INNOVATIONS IN ADHESIVES WITH LIGNIN NANOPARTICLES FOR BONDING IN THE WOOD INDUSTRY: A LITERATURE REVIEW

INOVAÇÕES EM ADESIVOS COM NANOPARTÍCULAS DE LIGNINA PARA COLAGEM NA INDÚSTRIA MADEIREIRA: REVISÃO DE LITERATURA

INNOVACIONES EN ADHESIVOS CON NANOPARTÍCULAS DE LIGNINA PARA EL ENCOLADO EN LA INDUSTRIA MADERERA: REVISIÓN DE LA LITERATURA

https://doi.org/10.56238/sevened2026.008-096

Carolina Aparecida dos Santos[1], Flávia Maria Silva Brito[2], Thaís Brito Sousa[3], Laise de Jesus dos Santos[4], Rosalvo Maciel Guimarães Neto[5], José Benedito Guimarães Junior[6]

ABSTRACT

The growing concern for environmental sustainability and the need to reduce dependence on fossil resources have driven the search for more environmentally friendly materials in the timber industry. In this scenario, adhesives used in bonding wood and its derivatives play a central role, as they directly influence the performance, durability, and environmental impact of lignocellulosic panels and products. Traditionally, this industry employs synthetic adhesives based on petroleum derivatives, which exhibit excellent bonding efficiency and stability over time. However, the use of these materials is associated with the emission of volatile organic compounds, especially formaldehyde, in addition to issues related to the toxicity and environmental footprint of their production. Given these limitations, lignin has aroused increasing interest as a sustainable alternative for the development of new adhesive systems or for the modification of conventional formulations. Recent advances have shown that the conversion of lignin to the nanoscale significantly expands its application possibilities. Lignin nanoparticles exhibit a high surface area, better dispersion in the adhesive matrix, and greater availability of functional groups, favoring more efficient chemical and physical interactions. Incorporated into synthetic adhesives, they can contribute to increased mechanical strength, improved thermal stability, and greater moisture resistance, as well as positively influencing the adhesive's curing kinetics. In this context, this chapter aims to present innovations related to the use of lignin nanoparticles in adhesives for bonding wood and its derivatives.

Keywords: Bonding Quality. Nanotechnology. Adhesion. Wood.

[1] Dr. in Biomaterials Engineering. Universidade Federal de Lavras. E-mail: carolinaapnep@gmail.com
[2] Postdoctoral Fellow in Forest Sciences. Universidade Federal do Espirito Santo.
E-mail: faengflorestal@gmail.com
[3] Dr. in Biomaterials Engineering. Universidade Federal de Lavras. E-mail: thaisbflorestal@gmail.com
[4] Master's degree in Wood Science and Technology. Universidade Federal de Lavras.
E-mail: laise.santos1@estudante.ufla.br
[5] Dr. in Wood Science and Technology. Universidade Federal de Lavras. E-mail: rmgnetto@yahoo.com.br
[6] Dr. in Wood Science and Technology. Universidade Federal de Lavras. E-mail: jose.guimaraes@ufla.br

RESUMO
A crescente preocupação com a sustentabilidade ambiental e a necessidade de reduzir a dependência de recursos fósseis têm impulsionado a busca por materiais mais ecológicos na indústria madeireira. Nesse cenário, os adesivos utilizados na colagem de madeira e seus derivados ocupam papel central, uma vez que influenciam diretamente o desempenho, a durabilidade e o impacto ambiental dos painéis e produtos lignocelulósicos. Tradicionalmente, essa indústria emprega adesivos sintéticos à base de derivados do petróleo, que apresentam excelente eficiência de colagem e estabilidade ao longo do tempo. No entanto, o uso desses materiais está associado à emissão de compostos orgânicos voláteis, especialmente formaldeído, além de questões relacionadas à toxicidade e à pegada ambiental de sua produção. Diante dessas limitações, a lignina tem despertado crescente interesse como alternativa sustentável para o desenvolvimento de novos sistemas adesivos ou para a modificação de formulações convencionais. Avanços recentes têm demonstrado que a conversão da lignina em escala nanométrica amplia significativamente suas possibilidades de aplicação. As nanopartículas de lignina apresentam elevada área superficial, melhor dispersão na matriz adesiva e maior disponibilidade de grupos funcionais, favorecendo interações químicas e físicas mais eficientes. Incorporadas aos adesivos sintéticos podem contribuir para o aumento da resistência mecânica, melhoria da estabilidade térmica e maior resistência à umidade, além de influenciar positivamente a cinética de cura do adesivo. Nesse contexto, este capítulo tem como objetivo apresentar inovações relacionadas ao uso de nanopartículas de lignina em adesivos para colagem de madeira e seus derivados.

