ALKIMIA : Jurnal Ilmu Kimia dan Terapan

ARTICLES

View Article Online
View Journal | View Issue

OPEN ACCESS

Synthesis of Lignin–Urea Formaldehyde (LUF) Wood Adhesive Based on Lignin Extracted from Oil Palm Empty Fruit Bunches (EFB)

Dian Wardana[a]*, Eddiyanto[a], Nurfajriani[a], Dwi Sapri Ramadhan[a], Wulan Dwi Safitri[a], Jam'an Fahmi[a]

Abstract. Oil palm empty fruit bunches are one of the underutilized plantation wastes. Lignin is one of the components of plant cell walls besides cellulose and hemicellulose that can be used as a raw material for the synthesis of lignin-based adhesives, namely lignin-urea-formaldehyde (LUF) adhesive resins. The polymerization reaction of LUF formation was confirmed from the shift and change in the FTIR wavenumber of the -C-O-C - ether group of LUF compared to UF and LF obtained during the synthesis process. The tensile strength test results of all adhesives produced exceeded the tensile strength value of commercial UF adhesives, and it was found that increasing the lignin concentration in the synthesized adhesives was directly proportional to the tensile strength value. Increasing the lignin concentration was also able to reduce formaldehyde emissions from all variations of adhesives produced, but was unable to exceed the lower formaldehyde emission value of UF adhesives.

Keywords : Palm Oil EFB, Lignin, Wood Adhesives, LUF

[a] *Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Negeri Medan, Jalan Willem Iskandar, Ps.V, Deli Serdang, 20221, Indonesia.*
Correspondence and requests for materials should be addressed to Dian Wardana
(email: dianwardana@unimed.ac.id)

Introduction

Oil palm is one of Indonesia's major and strategic agricultural commodities, as reflected in the vast plantation area nationwide [1]. According to Statistics Indonesia (BPS) 2023 data, the total oil palm plantation area reached 16,833,985 ha, comprising 577,937 ha owned by the government, 8,614,259 ha managed by private enterprises, 6,736,516 ha cultivated by smallholders, and 905,273 ha designated as land subject to verification (LAD). Meanwhile, North Sumatera ranks among the top five province in Indonesia in terms of land area, covering approximately 2,018,727 hectares [2].

During the processing of Crude Palm Oil (CPO) in the industry, approximately 230 kg of empty fruit bunches (EFB) are generated from every 1 ton of fresh fruit bunches processed, which is equivalent to about 23% [3]. EFB is one of the largest waste streams generate by the plantation industry, whose utilization is still considered limited, as it is generally used only for compost production [4], burned in boilers or incinerators [3], or simply buried in soil as material for reinforcing plantation roads [5], [6]. Chemical composition analysis of EFB indicates that it contains approximately 33-44% cellulose [7], 12-24% hemicellulose [8], and 21-26% lignin [9], where the presence of these constituent materials suggest a strong potential for EFB to be processed into functional material feedstocks.

One of the functional materials with potential to be produced is a lignin-based urea-formaldehyde (UF) adhesive resin, which in this study is referred to as lignin-urea-formaldehyde (LUF) resin. UF resin itself has long been recognized in the plywood and composite wood industries, however, this resin has a major drawback, namely the high formaldehyde emission it produces, particularly when exposed to elevated temperatures [10]. Resin with formaldehyde emissions have negative effects on air quality, particularly in indoor environments, and may pose health risks as a result of exposure to the volatile nature of formaldehyde [11]. This condition has ultimately led to the implementation of stringent regulation governing the use of conventional formaldehyde-based resins [12], thereby necessitating the development of more environmentally friendly formaldehyde-based resin alternatives that remain suitable for plywood and related wood-based industries [11]. It is well known that lignin is a natural polymer that acts as a natural adhesive, binding cellulose and hemicellulose within the structural framework of plant wood [13]. Previous related studies using lignin extracted from sugarcane bagasse [14] and lignin derived from bamboo fibers [15] reported that the adhesive strength of the resin increased with increasing lignin composition in the mixture, while simultaneously reducing the resulting formaldehyde emissions. In this study, we synthesize LUF adhesive resin using lignin isolated from EFB. The addition of lignin is expected to enhance bonding strength due to the presence of phenolic and hydroxyl functional groups [16] that promote strong interactions with the urea-formaldehyde matrix and wood surfaces, thereby improving resin cohesion and adhesion [17]. Simultaneously, lignin acts as a formaldehyde scavenger and partially replaces UF components, which reduces free formaldehyde and contributes to lower formaldehyde emissions [18].

Experimental

The Materials and Tools. The materials and equipment used in this study are briefly described as follows. Oil-palm empty fruit bunches (EFB), sodium hydroxide (NaOH), sulfuric acid (H_2SO_4), urea, formaldehyde solution (≈37 wt%), formic acid (HCOOH), deionized water, ammonium hydroxide (NH_4OH, 10%), hydrochloric acid (HCl, 0.1 N and 1 N), and a mixed indicator (methyl red/methylene blue) were used. The equipment included cutting tools, a grinder, sieves (60- and 100-mesh), a hot plate with magnetic stirring, a reflux setup, a water bath, a pH meter, filtration apparatus, an analytical balance, a Fourier transform infrared (FTIR) spectrometer, a universal testing machine, and hot and cold presses

Lignin Isolation from Oil-Palm Empty Fruit Bunches (EFB). EFB was cleaned, chopped to reduce size, sun-dried to constant mass, and milled to approximately 60-mesh. Delignification was performed using 5% (w/v) NaOH at a solid–liquid ratio of 1:10 (EFB:NaOH). The slurry was heated at 100 °C for 30 min, cooled, and the resulting black liquor was separated by filtration. The solid residue was washed with deionized water to neutrality (pH ≈ 7). The black liquor was heated and stirred at 60°C, while H_2SO_4 was added dropwise until the pH reached 2 and a brownish color was formed. The mixture was the allowed to stand for 24h to allow lignin precipitation. Subsequently, the precipitate was filtered, dried, ground, and sieved to approximately 100-mesh to obtain lignin powder [19].

