Proceedings of CONF-MSS 2026 Symposium: Advanced Composite Materials and Polymer Chemistry
DOI: 10.54254/2755-2721/2026.AD35395

Research Progress in Catalytic Conversion of Lignin to Prepare High-Grade Liquid Fuels

Jie Wang

School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing, China
2365315805@qq.com

Abstract. Lignin is an abundant renewable aromatic polymer in nature and an important raw material for preparing high-grade liquid fuels and high value-added chemicals. However, due to its complex structure and difficulty in decomposition, the efficient separation and directional conversion of lignin still face many challenges. Focusing on the research progress of catalytic conversion of lignin to produce high-grade liquid fuels, this paper systematically reviews the effects of lignin separation methods on depolymerization behavior, and summarizes the roles of harsh separation and mild separation in improving monomer yield and structural integrity. It further discusses the research progress of catalysts, solvents, and advanced methods such as oxidation-reduction, microwave, and photocatalysis in liquid-phase depolymerization, and analyzes key strategies to inhibit secondary condensation of depolymerization products. Finally, it summarizes the pathways and development directions of upgrading and modifying lignin bio-oil to produce aromatic hydrocarbons, cycloalkanes, and high-energy fuels. In the future, efficient separation, directional catalysis, and process coupling technologies should be combined to promote the green conversion of lignin into high-grade liquid fuels and high-value products.

Keywords: lignin, catalytic conversion, method, liquid fuel

1. Introduction

In the current era, with the development of industry and science and technology, the demand for crude oil has surged. Coupled with the tense situation in the Middle East, crude oil prices have skyrocketed, which has exerted a huge impact on transportation and industry in particular [1]. Meanwhile, environmental problems caused by traditional fuels, such as global warming and air pollution, are becoming increasingly severe, which has undoubtedly triggered research in various countries to find new, clean, and sustainable fuels.

In recent years, lignin has attracted widespread attention in the energy and fuel fields due to its advantages of high yield and cleanliness. Biorefineries, paper mills, and the agricultural sector produce a large number of lignin by-products, with an annual output of about 1.8 trillion tons. If lignin can be efficiently converted, it is expected to meet 20% of global energy demand by 2050 [2, 3]. However, due to its high heterogeneity and complex structure, lignin is very difficult to degrade and utilize, which greatly restricts the development and research of lignin catalytic processes. For

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.AD35395

this reason, the energy utilization rate of lignin is still less than 1%, and most lignin is incinerated or landfilled, wasting a large amount of energy and increasing the environmental burden [4]. Over the past decades, researchers have devoted a great deal of effort to the research of lignin utilization technologies. In recent years, major breakthroughs have been made in separation methods, solvent and catalyst selection, and bio-oil upgrading and modification.

Based on the above research reports, this review sorts out the latest research on the catalytic conversion of lignin to prepare high-grade liquid fuels in recent years from three aspects: separation methods, liquid-phase depolymerization, and terminal products, aiming to provide references for the catalytic conversion of lignin. Some methods have not been reviewed before and need to be discussed and summarized.

2. Lignin separation, depolymerization and characteristics

2.1. Theoretical monomer yield

The theoretical monomer yield of lignin refers to the maximum yield that can be achieved when lignin is completely depolymerized into aromatic monomers under ideal conditions. Since most current lignin conversion methods produce high-grade products by cleaving carbon-oxygen bonds (mainly β-O-4' bonds) with low dissociation energy (about 60 kcal mol^{-1}), the theoretical yield mainly depends on the content of β-O-4' bonds in lignin. Assuming that lignin is an infinitely long polymer with randomly distributed bonds, and x is the content of β-O-4' bonds, the probability that a single unit connects two adjacent units through β-O-4' bonds at the same time is x^2. The content of β-O-4' bonds in lignin from different sources varies greatly, and the theoretical monomer yields also differ. The content of β-O-4' bonds in lignin can be determined by thioacidolysis [5]. The following table briefly introduces the theoretical monomer yields of several common lignins.

Table 1. Theoretical monomer yields of different lignins

Type	β-O-4' bond content	Theoretical monomer yield
Hardwood	60%	36%
Softwood	50%	25%
Bagasse	69%	48%
Wheat straw	65%	42%
Paper mill waste liquor	40%~60%	24%~36%

2.2. Harsh separation

Due to the complex structure of lignin (as shown in Figure 1), a method has been derived that treats lignocellulose with strong acids and strong bases, reacts under high temperature and high pressure conditions, or uses strong oxidizing substances to promote the separation of lignin from other components. The LignoBoost method and LignoForce method extract lignin with 98% concentrated sulfuric acid at high temperatures, with yields of 24.27%~43.20% and 27.21%~35.73%, respectively [6]. For the organic acid method, under the conditions of 160°C, pyruvic acid concentration of 6%, and ethanol concentration of 40%, the separation efficiency of lignin reaches as high as 82.36% after 40 min of reaction [7].

