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Lignocellulosic Biomass to Value-Added Products: An Artificial Intelligence-Enabled Sustainable Biorefinery Approach

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ABSTRACT

Rising concerns over climate change, fossil fuel depletion, organic waste accumulation, and greenhouse gas emissions have intensified the transition toward sustainable bio-based energy and chemical production. Biomass resources, particularly lignocellulosic biomass (≈90% of global plant biomass), food waste, and organic residues are abundant, renewable, and carbon-neutral feedstocks supporting defossilization, decarbonization, and waste management. Instead of being burned or landfilled, lignocellulosic biomass can be valorized through integrated biorefinery approaches that combine green pre-treatment technologies, biological funneling, and artificial intelligence (AI) to recover multiple value-added products simultaneously. This review critically examines advances in biomass valorization within integrated biorefinery frameworks, focusing on lignocellulosic conversion, waste-to-energy pathways, and digital innovations. Key processes include bioethanol production via pre-treatment, enzymatic hydrolysis, and microbial fermentation; biofuel generation through dark fermentation and anaerobic digestion; production of furanic chemicals such as furfural and 5-hydroxymethylfurfural (HMF); and biomass-derived activated carbon for environmental and carbon capture applications. The roles of advanced pre-treatment, metabolic and microbial engineering, consolidated bioprocessing, life cycle assessment (LCA), techno-economic analysis, and supportive policy frameworks are evaluated. AI, machine learning, artificial neural networks (ANN), response surface methodology (RSM), IoT, and blockchain are identified as transformative tools for process optimization, real-time monitoring, yield prediction, and supply chain management. Integrated bioprocesses enhance energy recovery, stability, and resource efficiency. Despite progress, challenges such as feedstock heterogeneity, inhibitor formation, costly pre-treatment, and scale-up persist. Coordinated technological, digital, and policy strategies are essential to advance biomass-based systems toward commercial viability and a circular bioeconomy.

Keywords: *Biorefinery, Lignocellulosic biomass, Artificial intelligence, Sustainability, Fermentation, circular bioeconomy*

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