Urea Hydroxymethylation. Urea and formaldehyde were mixed at a molar ratio of 1:2. The pH was adjusted to ~8.0 using 50% (w/w) NaOH. The mixture was refluxed at 40 °C under stirring for 30 min, then the temperature was raised to 90 °C and maintained for 60 min. Afterward, a few drops of formic acid (HCOOH) were added to adjust the pH to 5.0-5.5 [20].

Lignin Hydroxymethylation In a beaker, lignin and formaldehyde were combined; the pH was adjusted to 12.5 with 50% (w/w) NaOH and stirred until the lignin dissolved. The mixture was refluxed at 60°C for 90 min. The pH was then adjusted to 5.0-5.5 with formic acid and stirred at room temperature for 90 min. Three lignin-to-formaldehyde molar ratios were prepared: LUF-1 (0.25:1), LUF-2 (0.50:1), and LUF-3 (0.75:1) [21].

Synthesis of Lignin-Urea-Formaldehyde (LUF) Adhesive. The two prepolymers (hydroxymethylated urea and hydroxymethylated lignin) were combined and refluxed at 90 °C for 90 min with magnetic stirring. The mixture was cooled to room temperature and neutralized to pH ~7 with 50% (w/w) NaOH. The resulting LUF adhesive was then ready for testing [22].

FTIR Analysis. Fourier transform infrared (FTIR) spectroscopy was employed to analyze lignin-formaldehyde (LF) resin and its precursors (lignin and formaldehyde), urea-formaldehyde (UF) resin and its precursors (urea and formaldehyde), as well as the lignin-urea-formaldehyde (LUF) resin. The analysis was conducted to identify changes in absorption band intensities and wavenumber shifts, thereby confirming the formation of the LUF resin through comparative evaluation of its FTIR spectrum with those of the LF resin, UF resin, and their respective precursors.

Lap-Shear Bond Strength Test. Wood adherends (10 cm × 1 cm × 0.4 cm) with an overlap (shear) area of 4 cm × 1 cm (4 cm²) were used. Adhesive was applied uniformly at a spread rate of 190 g m^{-2} to one bonding surface. Cold pressing was conducted for 10 min, followed by hot pressing at 130 °C for 5 min. The laminates were conditioned at ambient temperature for 7 days. Dry-state bond strength was measured; a commercial adhesive was tested in parallel as a reference [23].

Formaldehyde Emission Test (Titrimetric Method). An adhesive sample (5.00 g) was placed in an Erlenmeyer flask, mixed with 15 mL deionized water, and homogenized. Two to three drops of mixed indicator (methyl red/methylene blue) were added. Subsequently, 5 mL of 10% NH_4OH and 5 mL of 1 N NaOH were added; the mixture was neutralized with 0.1 N HCl, capped, shaken, and incubated in a water bath at 30 °C for 30 min. The solution was titrated with 1 N HCl to the endpoint indicated by a color change from green to bluish-gray and finally to reddish-purple. A blank (without adhesive) was processed identically. Formaldehyde emission was calculated using Eq. (1).

$$Formaldehyde\ Emission\ (\%) = \frac{(V\ blank - V\ sample)\ x\ N\ HCl\ x\ 30{,}03}{m\ sample\ x\ 1000}\ x\ 100\% \tag{1}$$

Where *V* is the HCl volume (mL), *N* HCl is HCl normality (eq L^{-1}), *m* sample is sample mass (g), and 30.03 is the molar mass of formaldehyde (g mol^{-1}) [24].

Result and Discussion

FTIR Analysis. FTIR analysis is essential for identifying changes in functional groups and chemical bonding during resin formation. Figure 1 shows the FTIR spectra of lignin and formaldehyde in comparison with the corresponding lignin–formaldehyde (LF) resin (A), as well as urea and formaldehyde in comparison with the urea–formaldehyde (UF) resin (B), enabling evaluation of molecular interactions and structural evolution in the resin systems.

The FTIR spectrum of the isolated lignin exhibits characteristic absorption bands that are consistent with those reported for reference lignin in the literature. The presence of a broad absorption band at a wavenumber of 3425.40 cm^{-1}, attributed to -OH stretching, confirms the presence of phenolic structures, which are characteristic features of lignin molecular structure [25]. The presence of aromatic lignin groups was confirmed by absorption bands at a wavenumber of 2925.49 cm^{-1}, attributed to C-H stretching, and at 1637.48 cm^{-1} attributed to C=C stretching. This indicates that the backbone of the lignin structure is predominantly composed of aromatic compounds [26], [27]. Furthermore, the absorption band at wavenumber of 1222.65 cm-1 indicates vibrations f the aromatic ring attributed to the C-O stretching, which is characteristic of guaiacyl

