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Nanostructured and Atomically Dispersed Catalysts on Biomass-Derived Supports for Lignin Depolymerization

The urgent need to replace fossil-based resources with sustainable alternatives calls for innovative strategies in biomass valorization. Among these, the efficient use of lignocellulosic biomass has proven particularly promising. Although a complete substitution of fossil fuels is unlikely, biomass can serve as a viable and renewable feedstock for a significant fraction of chemical production. To avoid conflicts with food supply, research efforts must focus on second-generation (2G) biomass sources—such as agricultural residues, food processing by-products, and invasive plant species.

Electrochemical lignin depolymerization has emerged as a powerful approach for the production of valuable chemical intermediates. Historically, bulk electrodes composed of carbon, nickel, lead, platinum, or copper have been used, but their limited structural tunability restricts both reactivity and selectivity. Overcoming these limitations requires a transition to nanostructured systems. Nanoparticle-based electrodes have already shown improved catalytic performance, while further advances can be achieved using single-atom (SACs) or dual-atom catalysts (DACs), in which nearly every metal atom contributes as an active site, enabling close to 100% atomic efficiency.

These catalysts rely on stable support materials, with carbon-based matrices being widely applied. To enhance the overall sustainability of the system, carbon supports derived from waste biomass—such as spent coffee grounds, brewers' spent grains, or invasive plants like Japanese knotweed—have been successfully implemented. Iron, nickel, and copper nanoparticles or atoms dispersed on such supports have proven effective in reductive electrochemical lignin depolymerization. Catalyst structures and dynamics have been characterized using XRD, XPS, SEM-EDX, LEIS, TEM, and *in-operando* XAS. The time resolution of modern synchrotron-based spectroscopy enables the investigation of structural and electronic transformations on millisecond to hour timescales, providing insight into the behavior of catalysts under reaction conditions.

The resulting depolymerization products offer synthetic potential and support the development of a more sustainable, circular chemical economy.

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