DOI: 10.54254/2755-2721/2026.AD35395

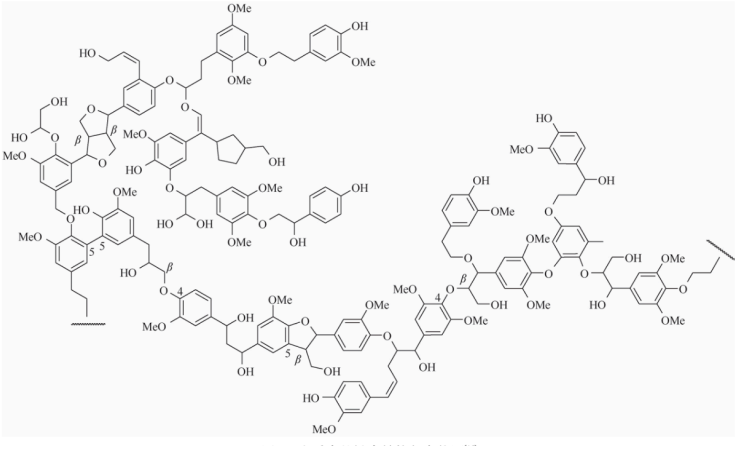

Figure 1. Lignin structure and functional groups

Creating harsh conditions can indeed achieve a certain separation effect, but if the separation environment is too harsh, it will instead reduce the separation efficiency. Experiments on pretreating hemp fibers with supercritical carbon dioxide and extracting water and lignin derivatives with supercritical CO_2 show that at 100°C, lignin derivatives undergo side reactions such as condensation at a relatively low degree. As the temperature rises, the condensation reaction in lignin derivatives intensifies, leading to an increase in molecular weight and a decrease in phenolic hydroxyl content. At 180°C, a significant degradation reaction occurs, which reduces the average molecular weight of the separated lignin derivatives and results in the release of more phenolic hydroxyl groups [8].

2.3. Mild separation

The core of mild lignin separation methods is to carry out the process at lower temperatures and in a near-neutral or weak acid-base environment. Compared with harsh separation, it can better reduce the damage to the molecular structure of lignin (such as key linkages like β-O-4 bonds), and at the same time reduce equipment corrosion and environmental burden. Deep eutectic solvent separation is one of the most common mild separation methods at present. Deep eutectic solvents are eutectics formed mainly through hydrogen bonding between hydrogen bond acceptors and hydrogen bond donors, generally composed of 2 or 3 components, and their melting points are lower than any single component [9].

Lignin-carbohydrate complexes are the main obstacle restricting lignin separation. They are formed by further cross-linking of lignin and hemicellulose (containing benzyl esters, benzyl ethers, and phenyl glycoside groups) through covalent bonds and strong hydrogen bond interactions. Since Cl^- in deep eutectic solvents competes with hydroxyl groups in carbohydrates and lignin to form hydrogen bonds, the strong hydrogen bond interactions in lignin are weakened, thereby destroying the connections of lignin-carbohydrate complexes and achieving a good separation effect [10]. Another commonly used method is enzymatic hydrolysis of lignin. Biological enzymes have the function of directional cleavage (hydrolysis), so they can directionally cleave the connection sites of various components of materials such as straw according to enzymes, thereby obtaining lignin products with intact biological morphology [11].

DOI: 10.54254/2755-2721/2026.AD35395

3. Catalytic conversion of lignin and its mechanism

3.1. Catalysts

The core of catalysts for lignin catalytic conversion focuses on cleaving C-O/C-C bonds in lignin molecules, inhibiting secondary condensation of products, and improving deoxygenation efficiency. Noble metal catalysts are highly efficient active components for lignin depolymerization. For example, 1 wt% Pt/γ-Al_2O_3 can effectively cleave lignin linkages in liquid-phase reforming reactions, reducing the molecular weights of organosolv lignin and kraft lignin by 32% and 57% respectively, with monomer yields of 11% and 9%. When synergized with NaOH co-catalyst, it can also inhibit coke formation [12]. The Pd/C catalyst, combined with formic acid (hydrogen source) in methanol solvent, directionally cleaves β-O-4 ether bonds, which account for 40-80% of lignin linkages, and some C-C bonds, promoting the gradual depolymerization of lignin into phenolic monomers, dimers, and oligomers [13].

