (2023). "Characterization and application of non-formaldehyde binder based citric acid, maleic acid, and molasses adhesive for plywood composite," *Polymers* 15(19), article 3897. DOI: 10.3390/polym15193897
- Syamani, F. A., Ramatia, D., Sudarmanto, Akbar, F., Kusumah, S. S., and Hermawan, D. (2020). "Combination of citric acid and maltodextrin as bonding agent in sorghum bagasse particleboard," *IOP Conference Series: Materials Science and Engineering* 935(1), article 012058. DOI: 10.1088/1757-899X/935/1/012058
- Taguchi, T., Saito, H., Uchida, Y., Sakane, M., Kobayashi, H., Kataoka, K., and Tanaka, J. (2004). "Bonding of soft tissues using a novel tissue adhesive consisting of a citric acid derivative and collagen," *Materials Science and Engineering: C* 24(6-8), 775-780. DOI: 10.1016/j.msec.2004.08.037
- Tajvidi, M., and Ebrahimi, G. (2003). "Water uptake and mechanical characteristics of natural filler-polypropylene composites," *Journal of Applied Polymer Science* 88(4), 941-946. DOI: 10.1002/app.12029
- Takarini, V., Djustiana, N., and Febrida, R. (2012). "Effect of filler particles on the elastic moduli of resin composites," *Journal of Dentomaxillofacial Science* 11(1), article 39. DOI: 10.15562/jdmfs.v11i1.292
- Umemura, K., Inoue, A., and Kawai, S. (2003). "Development of new natural polymer-based wood adhesives I: Dry bond strength and water resistance of konjac glucomannan, chitosan, and their composites," *Journal of Wood Science* 49(3), 221-226. DOI: 10.1007/s10086-002-0468-8

- Umemura, K., Ueda, T., and Kawai, S. (2012a). "Characterization of wood-based molding bonded with citric acid," *Journal of Wood Science* 58(1), 38-45. DOI: 10.1007/s10086-011-1214-x
- Umemura, K., Ueda, T., Munawar, S. S., and Kawai, S. (2012b). "Application of citric acid as natural adhesive for wood," *Journal of Applied Polymer Science* 123(4), 1991-1996. DOI: 10.1002/app.34708
- Wang, H., Wang, F., and Du, G. (2019). "Enhanced performance of urea-glyoxal polymer with oxidized cassava starch as wood adhesive," *Iranian Polymer Journal* 28(12), 1015-1021. DOI: 10.1007/s13726-019-00760-0
- Wibowo, E. S., Kusumah, S. S., Subyakto, and Umemura, K. (2021). "Modification of novel bio-based adhesive made from citric acid and sucrose by ZnCl_2 ," *International Journal of Adhesion and Adhesives* 108, article 102866. DOI: 10.1016/j.ijadhadh.2021.102866
- Widyorini, R., Nugraha, P. A., Rahman, M. Z. A., and Prayitno, T. A. (2016). "Bonding ability of a new adhesive composed of citric acid-sucrose for particleboard," *BioResources* 11(2), 4526-4535. DOI: 10.15376/biores.11.2.4526-4535
- Widyorini, R., Umemura, K., Kusumaningtyas, A. R., and Prayitno, T. A. (2017). "Effect of starch addition on properties of citric acid-bonded particleboard made from bamboo," *BioResources* 12(4), 8068-8077. DOI: 10.15376/biores.12.4.8068-8077
- Yu, J.-G., Wang, N., and Ma, X.-F. (2005). "The effects of citric acid on the properties of thermoplastic starch plasticized by glycerol," *Starch - Stärke* 57(10), 494-504. DOI: 10.1002/star.200500423
- Zhao, X., Peng, L., Wang, H., Wang, Y., and Zhang, H. (2018). "Environment-friendly urea-oxidized starch adhesive with zero formaldehyde-emission," *Carbohydrate Polymers* 181, 1112-1118. DOI: 10.1016/j.carbpol.2017.11.035
- Zhao, Z., Sakai, S., Wu, D., Chen, Z., Zhu, N., Huang, C., Sun, S., Zhang, M., Umemura, K., and Yong, Q. (2019). "Further exploration of sucrose-citric acid adhesive: Investigation of optimal hot-pressing conditions for plywood and curing behavior," *Polymers* 11(12), article 1996. DOI: 10.3390/polym11121996
- Zheng, G., Pan, A., Xu, Y., and Zhang, X. (2024). "Preparation of a superior soy protein adhesive with high solid content by enzymatic hydrolysis combined with cross-linking modification," *Industrial Crops and Products* 213, article 118446. DOI: 10.1016/j.indcrop.2024.118446
- Zhu, D., and Damodaran, S. (2014). "Chemical phosphorylation improves the moisture resistance of soy flour-based wood adhesive," *Journal of Applied Polymer Science* 131(13), article 40451. DOI: 10.1002/app.40451
- Zorba, T., Papadopoulou, E., Hatjiissaak, A., Paraskevopoulos, K. M., and Chrissafis, K. (2008). "Urea-formaldehyde resins characterized by thermal analysis and FTIR method," *Journal of Thermal Analysis and Calorimetry* 92(1), 29-33. DOI: 10.1007/s10973-007-8731-2

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