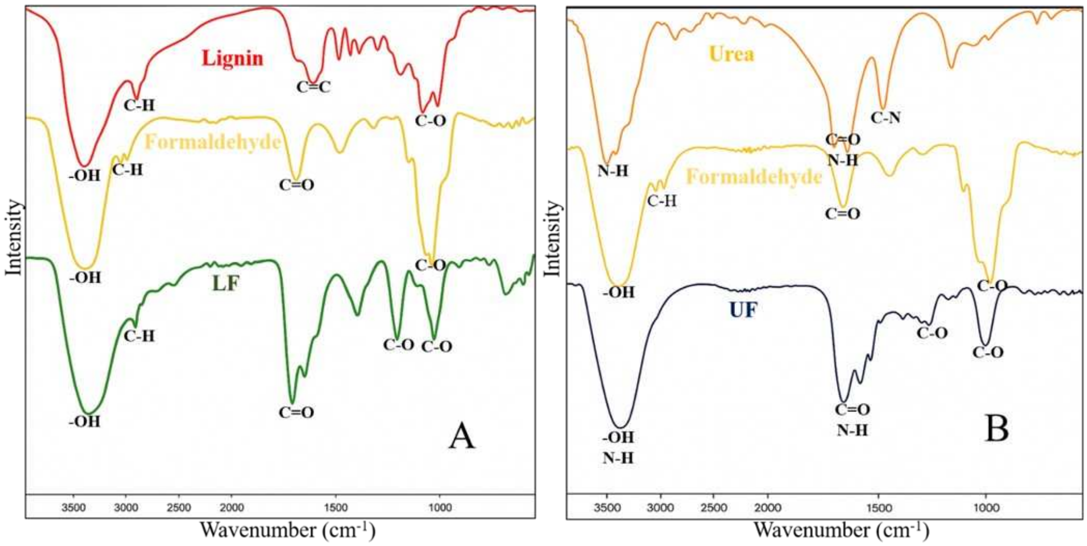

Figure 1. FTIR spectra of lignin-formaldehyde, LF (A) and urea-formaldehyde, UF (B) systems

units, while absorption band at 1328.80 cm-1 corresponds to aromatic ring vibrations originating from C-O stretching enchanced by the presence of methoxy groups in syringyl units [28], [29]. The C-O vibrations associated with methoxy ($-OCH_3$) ether groups were also identified in the 1222.65-1046.00 cm^{-1} region [29], [30]. The good agreement between the present results and the reference spectra provides strong evidence for the successful isolation of lignin. Although no quantitative purity measurement was conducted, the absence and significant reduction of cellulose and hemicellulose-related bands, typically observed around ±1730 cm^{-1} and within the 1420-1030 cm^{-1} region, qualitatively indicate a relatively high lignin purity [31].

The FTIR spectrum of formaldehyde exhibited an –OH stretching band at 3340.75 cm^{-1}, which is likely associated with the alcoholic solvent present in the 37% formaldehyde solution. An absorption at 2912.71 cm^{-1} indicates the presence of –CH groups [32], [33]. The aldehyde carbonyl was assigned to a band at 1641.38 cm^{-1} (–C=O), supported by a signal at 989.91 cm^{-1} corresponding to the symmetric stretching of the C–O–C linkage [34]. FTIR analysis of urea showed the $-NH_2$ functionality, identified by N-H stretching at 3442.56 cm^{-1} [35], [36]. An overlapping absorption of -C=O and -NH was observed at a wavenumber of 3332.48 $cm^{-1,}$ and a band at 1623.06 cm^{-1} was identified, originating from C-N bending [35].

FTIR spectroscopy was also employed to determine chemical interactions and condensation phemomena occurring during resin formation by

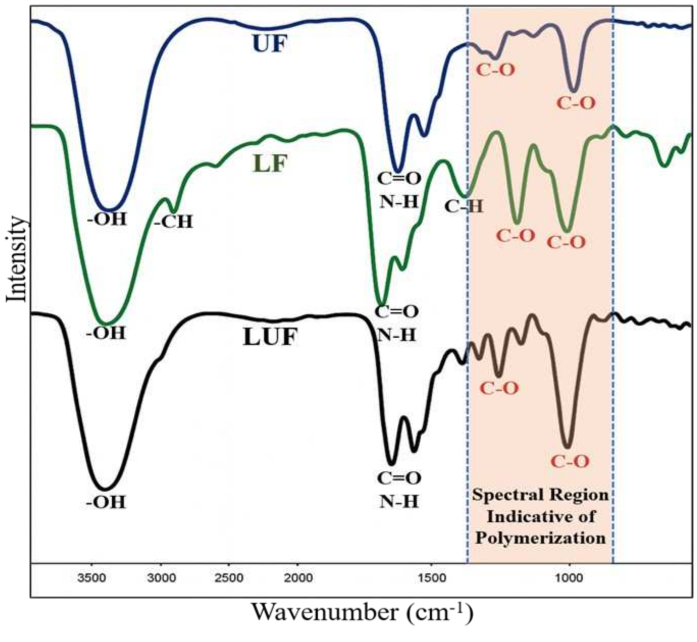

Figure 2. FTIR spectra acquired during LUF formation

examining changes in intensity and shifts in wavenumbers from the individual reactants to the final polymer system, as shown in Figure 2.