Transition metal and bimetallic catalysts have cost advantages and synergistic effects. CoMo/Al_2O_3 and Mo_2C/CNF can convert oxygen-containing aromatic compounds in lignin oil into oxygen-free compounds such as benzene, toluene, and xylene in the hydrodeoxygenation step. Among them, Mo_2C/CNF achieves a total monomer yield of 9% for organosolv lignin oil, with oxygen-free compounds accounting for 36% [12]. Ni-based catalysts modified with alumina coating can effectively inhibit particle sintering and carbon deposition. The deactivation rate in continuous flow reactions is only 1/3 of that of uncoated catalysts, significantly improving stability [14]. Bimetallic composite catalysts such as Ni-Cu/H-Beta and Nb_m-Ni_n/ZnO-Al_2O_3 further optimize depolymerization and deoxygenation efficiency through intermetallic synergy. Ni-Cu/H-Beta can achieve 98.8% kraft lignin conversion and 50.8% monomer yield [3].

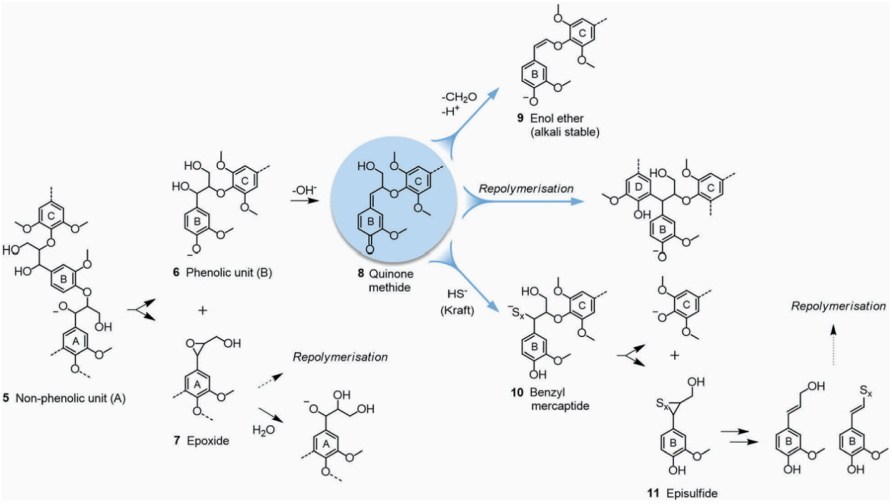

Figure 2. Base-catalyzed depolymerization and condensate formation

In addition, acid-base catalysts can achieve directional regulation of reaction pathways. NaOH is an important catalyst that promotes hydrolysis by polarizing β-O-4 ether bonds (as shown in Figure 2). When synergized with boric acid, it can cap phenolic hydroxyl groups to inhibit condensation, increasing the oil yield from 23 wt% to 52 wt% [3]. Zeolite-based solid acid catalysts such as HZSM-5 and HUSY enhance the interaction with lignin by virtue of their specific pore structure and acid sites, and the monophenol yield can reach 19.4-60% [2].

DOI: 10.54254/2755-2721/2026.AD35395

3.2. Solvents

As a key medium in the process of lignin catalytic conversion, the type, composition, and physicochemical properties of solvents directly affect the solubility of lignin, reaction mass transfer efficiency, intermediate stability, and product distribution (as shown in Figure 3), becoming core factors regulating depolymerization efficiency and inhibiting secondary condensation. Among polar protic solvents, alcohol solvents such as methanol and ethanol are widely used due to their both dissolving ability and hydrogen-donating properties. Supercritical methanol can generate active H^+ through reforming reactions to stabilize reaction intermediates, while ethanol can cap highly active intermediates through O-alkylation and C-alkylation, and simultaneously capture formaldehyde generated by lignin demethoxylation, reducing phenolic monomers [15].