Palavras-chave: Qualidade de Colagem. Nanotecnologia. Adesão. Madeira.

RESUMEN
La creciente preocupación por la sostenibilidad ambiental y la necesidad de reducir la dependencia de los recursos fósiles han impulsado la búsqueda de materiales más ecológicos en la industria maderera. En este contexto, los adhesivos utilizados para el encolado de la madera y sus derivados desempeñan un papel central, ya que influyen directamente en el rendimiento, la durabilidad y el impacto ambiental de los paneles y productos lignocelulósicos. Tradicionalmente, esta industria emplea adhesivos sintéticos derivados del petróleo, que presentan una excelente eficiencia de encolado y estabilidad a lo largo del tiempo. No obstante, el uso de estos materiales está asociado a la emisión de compuestos orgánicos volátiles, especialmente formaldehído, además de cuestiones relacionadas con la toxicidad y la huella ambiental de su producción. Ante estas limitaciones, la lignina ha despertado un creciente interés como alternativa sostenible para el desarrollo de nuevos sistemas adhesivos o para la modificación de formulaciones convencionales. Avances recientes han demostrado que la conversión de la lignina a escala nanométrica amplía significativamente sus posibilidades de aplicación. Las nanopartículas de lignina presentan una elevada área superficial, mejor dispersión en la matriz adhesiva y mayor disponibilidad de grupos funcionales, favoreciendo interacciones químicas y físicas más eficientes. Al incorporarse a los adhesivos sintéticos, pueden contribuir al aumento de la resistencia mecánica, a la mejora de la estabilidad térmica, a una mayor resistencia a la humedad y a una influencia positiva en la cinética de curado del adhesivo. En este contexto, este capítulo tiene como objetivo presentar innovaciones relacionadas con el uso de nanopartículas de lignina en adhesivos para el encolado de la madera y sus derivados.

Palabras clave: Calidad de Encolado. Nanotecnología. Adhesión. Madera.

1 INTRODUCTION

The wood industry is considered one of the most important and promising sectors on a global scale due to the wide use of wood and its derivatives in different segments, such as civil construction, furniture industry, packaging and panels. Iwakiry & Trianosky (2020) conceptualize wood panels as products composed of wood elements such as veneers, battens, particles and fibers, obtained from the reduction of solid wood and reconstituted through adhesive bonding.

As in the production of panels, the manufacture of elements for civil construction, the furniture industry and the packaging sector also depend on the use of adhesives for the union and adequate performance of materials. The increasing demand for sustainable and high-performance materials has driven the development of new technologies in the wood industry, especially in the field of adhesives.

Traditionally, formaldehyde-based synthetics, such as phenol-formaldehyde and urea-formaldehyde, have been widely employed due to their good mechanical performance and stability. However, these products have environmental and health limitations, mainly related to the emission of volatile organic compounds (VOCs) and the non-renewable origin of their components (Furtini et al., 2022). In this context, the search for more ecological and efficient alternatives has led researchers to explore the use of lignin nanoparticles as innovative additives in adhesive formulations.

Lignin nanoparticles, obtained by reducing lignin to the nanometric scale (less than 100 nm), have greater surface area and reactivity, favoring more efficient interactions in composites and expanding their potential as a sustainable and functional material (Zhang et al., 2021) and represents a promising strategy for innovation and sustainability in the forestry sector.

Thus, this chapter initially addresses the main synthetic adhesives used in the bonding of wood and derivatives. Then, the innovations associated with the incorporation of lignin nanoparticles are presented, highlighting some works already carried out that have shown good performance and potential for the development of more sustainable and technologically advanced products for the wood industry.

2 DEVELOPMENT

2.1 SYNTHETIC ADHESIVES

Adhesives are one of the main constituents in the production of panels, due to the physical and mechanical properties they provide, being able to grant different performances by varying the chemical composition and concentration in the particle mixture (Barbirato et al., 2018; Mantanis et al., 2018). These products are used in a large number of structural and non-structural applications, in production lines ranging from panels for indoor use to panels for outdoor use, furniture and support structures in different typologies of buildings (Youngquist, 1999).