Evidence of polymerization through condensation processes was identified by observing shifts in wavenumbers and/or the emergence of new C-O absorption bands, which confirm the occurrence of condensation reaction between lignin-formaldehyde (LF) and urea-formaldehyde (UF) species. The specific region analysed was the wavenumber range of 1300-1100 cm^{-1}, which corresponds to the presence of C-O stretching vibrations of ether linkages [34]. The phenomenon of a reduced presence of free formaldehyde associated with formaldehyde emissions can also be observed from this spectrum. During LF formation, a decrease in absorption band corresponding to symmetric C-O-C stretching was observed, indicating the consumption of a portion of formaldehyde during the condensation process. It should be noted that two ether C-O-C absorption bands appeared during this process, suggesting that lignin is also capable of accommodating a portion of free formaldehyde. This phenomenon is consistent with the expectation of this study, in which the addition of lignin is able to reduce the resulting formaldehyde emissions [37], [38]. A similar phenomenon was also observed during the formation of UF, where the C-O band intensity diminished even further, indicating that urea more effectively scavenges free formaldehyde than lignin, consistent with lignin's comparatively lower reactivity as a reactant [39].

In the lignin-urea-formaldehyde (LUF) system, additional shifts and intensity changes of C-O bands relative to the LF and UF spectra signify the formation of new ether C-O linkages, confirming condensation between LF and UF to produce LUF [34]. Based on the previous FTIR analysis results, the condensation phenomena are schematically represented through chemical reaction as shown in Figure 4. It should be noted that this reaction provides only simplified conceptual description of the formation of new ether linkages as evidence of condensation occurring within the LUF system. The process is initiated by hydroxymethylation (stage 1.), followed by condensation (stage 2).

Tensile Strength Test. Tensile strength testing was conducted to evaluate the bonding strength of the synthesized adhesive resin, as well as to assess its ability to transfer stress across the wood-adhesive interfacial surface, as shown in Figure 5.

Urea-formaldehyde is a thermosetting resin that function by penetrating the wood surface and hardening through heating, forming strong polymeric bonds between the bonded wood surfaces [40]. Meanwhile, lignin adheres to the wood surface through hydrogen bonding with cellulose [41], [42]. The combination of these two adhesion mechanisms subsequently results in an adhesive with high bonding strength, as demonstrated by tensile strength testing, in which all synthesized adhesive variations exhibited bonding strengths exceeding that of commercial UF adhesive. This clearly demonstrates that increasing lignin concentration within a certain threshold has a direct correlation with the