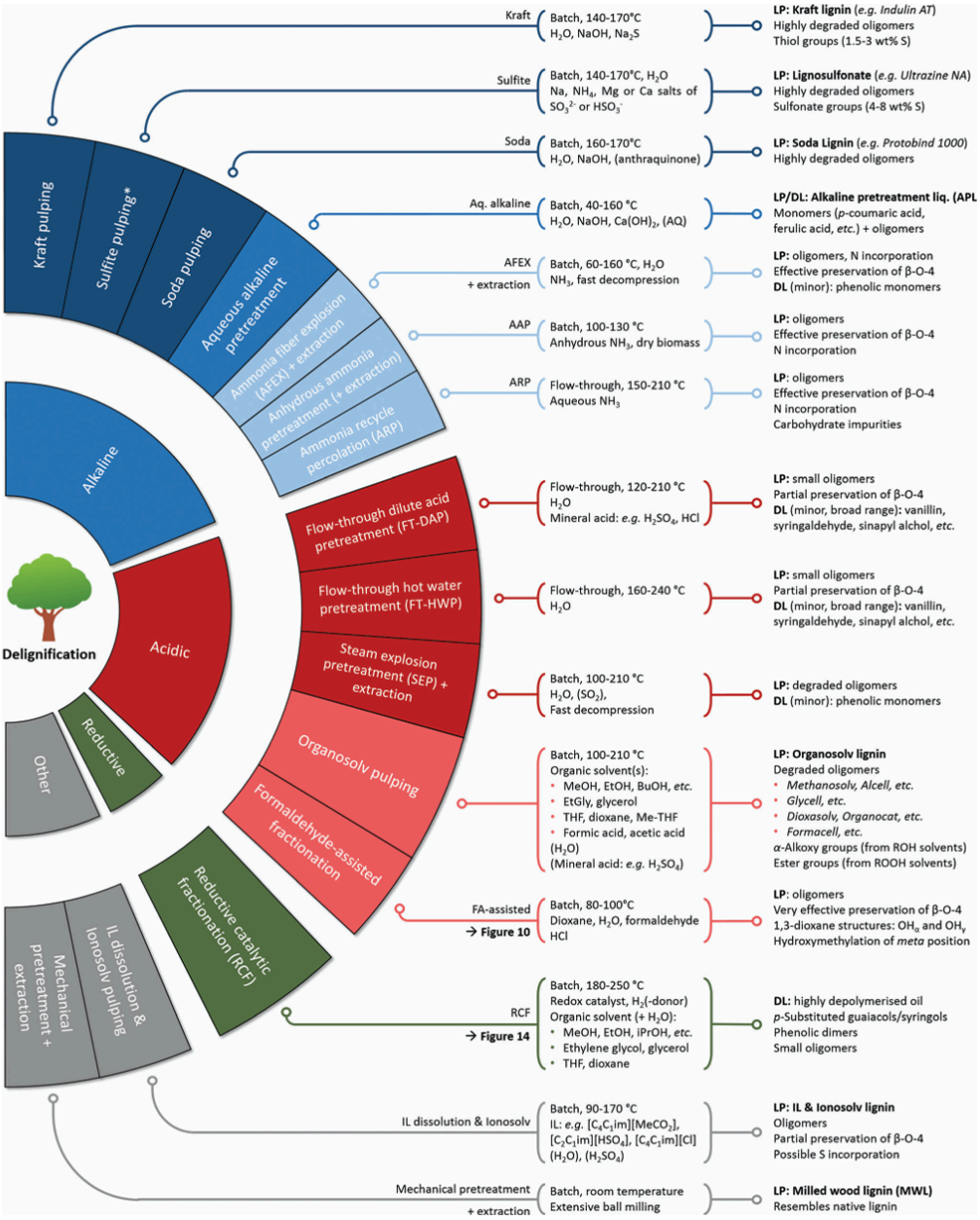

Figure 3. Overview of solvent-driven biomass fractionation pathways and lignin products

DOI: 10.54254/2755-2721/2026.AD35395

The synergistic effect of binary mixed solvents has a good effect. For example, methanol/water mixed solvents can regulate lignin conformation by adjusting the molar fraction of methanol. Softwood lignin presents an extended coil conformation when the molar fraction of methanol is 0.8, and hardwood lignin reaches the optimal dissolution state when the molar fraction of methanol is 0.4, significantly reducing intermolecular interactions and the tendency of secondary condensation [2]. The ethanol-water 1:1 mixed solvent provides a homogeneous environment for lignin in liquid-phase reforming reactions, synergizes with NaOH to improve solubility, avoids recondensation of lignin molecules during depolymerization, adapts to high temperature and high pressure reaction conditions, and is stable itself [12].

In addition, the development of solvent screening technology has further optimized product separation efficiency. The NIST-UNIFAC group contribution model can accurately predict the liquid-liquid phase equilibrium of lignin-derived molecules, and screen out ideal binary solvent systems such as dimethyl sulfoxide + diethyl ether, sulfolane + triethylamine, as well as Arizona series quaternary solvents, achieving efficient separation of monomers such as vanillin and syringaldehyde [16]. Supercritical solvents (such as supercritical ethanol and supercritical water), by virtue of their low viscosity and high solubility, promote the cleavage of lignin ether bonds while enhancing mass transfer. When used in synergy with formic acid, they can enhance hydrogen generation and quench free radicals to inhibit repolymerization, achieving >95% conversion even for highly condensed lignin [17].