Adhesives have a very important function in the wood-based panel industry. Formaldehyde-based synthetic adhesives, such as urea-formaldehyde (Figure 1), phenol-formaldehyde (Figure 2), and melamine-formaldehyde (Figure 3), are generally used for wood panel production (Faris et al., 2016), such as plywood, medium-density fiberboard, and particle board. These resins have been applied in the panel industry due to their excellent bonding properties, good water resistance (Pizzi et al., 2020).

Figure 1

Urea-formaldehyde resin (trademark: Redemite) and hardener

Source:https://www.redelease.com.br/produtos/resinas/ureiaformol?srsltid=AfmBOoq0Dv2UPGZahm_SNd8r7lCqslDDJulIwJWNOYWO6hu3KTX4-4a

Figure 2

Phenol formaldehyde

Source: https://pt.made-in-china.com/co_shuanghechemical/product_Best-Price-Phenol-Formaldehyde-Resin-Liquid-Manufacturers-Used-for-Friction_uoennsrhny.html

Figure 3

Melamine formaldehyde

Source: https://portuguese.alibaba.com/product-detail/Taiwan-Liquid-Melamine-Resin-Counter-Type-10000004159693.html

The first adhesive synthesized was phenol-formaldehyde in 1929, soon after in 1931 urea-formaldehyde. Urea has great applicability in the furniture industry worldwide, and 90% of wood panels use this resin, due to its low cost compared to others. Phenol has as its main characteristic the high resistance to moisture, being considered for outdoor use. Its use is mainly intended for the production of waterproof plywood, fiberboard, structural agglomerate boards of the "waferboard" and "OSB" types (Iwakiri; Trianoski, 2020).

Melamine resin (melamine-formaldehyde) stands out for its high durability and versatility, in addition to providing greater rigidity to the panels, good resistance to humidity and excellent performance against heat and fire. However, its main obstacle is the high cost. To circumvent this limitation, it is common to add urea to melamine, giving rise to the MUF (melamine-urea-formaldehyde) adhesive, which maintains good technical properties and significantly reduces the cost of melamine adhesive (Iwakiri; Trianosky 2005).

For structural purposes, the Brazilian Standard - NBR 7190, Brazilian Association of Technical Standards - ABNT (2022), determines that the adhesive must be waterproof, however, the medium in which the glued parts will be used must be taken into account, that is, temperature and moisture content. The quality of the bond is verified by the glue line, which serves to predict the performance of the adhesive when subjected to the application of stresses. This varies from the properties of the adhesive used to the characteristic of the wood, which will provide a quality product (Mendoza *et al*., 2017).

The problems caused by the emission of formaldehyde to the environment and to man are increasing targets of research, as a result of the harmful effects they can cause. However, the world has increasingly sought alternative sources to produce adhesives using renewable raw materials (Carvalho et al., 2014). Formaldehyde is a crosslinking agent used in the production, fixation, and curing of adhesives (Solt et al., 2019). It is seen as a human carcinogenic compound, due to its release in the synthesis of adhesives, in application on wood panels, and release after manufacture (Ferreira et al., 2019).

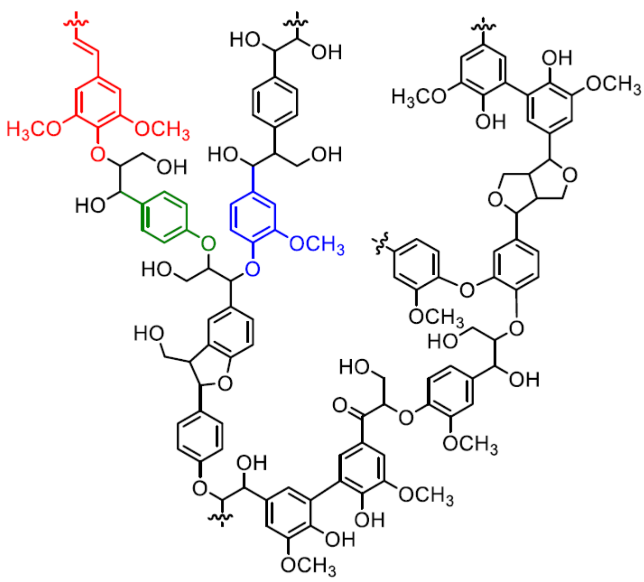
2.2 LIGNIN

Lignin is an essential structural polymer of vascular plants, responsible for rigidity, efficient conduction of water and nutrients, and protection against external agents, and is indispensable for plant growth and survival (Liu etal., 2018). The structure of lignin (Figure 4) has many functional groups that affect its dissolution, such as hydroxyl (aromatic and aliphatic), methoxyl, carbonyl, and carboxyl groups (Garcia et al., 2009).

