

Advances in Waste Biomass and Environmental Sustainability

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The accelerating depletion of fossil fuel reserves, together with the growing global demand for sustainable materials and energy, has intensified the need for renewable and carbon-neutral alternatives [1–3]. The transition to a low-carbon and resource-efficient society requires innovative strategies that can reduce dependence on fossil resources while minimizing environmental impacts. In this context, the valorization of waste biomass has emerged as a key approach for producing sustainable fuels, functional materials, and value-added chemicals [4,5]. By converting otherwise underutilized residues into productive resources, waste biomass valorization supports circular-economy principles, contributes to carbon-neutrality targets, and enables the development of environmentally friendly technologies [6].

Recent research continues to expand the fundamental understanding of the composition, structure, and reactivity of lignocellulosic biomass, thereby supporting advanced valorization strategies [1,7]. Comprehensive analyses of the structural complexities of cellulose, hemicellulose, and lignin highlight how compositional variability among biomass types directly influences the severity of pretreatment, catalytic performance, and achievable yields of high-value products [5,6,8–10]. Such insights are crucial for designing feedstock-specific conversion routes and integrating fractionation steps into modern biorefinery systems [11,12].

Thermochemical processing, including pyrolysis, hydrothermal conversion, and liquefaction, remains a central research focus due to its versatility in transforming diverse waste streams into bio-oils, gases, and carbon-based materials [13–15]. Advances in catalytic pyrolysis and co-pyrolysis have improved product selectivity and carbon utilization efficiency, particularly through optimized reaction pathways and rational catalyst design [9]. Hydrothermal technologies have similarly evolved, enabling efficient conversion of wet biomass without energy-intensive drying while producing intermediates compatible with downstream catalytic upgrading [15–17]. These developments support scalable and energy-efficient thermochemical routes for sustainable fuel and chemical synthesis [18].

Catalytic valorization pathways also play a pivotal role in the conversion of biomass-derived platform molecules into high-value chemicals [1]. Advances in acid, metal, and bifunctional catalysis continue to expand the range of renewable products accessible from carbohydrate-rich and lignin-rich feedstocks. Numerous studies highlight the role of bio-derived organic acids, furanics, and polyols as versatile intermediates for producing solvents, fuel additives, and monomers for advanced polymer systems [5,19]. Parallel efforts in lignin-first biorefineries are helping unlock the potential of lignin as a renewable aromatic feedstock by employing mild depolymerization strategies that preserve reactive monomeric structures for subsequent transformations [6].

Marine and alternative waste biomass resources also contribute to the diversification of renewable carbon sources. Studies on the thermochemical behavior of unconventional

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biomass, including residues with complex compositions and variable moisture contents, emphasize the importance of tailored pretreatment strategies and optimized catalytic systems to ensure consistent performance under industrial conditions [6].

Another rapidly growing research area concerns biomass-derived functional materials. Carbonaceous materials synthesized from biomass are increasingly used in energy storage, adsorption, and catalysis [20–24]. Recent studies demonstrate that optimized pretreatment, controlled porosity development, and tailored surface functionalities are essential for enhancing performance and enabling the development of next-generation biomaterials [9,25].

Integrated biorefinery approaches, combining biochemical, thermochemical, and catalytic processes, continue to gain importance as models for maximizing resource efficiency. The integration of fractionation, conversion, and upgrading steps enables simultaneous production of fuels, chemicals, and materials while minimizing waste and improving process economics. Recent advances on process integration highlight the need for flexible designs that can accommodate the inherent variability of biomass composition and supply chains [12,26,27].

As biomass technologies progress toward commercialization, sustainability assessment tools such as techno-economic analysis (TEA), life-cycle assessment (LCA), and hybrid environmental metrics have become indispensable [28–30]. Studies emphasize that accurate evaluation of energy use, emissions, carbon intensity, and social costs is essential for guiding both policy and industrial decision-making [31]. Emerging methodologies propose moving beyond process-specific assessments toward more generalizable, state-based approaches that can accelerate decision-making across technology readiness levels and biomass–product pathways [6]. Together, these tools strengthen the scientific basis for developing sustainable and economically viable biomass valorization systems.

This Special Issue, *Advances in Waste Biomass and Environmental Sustainability*, presents studies that highlight not only technological advances but also the environmental and societal benefits associated with waste biomass utilization. The collection includes six contributions covering diverse transformation pathways and sustainability considerations.

Ribeiro and Pereira reviewed the potential of lignocellulosic biomass as a feedstock for sustainable aviation fuels (SAF), outlining catalytic strategies for upgrading biomass-derived intermediates and identifying key technological barriers along with future research directions [32]. Herrera-Rodríguez and González-Delgado evaluated a conceptual biorefinery converting avocado residues into bio-oil, chlorophyll, and biopesticide using an inherent safety index methodology, demonstrating overall acceptable safety performance while identifying operational risks requiring attention [33]. Jankovičová et al. investigated the use of biogas plant digestate as a pretreatment medium for lignocellulosic maize waste; digestate soaking increased biodegradability and significantly enhanced biogas yields, offering a simple and cost-effective strategy for improving energy recovery from agricultural residues [34].

Li et al. examined steam explosion pretreatment of bitter melon vine prior to low-temperature pyrolysis to produce biochar with enhanced adsorption capacity for dyes, illustrating its potential for wastewater purification and agricultural waste utilization [35]. Spencer et al. proposed a one-step activation method using goethite iron ore to convert waste wood into high-surface-area activated carbon, with simultaneous reduction of the iron ore to a valuable metallic co-product [36]. Kuloglija et al. applied chemical activation to sunflower-seed-derived biochar, yielding activated carbon with high specific surface area and notable CO₂ adsorption capabilities, further demonstrating the viability of agro-industrial residues as precursors for high-performance adsorption materials [37].

Collectively, the contributions in this Special Issue underscore the transformative potential of waste biomass in advancing global sustainability goals. They illustrate not only technological progress, but also a broader shift in mindset: recognizing waste as a resource. Through innovations in biochar production, activated carbon synthesis, biogas enhancement, and renewable fuel development, these studies point toward a future in which biomass residues serve as integral components of sustainable energy and material systems.

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