3.3. Advanced depolymerization methods

Advanced lignin depolymerization methods focus on three major directions: oxidation-reduction, microwave, and photocatalysis. The core goals are to efficiently cleave C-O/C-C bonds, directionally regulate product distribution, and inhibit secondary condensation, providing technical support for the preparation of high-grade liquid fuels [18]. Oxidation-reduction depolymerization is currently the most widely studied strategy, covering single oxidation/reduction pathways and two-step coupling processes. Oxidative depolymerization mostly uses H_2O_2 and oxygen as oxidants, combined with catalysts such as vanadium-based, copper-based, and metalloporphyrin catalysts, to selectively cleave the linkages between lignin units in alkaline solutions or organic solvents while retaining the aromatic ring structure. For example, H_2O_2 can achieve 86.24% depolymerization of wheat alkali lignin in a water-methanol system [3]. Reductive depolymerization relies on noble metal (Pt, Ru, Pd) or transition metal (Ni, Mo) catalysts, combined with hydrogen-donating solvents (methanol, ethanol) or hydrogen sources (formic acid), to achieve ether bond hydrogenolysis and intermediate stabilization. For example, Pd/C-catalyzed reductive depolymerization can directionally cleave β-O-4 ether bonds, which account for 40-80% of lignin linkages, to generate phenolic monomers and oligomers [13]. The two-step method (such as liquid-phase reforming-hydrodeoxygenation) shows more synergistic advantages: first, mild depolymerization via liquid-phase reforming reduces the molecular weight of lignin, and then oxygen-containing functional groups are removed through hydrodeoxygenation to generate oxygen-free compounds such as benzene, toluene, and xylene, with the proportion of oxygen-free compounds reaching up to 36% [12].

Microwave depolymerization has efficient heating characteristics. It achieves uniform temperature rise of materials through volumetric energy conversion and reduces activation energy. Combined with metal salts or modified zeolite catalysts, it can rapidly degrade lignin model compounds and native lignin. At 550°C, phenolic products account for 71-87% of bio-oil, and the liquid product yield can be directionally increased to 37 wt% by regulating the heating rate (optimal

DOI: 10.54254/2755-2721/2026.AD35395

90°C/min) [15]. As a mild and green method, photocatalytic depolymerization uses visible light as the energy source. With the help of photocatalysts such as $[Ir(ppy)_2(dtbbpy)]PF_6$ and LED light sources, it generates active species such as PINO radicals to selectively oxidize the α-OH group of lignin and cleave β-O-4 bonds. It is suitable for efficient depolymerization of oxidized phenolic lignin model compounds, with mild reaction conditions and reduced product condensation [18].

Table 2. Introduction, advantages and disadvantages of different depolymerization methods

Depolymerization direction	Reaction medium	Key reactions and bond cleavage modes	Advantages	Limitations
Oxidative depolymerization	H_2O_2 / O_2 + alkaline solution or organic solvent	Selective cleavage of Cα–Cβ or C–O; retention of aromatic rings	Good retention of aromatic rings, high product added value	Prone to over-oxidation and aromatic ring opening
Reductive depolymerization	H_2 / hydrogen-donating solvent	β-O-4 ether bond hydrogenolysis; intermediate hydrogenation stabilization	High monomer yield, inhibition of condensation	High catalyst cost
Oxidation-reduction coupling	Liquid-phase reforming + HDO	Mild depolymerization first → deep deoxygenation later	High product energy density, close to gasoline/aviation fuel	Complex process and high energy consumption
Microwave depolymerization	Microwave volumetric heating (solvent-free or small amount of solvent)	Pyrolysis + catalytic cleavage of C–O/C–C	Fast temperature rise, low activation energy, tunable products	High temperature easily leads to aromatic ring saturation
Photocatalytic depolymerization	Visible light + LED	Generation of free radicals such as PINO·, selective oxidation of αOH → cleavage of βO4	Mild conditions, green, high selectivity	Low efficiency for complex native lignin

3.4. Reduction of secondary condensation of depolymerization products

Reducing the secondary condensation of lignin depolymerization products is the key to improving the yield and quality of target products, which focuses on solvent regulation, catalyst optimization, reaction process design, and stabilization of active intermediates. At the solvent level, excellent solvents can inhibit aggregation by improving lignin solubility and regulating molecular conformation. For example, methanol/water mixed solvents can transform lignin from a spherical folded conformation to an extended coil conformation, reducing close intermolecular contact. The condensation tendency of softwood lignin is significantly reduced in an 80 mol% methanol system [2]. Alcohol solvents such as ethanol and isopropanol can not only dissolve monomers and oligomers, but also cap highly active intermediates through O-alkylation and C-alkylation, or capture formaldehyde generated by demethoxylation to reduce repolymerization of phenolic monomers [3]. The mixed system of supercritical ethanol and formic acid can stabilize small molecule intermediates through hydrogen transfer. Hydrogen donors can quench free radicals, resulting in the solid residue production of highly condensed Klason lignin being less than 2.5 wt% [17].

