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The Promising Future of Lignin Depolymerization in Biomass Valorization: Rajdeep Deka

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Editorial

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Editorial

Lignin is the second most abundant biopolymer besides cellulose in nature and accounts for a large fraction of biomass components in higher vascular plants, but this resource has been underutilized. Even though lignin, with its complex and highly heterogeneous structure, is difficult to extract from biomass and convert into value-added compounds, large scale production of lignin-derived chemicals has the potential to promote a sustainable circular bioeconomy. The recent progress in lignin depolymerization opens a prospective direction for converting this recalcitrant biopolymer to useful chemicals and materials, which will be helpful toward the achievement of full biomass utilization and zero waste.

The structure of lignin consists of three main phenolic units, p-coumaryl coniferyl and sinapyl, linked by different bonds among which β-O-4 ether linkages are the most common one and provides plant cell wall their mechanical strength as well as defense mechanism. Its highly branched 3D structure, however, renders it recalcitrant to disassembly and thus challenging for stream valorization. New technological advancements being implemented have been much more efficient than classic lignin extraction and depolymerization techniques of the past.

Different biomass sources exhibit distinct lignin characteristics, influencing their suitability for various depolymerization methods. For instance, corn stover lignin, with its lower hydrophobicity and molecular weight, is more readily exploded during processes like steam pretreatment compared to wood lignin. Corn stover lignin primarily consists of β-O-4 linkages, which are susceptible to cleavage under acidic conditions, facilitating its conversion into value-added products. In contrast, wood lignin composition varies between gymnosperms and angiosperms, with differences in lignin content and the types of phenolic units present.

The depolymerization of lignin to monomeric aromatic derivatives can provide a route for the synthesis of many high-value products such as plastics, adhesives, chemicals, fuels and bioenergy-based coproducts. In particular, it can be used by the biorefinery industry to turn lignin into bioenergy and some other excellent value-added products. Thermochemical, chemical catalysis, electrocatalysis and biological depolymerization are being developed, each offering unique advantages and challenges.

Catalytic depolymerization has shown significant potential, yielding high-value products like monophenols and biofuels. Metal catalysts, such as cobalt-supported calcium oxide (Co/CaO) and ruthenium-nickel/aluminum-hydrogen catalysts, have demonstrated effectiveness in producing phenolic monomers with high selectivity. Innovations like ionic liquids in ionoSolv pretreatment and green solvents in continuous-flow reactors are enhancing the efficiency and selectivity of these processes.

A detailed understanding of the kinetics and mechanisms associated with lignin depolymerization is required to enhance these processes. Kinetic models have been established to gain insights into the fractionation dynamics and chemical moieties migration during extraction and depolymerization reactions, respectively. For the synthesis of phenolic monomers, yield largely depends on factors like temperature, pH, and solvent type. In general, higher temperatures promote depolymerization process by leading to the acceleration of reaction kinetics and increase

in solubility, while the choice of solvent type and catalyst is a crucial factor for efficiency as well as selectivity.

Lignin depolymerization into bio-oils can provide a sustainable alternative to fossil-based resources of fuels and/or chemicals, which show the possibility of tunable properties for different types of applications. Such bio-oils may contain high-value compounds such as vanillin and other phenolic derivatives for different sectors such as pharmaceuticals and cosmetics.

Moreover, the uses of lignin-derived products have applications that go beyond traditional end- uses. Lignin-based materials are used in the medical field for drug delivery and wound dressings. Lignin-derived compounds are promising sources for the development of electrochemical energy devices in the energy sector. The wide-ranging applications highlight the necessity for ongoing research and development of lignin depolymerization technologies.

Conclusion

Lignin depolymerization is highly promising in driving biomass valorization and reframing bioeconomy into sustainable operations. By overcoming such challenges linked to the complexity of lignin structure, these processes enable complete valorization of this plentiful biopolymer thus allowing high-value products to be created and contributing to sustainability. Further innovation in the depolymerization methods and high-value products looks to expand on these benefits, thereby maximizing biomass resource value.