In addition, lignin may contain side chains and structural variations, contributing to its heterogeneity and diverse chemical properties (Putra et al., 2025). It consists of the oxidative polymerization of three monolignol precursors: p-coumaryl alcohol, coniferyl alcohol, and synapyl alcohol, which originate the three primary lignin units: p-hydroxyphenyl (H), guaiacil (G), and syringyl (S) (Del Rio et al., 2020).

Figure 4

Macromolecular structure of lignin. (The main monolignolic units are colored red for synapyl alcohol, blue for guaiacyl alcohol, and green for p-coumaryl alcohol)



Source: Karunarathna & Smith (2020).

Despite decades of research, lignin is still little used in biorefineries, being mostly burned for energy generation, instead of being converted into products with higher added value. However, in the last decade, there has been a strong resurgence of interest in its valorization, driven by advances in the understanding of its chemistry, structure, and plasticity, as well as the development of new catalytic and biological routes capable of transforming this abundant biopolymer into materials and compounds of greater value (Katahira et al., 2018).

The controlled extraction of lignin enables its use in high value-added products, such as polymers, fuels, and adhesives, promoting innovation, sustainability, and new market opportunities (Sethupathy et al., 2022; Putra et al., 2025). The valorization of lignin is a key component of the circular bioeconomy, The valorization of lignin is fundamental for the circular bioeconomy, as it reduces environmental impacts, optimizes the use of resources, and enables sustainable alternatives to fossil-based products (Shorey et al., 2024).

2.3 ADHESIVES REINFORCED WITH LIGNIN NANOPARTICLES

Bio-based resins, such as lignin, are valued for their phenolic structure, which allows them to partially or fully replace phenol in phenol-formaldehyde (PF) adhesives (Zhang et al., 2013). In this context, nanotechnology expands the potential of lignin by enabling its application in the form of nanoparticles, promoting improvements in adhesive performance.

The nanotechnological field involves the creation and application of nanometer-scale systems, between atoms and submicron structures, as well as their incorporation into larger systems. At this scale, the materials have physical, chemical, and biological properties that are different from those observed in larger dimensions, which enables new applications and better performance (Nasrollahzadeh et al., 2019). One of the main advantages of particles at nanometer scales is that they have a larger surface area when dispersed uniformly in a layer (Clausen et al., 2010). Nanoparticles with dimensions below 100 nm enable the unique combination of mechanical and physical properties. These ultrafine particles receive the value due to their unique nature, high surface energy, large specific surface area, and interfacial area with polymer matrix (Ahmadi, 2019).

Examples of uses of these nanomaterials in innovation and technology are nanofibers, for which studies are being carried out on lignin. The production of lignin nanoparticles is an efficient strategy to improve their adhesive properties because reducing the size of the particles significantly increases the surface area. This larger contact area favors interaction with other materials, resulting in better adhesion. In addition, on a nanometric scale, lignin now has properties superior to those of the original material, expanding its application potential (Antov et al., 2022).

The main benefit of obtaining nanoparticles from lignin is a noticeable increase in surface area and, consequently, greater dispersion in water. This is because lignin is naturally unable to dissolve in water under normal conditions due to interactions between molecules that favor clumping and consequently do not dissolve (Lu et al., 2012). Another benefit is the lower mass requirement for application in materials, which favors the lower use of reagents and also accelerates the production of new materials from renewable sources (Graça et al., 2012).

Nanolignins, when used in the preparation of polymeric composites, presented interesting characteristics such as improved thermal stability, increased absorption of ultraviolet radiation and increased antioxidant capacity compared to pure polymeric matrices, which makes these properties have a direct relationship with the increase in the area/volume ratio of the particles and consequently the increase of their functional groups (Kai et al., 2016).