DOI: 10.54254/2755-2721/2026.AD35395

In terms of catalysts and additives, boric acid, as a phenolic hydroxyl capping agent, can form stable esters with phenolic hydroxyl groups to block active sites. When synergized with NaOH (weight ratio 0.75), the oil yield increases from 23 wt% to 52 wt%, significantly inhibiting C-C bond formation. Zr-KIT-5 Lewis acid catalyst, Ni-Cu/H-Beta bimetallic catalyst, etc., reduce recombination reactions and aldehyde condensation through acid regulation or mesoporous structure [3]. Optimization of processes and reaction conditions is also crucial. The two-step liquid-phase reforming-hydrodeoxygenation method avoids severe condensation caused by direct high-temperature depolymerization through mild depolymerization under mild conditions and subsequent directional deoxygenation. Meanwhile, dodecane solvent can dissolve products in time to reduce intermolecular interactions [12]. Selective oxidation modification of α-OH groups (such as TEMPO, DDQ/NHPI systems) can hinder the formation of $C\alpha^{+}$ cations, reduce β-O-4 bond energy, and reduce condensation and coking. In addition, controlling reaction temperature, shortening product residence time, and low lignin concentration can also effectively inhibit secondary condensation [3].

4. Terminal products — upgrading and modification of lignin bio-oil

Lignin-derived bio-oil cannot be directly used as high-grade liquid fuel due to its high oxygen content, high acidity, and instability, so it must be upgraded and modified. At present, the upgrading and modification of lignin bio-oil mainly focuses on three target products: aromatic hydrocarbons, cycloalkanes, and high-energy fuels. Their formation pathways and selectivity are comprehensively affected by lignin source, pretreatment method, catalyst type, and reaction conditions.

4.1. Aromatic hydrocarbons

Aromatic hydrocarbons (such as benzene, toluene, xylene) are important chemical platform molecules. Studies have found that pretreatment of lignin can significantly improve its conversion efficiency to aromatic hydrocarbons. For example, reductive catalytic fractionation with Pd/C catalyst in supercritical ethanol can effectively depolymerize lignin and increase the yield of aromatic hydrocarbons. After pretreatment, the total carbon yield of monocyclic and bicyclic aromatic hydrocarbons can reach 11-14 C% when corn stover lignin oil undergoes catalytic pyrolysis over ZSM-5 catalyst, while the aromatic hydrocarbon yield of unpretreated lignin is only 7-9 C% [19].

Due to its unique pore structure and acidity, ZSM-5 zeolite catalyst can effectively promote the conversion of oxygenates to aromatic hydrocarbons. Phenolic compounds in lignin need to be degraded at external acid sites first, then enter the pores and generate aromatic hydrocarbons through cracking and hydrogen transfer reactions [20]. The natural structure of lignin affects the distribution of conversion products. Softwood lignin rich in guaiacyl units has high selectivity under mild conditions but low total monomer yield, while herbaceous lignin is easier to depolymerize and can produce high-yield low-molecular-weight bio-oil.

At the reaction mechanism level, studies have revealed the hydrodeoxygenation process of lignin model compounds, which can produce aromatic hydrocarbons. Taking guaiacol as an example, the selectivity of reaction pathways varies with different catalysts. Through a two-step strategy, first converting lignin to alkylphenols and then performing deep hydrodeoxygenation can increase the yield of oxygen-free aromatic hydrocarbons [21].

DOI: 10.54254/2755-2721/2026.AD35395

4.2. Cycloalkanes

Cycloalkanes have high energy density and excellent combustion performance. The process of upgrading to cycloalkanes requires deep hydrogenation saturation of aromatic rings. Hydrodeoxygenation of lignin bio-oil can produce monocyclic aromatic hydrocarbons and C2-C6 alkanes; meanwhile, hydrodeoxygenation of the water-soluble fraction can be converted into C2-C6 olefins and alkanes, thereby obtaining high-value cycloalkanes [19].

Reaction pathways include direct deoxygenation to form aromatic hydrocarbons, or hydrogenation of aromatic rings first to form cyclohexanol, followed by dehydration and hydrogenation to form cyclohexane. Catalyst selection and reaction conditions significantly affect product selectivity. Low temperature is favorable for alcohol formation, while high temperature promotes alkane formation [22]. The formation of low-value cycloalkanes can be avoided through two-step methods or mild reaction conditions.

4.3. High-energy fuels

The core of upgrading lignin bio-oil to high-energy fuels is to increase its energy density. Studies have shown that optimizing reaction conditions under glycerol-assisted hydrothermal conditions can significantly improve the fuel performance of bio-oil. For example, treatment with Pt/C catalyst at 350°C can achieve an energy density ratio of 1.17, and the gross calorific value increases from 29.70 KJ/g to 34.63 KJ/g [23].