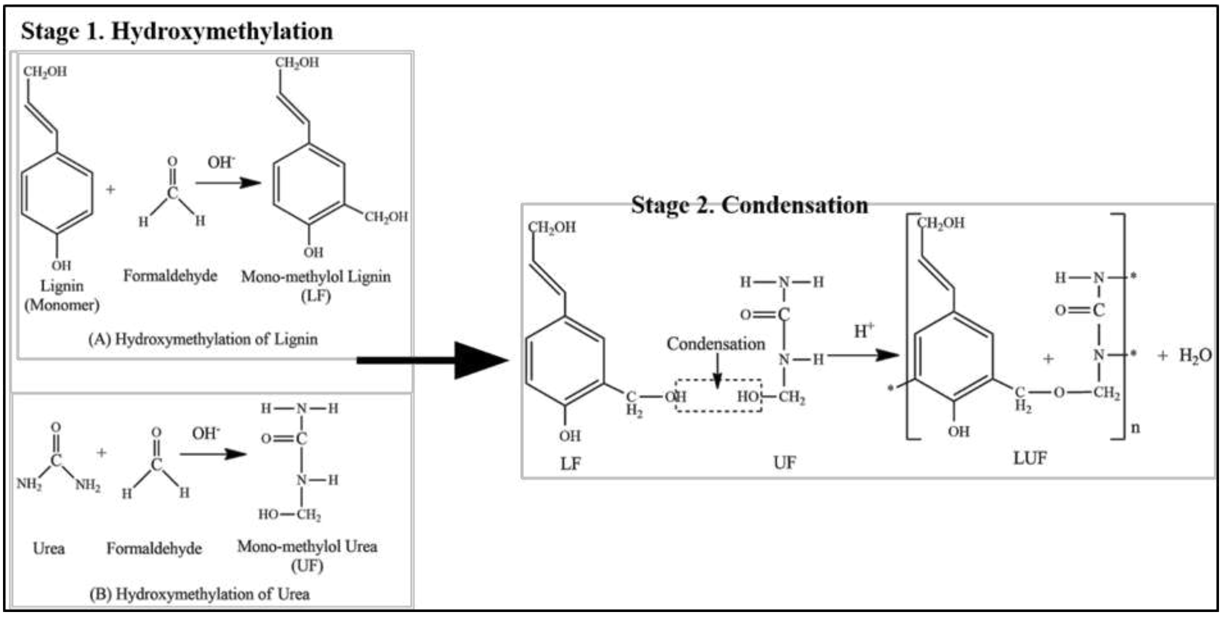

Figure 3. Proposed reaction scheme for LUF formation

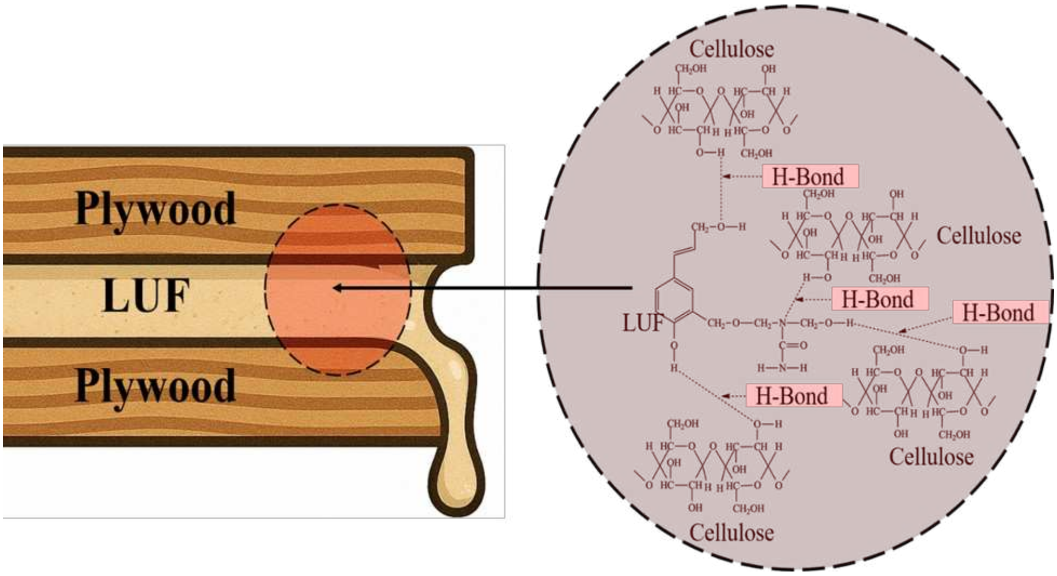

Figure 4. Ilustration of the molecular interaction between LUF and cellulose on

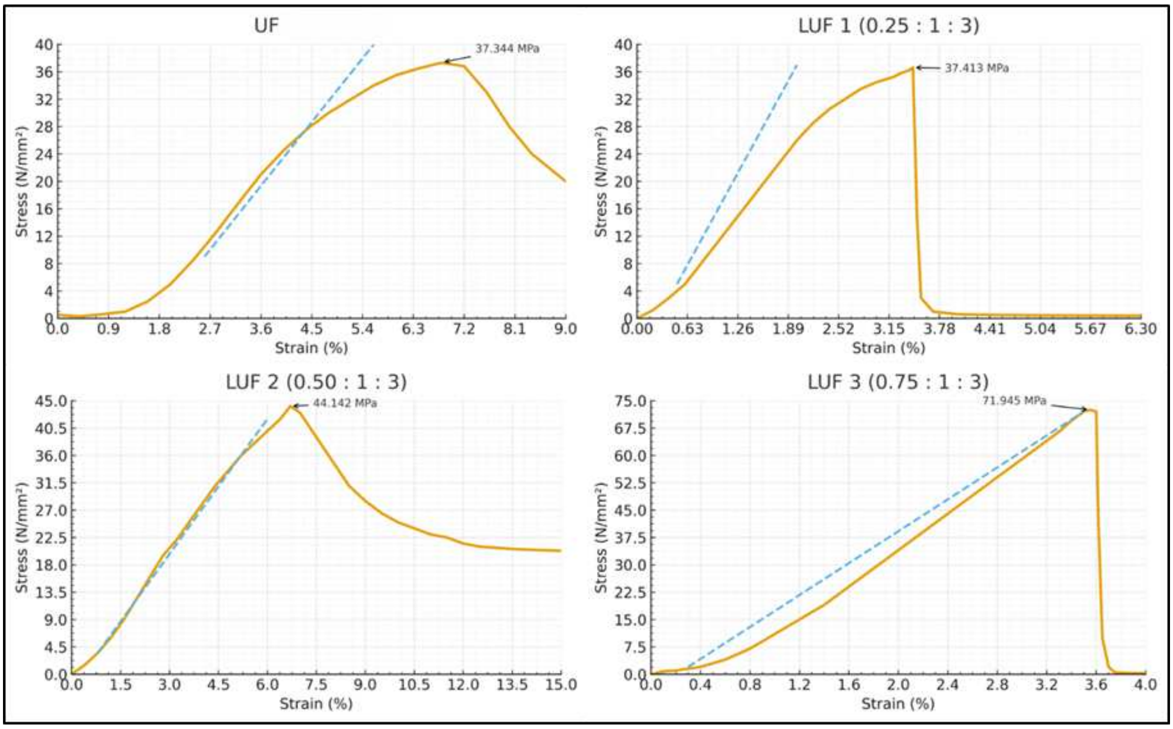

Figure 5. Tensile strength curves for all adhesive variations

resulting tensile strength.

This is directly reflected in the tensile strength values of each variation, namely 37.414 MPa (LUF 1), 44.142 MPa (LUF 2), and 71.945 MPa. The initial increase in tensile strength (37.414-44.142 MPa) indicates the initial reinforcing effect of lignin, where under these conditions lignin acts as an active component providing additional intermolecular interactions within the adhesive matrix [43]. The further increase in tensile strength to 71.945 MPa at the highest lignin concentration (LUF 3) indicates that lignin within the adhesive has transformed into a more rigid and highly interconnected polymeric network [44]. This enhancement phenomenon implies a more uniform distribution of stress across the wood -adhesive interface, which may occur through increased formation of hydrogen bonds with cellulose as well as an improvement in mechanical properties in the form of greater stiffness [45]. These results indicate that lignin does not merely function as a filler, but rather acts as an effective reinforcing agent that significantly enhances the mechanical performance of the LUF adhesive system at higher loadings.

Formaldehyde Emission Test Results. Formaldehyde emission testing showed that increasing lignin content in the formulation resulted in a gradual decrease in formaldehyde emissions, likely because the phenolic-hydroxyl groups in lignin can act as scavenging sites for free formaldehyde through hydroxymethylation and subsequent condensation reaction [46]. This trend indicates that a higher availability of formaldehyde will promote more effective interaction with reactive sites on lignin, thereby partially immobilizing free formaldehyde within the polymer network.