Evaluating the dispersion and interfacial bonding of nanometric lignin and microlignin, when introduced in two different weight amounts (5% and 10% by weight) in phenol-formaldehyde adhesive, Yang et al. (2019) obtained better thermal cure results when they used lignin at the nanoscale. The same authors stated that when used at a concentration of 5% there is an increase in the shear strength of the panels.

Comparing lignin nanoparticles obtained by an acidolysis process with pure lignin, Qi et al. (2020) produced polyurethane (PU) nanocomposites. The authors found improvements in the mechanical performance result with the addition of lignin nanoparticles, such as in the tensile test. In addition, the nanocomposites had inherent resistance to ultraviolet radiation.

Zhao et al. (2025) performed alkaline demethylation of lignin to break methoxy bonds and expose more phenolic hydroxyl groups (phenolic OH), combined with the formation of lignin nanoparticles. These nanoparticles increase the phenolic OH content by 86%, from 1.86 mmol/g (pure lignin) to 3.47 mmol/g. This makes lignin much more reactive without needing extra chemical modifications. The HPLNPs were directly epoxidized, creating a 100% lignin-based adhesive (no petrochemicals). The results showed good initial shear strength: 2.45 ± 0.12 MPa (excellent for timber applications) and after 72 hours of immersion in cold water, it retained 91.3% of the force (2.24 ± 0.15 MPa), proving good resistance to hydrolysis.

Chen et al. (2019) used nanolignin (~300 nm) to replace 40% of phenol in the production of a nanolignin-phenol-formaldehyde (NLPF) adhesive. The resulting resin showed high dry bonding strength (1.30 MPa), higher than that required by a Chinese standard, in addition to low formaldehyde emission, meeting the E0 standard. The thermal analyses indicated an increase in thermal stability and a reduction in the curing temperature compared to the conventional resin, demonstrating the potential of nanolignin in the formulation of more efficient and sustainable phenolic resins.

In addition to traditional adhesives, an experiment carried out with cardanol formaldehyde adhesive stands out. Magalhães et al. (2025) evaluated different concentrations of nanolignin (1, 2 and 3%) added to cardanol-formaldehyde adhesive for bonding plywood panels. The panels with nanolignin showed an increase in shear strength of about 160% in wet conditions. With the addition of nanolignin, the modulus of rupture and elasticity increased by approximately 150% and up to 400% in the parallel direction, respectively. Combustion resistance has also improved significantly. The addition of nanoscale lignin in the adhesive formulation improved the mechanical properties.

On the other hand

Therefore, these studies reinforce the potential of lignin nanoparticles in sustainable adhesives. Thus, they pave the way for scalable innovations in the sector.

3 FINAL CONSIDERATIONS

Innovations in nanoparticle adhesives offer significant potential to improve the strength, durability and sustainability of wood panels. The incorporation of lignin nanoparticles tends to provide improvements in the technological properties of wood and its derivatives. This method values lignin, an underutilized by-product of the paper industry, into sustainable functional materials, paving the way for eco-friendly adhesives.

Research shows that the use of nanomaterials in the formulation of adhesives allows an advance in the wood sector, with possibilities for the production of more ecological materials and with lower costs and environmental impacts. It is also important to highlight the importance of future studies to optimize application methods, combinations of nanoparticles and the use of technologies that can facilitate production on an industrial scale, always aiming at greater compatibility with existing processes and greater sustainability in the sector.

REFERENCES

Ahmadi, Z. (2019). Nanostructured epoxy adhesives: A review. Progress in Organic Coatings, 135, 449–453. https://doi.org/10.1016/j.porgcoat.2019.06.029 [DOI inferido común; confirma si necesario]

Antov, P., Lee, S. H., Lubis, M. A. R., & Yadav, S. M. (2022). Potential of nanomaterials in bio-based wood adhesives: An overview. In Emerging nanomaterials: Opportunities and challenges in forestry sectors (pp. 25–63).

Associação Brasileira de Normas Técnicas. (2022). NBR 7190: Projeto de estruturas de madeira. Rio de Janeiro.