By evaluating the carbon flow, the initial carbon conversion rate of red oak reaches 72.9%, generating a large amount of monocyclic aromatic hydrocarbons, which are important high-octane gasoline components [19]. In addition, economic analysis shows that producing high-value chemicals is more economical than directly producing alternative fuels. A plant processing 200,000 tons of lignin annually can have an annual income of 131 million euros, with a return on investment of about 12% [21]. The copyrolysis strategy provides a new way to directly upgrade lignin without external hydrogen. Pyrolysis of hydrogen-rich raw materials can generate hydrogen radicals, which participate in the deoxygenation reaction of lignin oxygenates [20].

5. Conclusion and prospect

This study reviews the latest progress in the catalytic conversion of lignin to prepare high-grade liquid fuels. As an abundant renewable resource, lignin can be converted into high-value aromatic hydrocarbons, cycloalkanes, and high-energy fuels after effective separation and depolymerization. Although the separation and conversion of lignin face challenges due to its structural complexity and diversity, researchers have made significant progress in improving product yield and quality by adopting methods such as supercritical solvents, mild and harsh separation technologies, and optimizing catalysts and reaction conditions.

Future research should continue to explore various efficient catalysts and new reaction processes to further improve the conversion efficiency of lignin and reduce the occurrence of secondary condensation reactions. Meanwhile, developing customized treatment schemes according to the characteristics of different lignin sources will help realize the sustainable utilization of lignin and contribute to the transformation of the global energy structure and environmental protection.

DOI: 10.54254/2755-2721/2026.AD35395

References

[1] Wanmolee, W., Daorattanachai, P., & Laosiripojana, N. (2016). Depolymerization of organosolv lignin to valuable chemicals over homogeneous and heterogeneous acid catalysts. *Energy Procedia, 100*, 173–177. https://doi.org/10.1016/j.egypro.2016.10.161

[2] Deepa, A. K., & Dhepe, P. L. (2014). Solid acid catalyzed depolymerization of lignin into value added aromatic monomers. *RSC Advances, 4*(22), 12625–12629. https://doi.org/10.1039/c3ra47818a

[3] Raikwar, D., Majumdar, S., & Shee, D. (2023). Effects of solvents in the depolymerization of lignin into value-added products: a review. *Biomass Conversion and Biorefinery, 13*, 11383–11416. https://doi.org/10.1007/s13399-021-02030-7

[4] Liu, X. D., Bouxin, F. P., Fan, J. J., Budarin, V. L., Hu, C. W., & Clark, J. H. (2020). Recent advances in the catalytic depolymerization of lignin towards phenolic chemicals: A review. *ChemSusChem, 13*(17), 4296–4317. https://doi.org/10.1002/cssc.202001213

[5] Subbotina, E., Rukkijakan, T., Marquez-Medina, M. D., Yu, X., Johnsson, M., & Samec, J. S. M. (2021). Oxidative cleavage of C–C bonds in lignin. *Nature Chemistry, 13*(11), 1118–1125. https://doi.org/10.1038/s41557-021-00783-2

[6] Fan, Z. Q., An, X. Y., & Liu, H. B. (2024). Research on lignin separation technology from wheat straw pulping black liquor. In *Proceedings of the 21st Academic Annual Conference of China Technical Association of the Paper Industry*. Nanning, China: China Technical Association of the Paper Industry. https://doi.org/10.26914/c.cnkihy.2024.012324

[7] Liang, J. R. (2024). Study on the mechanism of efficient separation of eucalyptus lignin through synergistic pretreatment with pyruvic acid/ethanol [Master's thesis, Guangxi University]. https://doi.org/10.27034/d.cnki.ggxiu.2024.000283

[8] Zhang, Y. H., Chen, H., Sun, H., Liu, Z. Q., Lei, B., Wu, B., & Feng, Y. H. (2024). Separation of lignin derivatives from hemp fiber using supercritical CO_2, ethanol, and water at different temperatures. *International Journal of Biological Macromolecules, 264*, 130390. https://doi.org/10.1016/j.ijbiomac.2024.130390

[9] Zhao, S. H., Li, Z. J., Hu, J. J., Yao, S., & Wang, W. (2023). Research progress on the application of deep eutectic solvents in lignocellulose pretreatment. *Chemistry and Industry of Forest Products, 43*(6), 130–138. https://doi.org/10.3969/j.issn.0253-2417.2023.06.017

[10] Zhong, L., Wang, C., Lyu, G. J., Ji, X. X., Yang, G. H., & Chen, J. C. (2020). A review of deep eutectic solvents for lignin isolation. *Chemistry and Industry of Forest Products, 40*(3), 12–22. https://doi.org/10.3969/j.issn.0253-2417.2020.03.002