Nevertheless, the emissions from all synthesized LUF adhesives remained significantly higher than those of commercial UF adhesive, which is associated with the large and heterogenous macromolecular structure of lignin and its inherently lower reactivity toward formaldehyde compared to urea [13], [47]. As a result, a portion of formaldehyde is not fully consumed during the curing process and may be released through the cleavage or hydrolysis of labile ether linkages within the cured network [48]. These findings indicate that although lignin incorporation contributes to the scavenging of a portion of free formaldehyde, additional treatments or procedures, such as chemical activation of lignin, optimization of curing conditions, or the addition of scavenging agents, are still required to further suppress the formaldehyde emissions [49].

Table 1. Formaldehyde emission test results for all adhesive variants

Variant	Formaldehyde Emission (%)
LUF 1 (0,25 : 1 : 3)	11.15
LUF 2 (0,50 : 1 : 3)	10.61
LUF 3 (0,75 : 1 : 3)	9.86
Commercial UF	3.74

Conclusion

In this study, lignin extracted from oil palm empty fruit bunches (EFB) was successfully incorporated into lignin–urea–formaldehyde (LUF) adhesive resin, as confirmed by FTIR analysis indicating the formation of new ether linkages. Increasing lignin content significantly enhanced tensile strength and reduced formaldehyde emissions due to its scavenging effect. However, the emission levels remained higher than those of commercial UF resin, suggesting that further optimization is required

Acknowledgements

The author would like to thank the Chemistry Laboratory of Universitas Negeri Medan for providing facilities and technical assistance thoughout this study.

Author Contributions

All authors made substantial contributions to the work, including conceptualization, data acquisition, supervision, and manuscript preparation. All authors reviewed and approved the final manuscript.

References

[1] K. F. Purba, N. A. Evalia, R. R. H. Teapon, N. Rumkel, and P. K. D. Hayati, “Foresight Strategy for Sustainable Oil Palm Development in East Halmahera Indonesia,” International Journal of Sustainable Development and Planning, vol. 18, no. 7, Jul. 2023, doi: 10.18280/ijsdp.180720.

[2] Badan Pusat Statistik, Statistik Kelapa Sawit Indonesia 2023, vol. 17. Jakarta: BPS, 2024.

[3] R. Nabila et al., “Oil palm biomass in Indonesia: Thermochemical upgrading and its utilization,” Apr. 01, 2023, Elsevier Ltd. doi: 10.1016/j.rser.2023.113193.

[4] O. B. Abogunrin-Olafisoye, O. Adeyi, A. J. Adeyi, and E. O. Oke, “Sustainable utilization of oil palm residues and waste in nigeria: practices, prospects, and environmental considerations,” Apr. 01, 2024, Elsevier B.V. doi: 10.1016/j.wmb.2024.01.011.

[5] T. Waluyo, M. Anggraini, and L. Dwi Putri, “The Shear Strength of Clay Stabilized with Palm Bunch Ash and Cement,” Civilla : Jurnal Teknik Sipil Universitas Islam Lamongan, vol. 8, no. 2, pp. 215–222, Oct. 2023, doi: 10.30736/cvl.v8i2.1139.

[6] Y. F. Arifin, M. Arsyad, R. Siswanto, I. K. T. F. Astawa, M. H. Ridha, and M. R. Ramadhani,

"TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL," International Journal of GEOMATE, vol. 23, no. 99, pp. 72–81, 2022, doi: 10.21660/2022.99.3610.

[7] S. Susi, M. Ainuri, W. Wagiman, and M. A. F. Falah, "High-Yield Alpha-Cellulose from Oil Palm Empty Fruit Bunches by Optimizing Thermochemical Delignification Processes for Use as Microcrystalline Cellulose," Int. J. Biomater., vol. 2023, 2023, doi: 10.1155/2023/9169431.

[8] M. Mahardika et al., "Recent Developments in Oil Palm Empty Fruit Bunch (OPEFB) Fiber Composite," 2024, Taylor and Francis Ltd. doi: 10.1080/15440478.2024.2309915.

[9] H. Setiawan et al., "Optimized supply chain of empty fruit bunches as feedstocks for second generation bioethanol production," Case Studies in Chemical and Environmental Engineering, vol. 10, Dec. 2024, doi: 10.1016/j.cscee.2024.100950.

[10] J. Chrobak, J. Iłowska, and A. Chrobok, "Formaldehyde-Free Resins for the Wood-Based Panel Industry: Alternatives to Formaldehyde and Novel Hardeners," Aug. 01, 2022, MDPI. doi: 10.3390/molecules27154862.

[11] L. Zhai, J. Zhao, B. Xu, Y. Deng, and Z. Xu, "Influence of indoor formaldehyde pollution on respiratory system health in the urban area of Shenyang, China," Afr. Health Sci., vol. 13, no. 1, Apr. 2013, doi: 10.4314/ahs.v13i1.19.

[12] X. Zhou, W. Li, X. Wang, and Y. Wang, "Health risk assessment of indoor formaldehyde exposure across Chinese residences: Effects of building material grades," J. Hazard. Mater., vol. 490, p. 137831, Jun. 2025, doi: 10.1016/j.jhazmat.2025.137831.

[13] G. Yang, Z. Gong, X. Luo, L. Chen, and L. Shuai, "Bonding wood with uncondensed lignins as adhesives," Nature, vol. 621, no. 7979, pp. 511–515, Sep. 2023, doi: 10.1038/s41586-023-06507-5.