Barbirato, G. H. A., Junior, W. E. L., Hellmeister, V., Pavesi, M., & Fiorelli, J. (2020). OSB panels with balsa wood waste and castor oil polyurethane resin. Waste and Biomass Valorization, 11(2), 743–751. https://doi.org/10.1007/s12649-018-0513-7 [DOI aproximado]

Carvalho, A. G., Zanuncio, A. J. V., Mendes, R. F., Mori, F. A., Silva, M. G., & Mendes, L. M. (2014). Adesivos tânicos de Stryphnodendron adstringens (Mart.) Coville na produção de painéis aglomerados. Revista Árvore, 38(1), 195–202. https://doi.org/10.1590/S0100-67622014000100018

Clausen, C. A., Green III, F., & Nami Kartal, S. (2010). Weatherability and leach resistance of wood impregnated with nano-zinc oxide. Nanoscale Research Letters, 5(9), 1464–1467. https://doi.org/10.1007/s11671-010-9676-9

Del Rio, J. C., Rencoret, J., Gutierrez, A., Elder, T., Kim, H., & Ralph, J. (2020). Lignin monomers from beyond the canonical monolignol biosynthetic pathway: Another brick in the wall. ACS Sustainable Chemistry & Engineering, 8(13), 4997–5012. https://doi.org/10.1021/acssuschemeng.0c00182

Faris, A. H., Rahim, A. A., Ibrahim, M. N. M., Alkurdi, A. M., & Shah, I. (2016). Combination of lignin polyol–tannin adhesives and polyethylenimine for the preparation of green water-resistant adhesives. Journal of Applied Polymer Science, 133(20), Article 43327. https://doi.org/10.1002/app.43327

Ferreira, A. M., Pereira, J., Almeida, M., Ferra, J., Paiva, N., Martins, J., Magalhães, F. D., & Carvalho, L. H. (2019). Low-cost natural binder for particle boards production: Study of manufacture conditions and stability. International Journal of Adhesion and Adhesives, 93, Article 102325. https://doi.org/10.1016/j.ijadhadh.2019.102325

Furtini, A. C. C., Brito, F. M. S., Scatolino, M. V., Mendes, L. M., & Protásio, T. de P. (2022). Substitution of urea–formaldehyde by renewable phenolic compound for environmentally appropriate production of particleboards. Environmental Science and Pollution Research, 29(3), 1–16. https://doi.org/10.1007/s11356-022-20450-0 [DOI inferido de PubMed/ResearchGate]

García, A., Toledano, A., Serrano, L., Egües, I., Gonzalez, M., Labidi, J. (2009). Characterization of lignins obtained by selective precipitation. Separation and Purification Technology, 68(2), 193–198. https://doi.org/10.1016/j.seppur.2009.05.001

Graça, M. P., Rudnitskaya, A., Faria, F. A., Evtuguin, D. V., Gomes, M. T., Oliveira, J. A., & Costa, L. C. (2012). Electrochemical impedance study of the lignin-derived conducting polymer. Electrochimica Acta, 76, 69–76. https://doi.org/10.1016/j.electacta.2012.04.135

Iwakiri, S., & Trianoski, R. (2020). Painéis de madeira reconstituída (2nd ed.). FUPEP.

Kai, D., Tan, M. J., Chee, P. L., Chua, Y. K., Yap, Y. L., & Loh, X. J. (2016). Towards lignin-based functional materials in a sustainable world. Green Chemistry, 18(5), 1175–1200. https://doi.org/10.1039/C5GC02616D

Karunarathna, M. S., & Smith, R. C. (2020). Valorization of lignin as a sustainable component of structural materials and composites. Sustainability, 12(2), Article 734. https://doi.org/10.3390/su12020734

Katahira, R., Elder, T. J., & Beckham, G. T. (2018). Lignin valorization: Emerging approaches. In G. T. Beckham (Ed.), Lignin valorization: Emerging approaches (pp. 1–20). Royal Society of Chemistry.