[11] Jin, D., Dong, W., Zhang, H., Ci, Y., Hou, L., Zang, L., Kong, F., & Lucia, L. A. (2019). Comparison of structural characteristics of straw lignins by alkaline and enzymatic hydrolysis. *BioResources, 14*(3), 5615–5629. https://doi.org/10.15376/biores.14.3.5615-5629

[12] Jongerius, A. L., Bruijnincx, P. C. A., & Weckhuysen, B. M. (2013). Liquid-phase reforming and hydrodeoxygenation as a two-step route to aromatics from lignin. *Green Chemistry, 15*, 3049–3056. https://doi.org/10.1039/c3gc41150h

[13] Cui, C. H., Chen, X. M., Liu, C. J., Zhu, Y. N., Zhu, L. Y., Ouyang, J. F., Shen, Y., Zhou, Z. Y., & Qi, F. (2021). In situ reactor-integrated electrospray ionization mass spectrometry for heterogeneous catalytic reactions and its application in the process analysis of high-pressure liquid-phase lignin depolymerization. *Analytical Chemistry, 93*(38), 12987–12994. https://doi.org/10.1021/acs.analchem.1c02710

[14] Talebkeikhah, F., Sun, S. L., & Luterbacher, J. S. (2023). Sinter-resistant nickel catalyst for lignin hydrogenolysis achieved by liquid phase atomic layer deposition of alumina. *Advanced Energy Materials, 13*, 2203377. https://doi.org/10.1002/aenm.202203377

[15] Roberts, V. M., Stein, V., Reiner, T., Lemonidou, A., Li, X. B., & Lercher, J. A. (2011). Towards quantitative catalytic lignin depolymerization. *Chemistry – A European Journal, 17*(21), 5939–5948. https://doi.org/10.1002/chem.201002438

[16] Jahan, N., Huda, M. M., Tran, Q. X., & Rai, N. (2022). Effect of solvent quality on structure and dynamics of lignin in solution. *The Journal of Physical Chemistry B, 126*(23), 5752–5764. https://doi.org/10.1021/acs.jpcb.2c03147

[17] Jalalinejad, A., Yousefi Seyf, J., Funke, A., & Dahmen, N. (2023). Solvent screening for separation of lignin-derived molecules using the NIST-UNIFAC model. *ACS Sustainable Chemistry & Engineering, 11*, 7863–7873. https://doi.org/10.1021/acssuschemeng.3c00906

[18] Park, J., Riaz, A., Insyani, R., & Kim, J. (2018). Understanding the relationship between the structure and depolymerization behavior of lignin. *Fuel, 217*, 202–210. https://doi.org/10.1016/j.fuel.2017.12.079

DOI: 10.54254/2755-2721/2026.AD35395

[19] Liu, C., Wu, S. L., Zhang, H. Y., & Xiao, R. (2019). Catalytic oxidation of lignin to valuable biomass-based platform chemicals: A review. *Fuel Processing Technology, 191*, 181–201. https://doi.org/10.1016/j.fuproc.2019.04.007

[20] Fan, L. L., Zhang, Y. N., Liu, S. Y., Zhou, N., Chen, P., Cheng, Y. L., Addy, M., Lu, Q., Omar, M. M., Liu, Y. H., Wang, Y. P., Dai, L. L., Anderson, E., Peng, P., Lei, H. W., & Ruan, R. (2017). Bio-oil from fast pyrolysis of lignin: Effects of process and upgrading parameters. *Bioresource Technology, 241*, 1118–1126. https://doi.org/10.1016/j.biortech.2017.05.129

[21] Chowdari, R. K., Ganji, P., & Likozar, B. (2025). Solvent-free catalytic hydrotreatment of lignin to biobased aromatics: Current trends, industrial approach, and future perspectives. *Energy & Fuels, 39*, 2943–2985. https://doi.org/10.1021/acs.energyfuels.4c05174

[22] Gao, J., Cao, Y., Zhang, Y. T., Luo, G., Fan, J. J., Clark, J. H., & Zhang, S. C. (2024). Highly efficient lignin depolymerization and enhanced bio-oil upgrading via in-situ hydrogenation: Impact of lignin structure. *Chemical Engineering Journal, 498*, 155837. https://doi.org/10.1016/j.cej.2024.155837

[23] Moon, G. Y., & Um, B. H. (2025). Upgrading oak lignin-derived oil to hydrocarbons under glycerol-assisted hydrothermal conditions: A study of reaction conditions. *Clean Technologies and Environmental Policy, 27*, 7785–7805. https://doi.org/10.1007/s10098-025-03303-9