[14] H. Younesi-Kordkheili, "Reduction of formaldehyde emission from urea-formaldehyde resin by maleated nanolignin," Int. J. Adhes. Adhes., vol. 132, p. 103677, Jun. 2024, doi: 10.1016/j.ijadhadh.2024.103677.

[15] S. Gürsoy and N. Ayrilmis, "Effect of Lignin Modification of Recycled and Fresh Wood Fibers on Physical, Mechanical, and Thermal Properties of Fiberboard," Forests, vol. 14, no. 10, Oct. 2023, doi: 10.3390/f14102007.

[16] N. Anter et al., "Dual-functionalized lignin as a sustainable modifier for high-performance phenol-formaldehyde adhesives in plywood production," RSC Adv., vol. 15, no. 39, pp. 32118–32130, 2025, doi: 10.1039/D5RA04233J.

[17] E. Bellinetto, N. Fumagalli, M. Astorri, S. Turri, and G. Griffini, "Elucidating the Role of Lignin Type and Functionality in the Development of High-Performance Biobased Phenolic Thermoset Resins," ACS Appl. Polym. Mater., vol. 6, no. 2, pp. 1191–1203, Jan. 2024, doi: 10.1021/acsapm.3c02136.

[18] Y. Zhang, S. Stepanova, K. Van Aelst, and B. F. Sels, "Consider lignin's hydroxyl groups content and type, its molecular weight and content when converting it into epoxy resin," Curr. Opin. Green Sustain. Chem., vol. 40, p. 100750, Apr. 2023, doi: 10.1016/j.cogsc.2022.100750.

[19] H. Hermansyah et al., "Delignification of Oil Palm Empty Fruit Bunch using Peracetic Acid and Alkaline Peroxide Combined with the Ultrasound," International Journal of Technology, vol. 10, no. 8, p. 1523, Dec. 2019, doi: 10.14716/ijtech.v10i8.3464.

[20] P. Christjanson, T. Pehk, and K. Siimer, "Hydroxymethylation and polycondensation reactions in urea–formaldehyde resin synthesis," J. Appl. Polym. Sci., vol. 100, no. 2, pp. 1673–1680, Apr. 2006, doi: 10.1002/app.23782.

[21] Y. Duan et al., "Lignin Impacts on the Lignin-urea-formaldehyde Copolymer Resin and the Reaction Mechanism," Chem.J.Chinese.Universities, vol. 40, 2019, doi: https://doi.org/10.7503/cjcu20180778.

[22] Z. Wang, J. W. Xue, J. B. Qu, and W. X. Liu, "Synthesis of Wood Lignin-Urea-Formaldehyde Resin Adhesive," Adv. Mat. Res., vol. 560–561, pp. 242–246, Aug. 2012, doi: 10.4028/www.scientific.net/AMR.560-561.242.

[23] ASTM, Standard test method for strength properties of adhesive bonds in shear by compression loading, vol. D905-08. ASTM International, West Conshohocken Pennsylvania, 2021.

[24] ASTM, Standard test method for determining formaldehyde concentrations in air from wood products using a small-scale chamber., vol. D 6007. ASTM International, 2014.

[25] B. Podkościelna, K. Wnuczek, M. Goliszek, T. Klepka, and K. Dziuba, "Flammability Tests and Investigations of Properties of Lignin-Containing Polymer Composites Based on Acrylates," Molecules, vol. 25, no. 24, Dec. 2020, doi: 10.3390/MOLECULES25245947.

[26] V. Hemmilä, R. Hosseinpourpia, S. Adamopoulos, and A. Eceiza, "Characterization of Wood-based Industrial Biorefinery Lignosulfonates and Supercritical Water Hydrolysis Lignin," Waste Biomass Valorization, vol. 11, no. 11, pp. 5835–5845, Nov. 2020, doi: 10.1007/s12649-019-00878-5.

[27] S. Gonçalves, J. Martins, N. T. Paiva, D. Paiva, L. H. Carvalho, and F. D. Magalhães, "The Potential of Visible Spectroscopy as a Tool for the In-Line Monitoring of Lignin Methylolation," Polymers (Basel)., vol. 15, no. 1, Jan. 2023, doi: 10.3390/polym15010178.

[28] S. Bhagia et al., "Nanoscale FTIR and Mechanical Mapping of Plant Cell Walls for Understanding Biomass Deconstruction," ACS Sustain. Chem. Eng., vol. 10, no. 9, pp. 3016–3026, Mar. 2022, doi: 10.1021/acssuschemeng.1c08163.

[29] S. Bhattacharyya, L. Matsakas, U. Rova, and P. Christakopoulos, "Melt stable functionalized organosolv and kraft lignin thermoplastic," Processes, vol. 8, no. 9, Sep. 2020, doi: 10.3390/pr8091108.

[30] X. Yue, Z. Li, S. S. Lam, W.-X. Peng, and Y. He, "Reuse of Cornus officinalis nutlet for bioenergy," Bioresources, vol. 17, no. 4, pp. 6411–6444, Sep. 2022, doi: 10.15376/biores.17.4.6411-6444.

[31] G. Zhou, G. Taylor, and A. Polle, "FTIR-ATR-based prediction and modelling of lignin and energy contents reveals independent intra-specific variation of these traits in bioenergy poplars," Plant Methods, vol. 7, no. 1, Apr. 2011, doi: 10.1186/1746-4811-7-9.

[32] K. K. Barakoti, P. Subedi, F. Chalyavi, S. Gutierrez-Portocarrero, M. J. Tucker, and M. A. Alpuche-Aviles, "Formaldehyde Analysis in Non-Aqueous Methanol Solutions by Infrared Spectroscopy and Electrospray Ionization," Front. Chem., vol. 9, Jul. 2021, doi: 10.3389/fchem.2021.678112.