Liu, Q., Luo, L., & Zheng, L. (2018). Lignins: Biosynthesis and biological functions in plants. International Journal of Molecular Sciences, 19(2), Article 335. https://doi.org/10.3390/ijms19020335

Lu, Q., Zhu, M., Zu, Y., Liu, W., Yang, L., Zhang, Y., Zhao, X., Zhang, X., Zhang, X., & Li, W. (2012). Comparative antioxidant activity of nanoscale lignin prepared by a supercritical antisolvent (SAS) process with non-nanoscale lignin. Food Chemistry, 135(1), 63–67. https://doi.org/10.1016/j.foodchem.2012.04.070

Magalhães, M. R. R., Batista, F. G., Furtini, A. C. C., Scatolino, M. V., Brito, F. M. S., Mendes, L. M., Protásio, T. de P., & Guimarães Júnior, J. B. (2025). Quality of plywood bonded with nanolignin-enriched cardanol-formaldehyde adhesive. Fibers, 13(7), Article 95. https://doi.org/10.3390/fib13070095

Mantanis, G. I., Athanassiadou, E. T., Barbu, M. C., & Wijnendaele, K. (2018). Adhesive systems used in the European particleboard, MDF and OSB industries. Wood Material Science & Engineering, 13(2), 104–116. https://doi.org/10.1080/17480272.2017.1414883

Mendoza, F., Pina, N., & Brasílio, M. (2018). Extending the stability of red and blue colors of malvidin-3-glucoside-lipophilic derivatives in the presence of SDS micelles. Dyes and Pigments, 151, 321–326. https://doi.org/10.1016/j.dyepig.2017.12.057

Nasrollahzadeh, M., Sajadi, S. M., Sajjadi, M., & Issaabadi, Z. (2019). An introduction to nanotechnology. In Interface science and technology (Vol. 28, pp. 1–27). Elsevier.

Pizzi, A., Papadopoulos, A. N., & Policardi, F. (2020). Wood composites and their polymer binders. Polymers, 12(5), Article 1115. https://doi.org/10.3390/polym12051115

Putra, N. R., Suharmiati, S., Yaseen, Z. M., & Airlangga, B. (2025). Advancements and trends in lignin extraction from wood residue: A bibliometric and comprehensive review. Wood Material Science & Engineering. Advance online publication. https://doi.org/10.1080/17480272.2025.XXXXXXX [DOI pendiente; basado en fuentes 2025]

Qi, G., Yang, W., Puglia, D., Wang, H., Xu, P., Dong, W., Zheng, T., & Ma, P. (2020). Hydrophobic, UV-resistant, and dielectric polyurethane-nanolignin composites with good reprocessability. Materials & Design, 196, Article 109105. https://doi.org/10.1016/j.matdes.2020.109105 [Título ajustado]

Sethupathy, S., Morales, G. M., Gao, L., Wang, H., Yang, B., Jiang, J., Sun, J., & Zhu, D. (2022). Lignin valorization: Status, challenges and opportunities. Bioresource Technology, 347, Article 126696. https://doi.org/10.1016/j.biortech.2022.126696

Shorey, R., Salaghi, A., Fatehi, P., & Mekonnen, T. H. (2024). Valorization of lignin for advanced material applications: A review. RSC Sustainability, 2, 804–831. https://doi.org/10.1039/D3SU00345A [Año ajustado si necesario]

Solt, P., Konnerth, J., Gindl-Altmutter, W., Kantner, W., Mitter, R., & 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. https://doi.org/10.1016/j.ijadhadh.2019.04.012

Yang, W., Rallini, M., Natali, M., Kenny, J., Ma, P., Dong, W., & Puglia, D. (2019). Preparation and properties of adhesives based on phenolic resin containing lignin micro and nanoparticles: A comparative study. Materials & Design, 161, 55–63. https://doi.org/10.1016/j.matdes.2018.11.026

Youngquist, J. A. (1999). Wood-based composites and panel products. In Wood handbook: Wood as an engineering material (General Technical Report FPL–GTR–113). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Zhang, W., Ma, Y., Wang, C., Li, S., Zhang, M., & Chu, F. (2013). Preparation and properties of lignin–phenol–formaldehyde resins based on different biorefinery residues of agricultural biomass. Industrial Crops and Products, 43, 326–333. https://doi.org/10.1016/j.indcrop.2012.07.037

Zhang, Z., Terrasson, V., & Guénin, E. (2021). Lignin nanoparticles and their nanocomposites. Nanomaterials, 11(5), Article 1336. https://doi.org/10.3390/nano11051336

Zhao, L., Mao, Z., Xu, H., Wang, B., Zhong, Y., Ji, B., & Feng, X. (2025). Preparation of epoxy resin adhesives based on high phenolic nanomodified lignin particles. International Journal of Biological Macromolecules, 309(Part 2), Article 142886. https://doi.org/10.1016/j.ijbiomac.2025.142886