[33] H.-Y. Jian, C.-T. Yang, and L.-K. Chu, "Gaseous infrared spectra of the simplest geminal diol CH 2 (OH) 2 and the isotopic analogues in the hydration of formaldehyde," Physical Chemistry Chemical Physics, vol. 23, no. 27, pp. 14699–14705, 2021, doi: 10.1039/D1CP01354H.

[34] R. Seidl, S. Weiss, R. W. Kessler, W. Kessler, E. M. Zikulnig-Rusch, and A. Kandelbauer, "Prediction of residual curing capacity of melamine-formaldehyde resins at an early stage of synthesis by in-line ftir spectroscopy," Polymers (Basel)., vol. 13, no. 15, Aug. 2021, doi: 10.3390/polym13152541.

[35] Z. Morávková, J. Podešva, V. Shabikova, S. Abbrent, and M. Dušková-Smrčková, "Hydrogen Bonding of Trialkyl-Substituted Urea in Organic Environment," Molecules, vol. 30, no. 7, Apr. 2025, doi: 10.3390/molecules30071410.

[36] E. Tan, N. Binti Julmohammad, W. Y. Koh, M. S. Abdullah Sani, and B. Rasti, "Application of ATR-FTIR Incorporated with Multivariate Data Analysis for Discrimination and Quantification of Urea as an Adulterant in UHT Milk," Foods, vol. 12, no. 15, Aug. 2023, doi: 10.3390/foods12152855.

[37] A. Dorieh, F. Pahlavan, K. Hájková, Š. Hýsek, M. Farajollah Pour, and E. H. Fini, "Advancing Sustainable Building Materials: Reducing Formaldehyde Emissions in Medium Density Fiber Boards with Lignin Nanoparticles," Adv. Sustain. Syst., vol. 8, no. 9, Sep. 2024, doi: 10.1002/adsu.202400102.

[38] D. Li et al., "Melamine–Urea–Formaldehyde Resin Adhesive Modified with Recycling Lignin: Preparation, Structures and Properties," Forests, vol. 14, no. 8, Aug. 2023, doi: 10.3390/f14081625.

[39] M. Fazeli et al., “Lignin beyond the status quo : recent and emerging composite applications,” Green Chemistry, vol. 26, no. 2, pp. 593–630, 2024, doi: 10.1039/D3GC03154C.

[40] M. Altgen et al., “Chemical imaging to reveal the resin distribution in impregnation-treated wood at different spatial scales,” Mater. Des., vol. 225, Jan. 2023, doi: 10.1016/j.matdes.2022.111481.

[41] T. Zhang, Y. Hu, Y. Dong, S. Jiang, and X. Han, “The Influence of Hydrogen Bonding in Wood and Its Modification Methods: A Review,” Polymers (Basel)., vol. 17, no. 15, p. 2064, Jul. 2025, doi: 10.3390/polym17152064.

[42] T. Meng et al., “In Situ Lignin Adhesion for High-Performance Bamboo Composites,” Nano Lett., vol. 23, no. 18, pp. 8411–8418, Sep. 2023, doi: 10.1021/acs.nanolett.3c01497.

[43] M. Hazwan Hussin, A. A. Aziz, A. Iqbal, M. N. M. Ibrahim, and N. H. A. Latif, “Development and characterization novel bio-adhesive for wood using kenaf core (Hibiscus cannabinus) lignin and glyoxal,” Int. J. Biol. Macromol., vol. 122, pp. 713–722, Feb. 2019, doi: 10.1016/j.ijbiomac.2018.11.009.

[44] M. A. R. Lubis et al., “Influence of Lignin Content and Pressing Time on Plywood Properties Bonded with Cold-Setting Adhesive Based on Poly (Vinyl Alcohol), Lignin, and Hexamine,” Polymers (Basel)., vol. 14, no. 10, p. 2111, May 2022, doi: 10.3390/polym14102111.

[45] [Y. Jin, T. Araki, N. Kamimura, E. Masai, M. Nakamura, and T. Michinobu, “Biodegradable and wood adhesive polyesters based on lignin-derived 2-pyrone-4,6-dicarboxylic acid,” RSC Sustainability, vol. 2, no. 7, pp. 1985–1993, 2024, doi: 10.1039/D4SU00163J.

[46] Y. Ma et al., “Biodegradable Films Prepared from Pulp Lignocellulose Adhesives of Urea Formaldehyde Resin Modified by Biosulfonate,” Polymers (Basel)., vol. 14, no. 14, Jul. 2022, doi: 10.3390/polym14142863.

[47] J. Karthäuser, V. Biziks, C. Mai, and H. Militz, “Lignin and lignin-derived compounds for wood applications—A review,” 2021, MDPI AG. doi: 10.3390/molecules26092533.

[48] Y. Chen, X. Gong, G. Yang, Q. Li, and N. Zhou, “Preparation and characterization of a nanolignin phenol formaldehyde resin by replacing phenol partially with lignin nanoparticles,” RSC Adv., vol. 9, no. 50, pp. 29255–29262, 2019, doi: 10.1039/C9RA04827H.

[49] H. Younesi-Kordkheili and A. Pizzi, “A Comparison among Lignin Modification Methods on the Properties of Lignin–Phenol–Formaldehyde Resin as Wood Adhesive,” Polymers (Basel)., vol. 13, no. 20, p. 3502, Oct. 2021, doi: 10.3390/polym13203502.