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Introduction to 'Exploring the frontiers: unveiling new horizons in carbon efficient biomass utilization'

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An introduction to the *Green Chemistry* themed collection on biomass conversion and utilization, featuring innovative approaches to unlock biomass' full potential.

The transition toward a sustainable, carbon-neutral future demands innovative solutions that harness renewable resources with minimal environmental footprint. Lignocellulosic biomass, as a renewable reservoir of energy and carbon, holds transformative potential to redefine industrial processes, reduce fossil resource dependence, and mitigate climate change. This themed collection, 'Exploring the frontiers: unveiling new horizons in carbon efficient biomass utilization', brings together an international team of guest editors from China, the United States, and Europe. It highlights the critical role of interdisciplinary collaboration in advancing biomass valorization for chemicals, fuels, and materials. Featuring cutting-edge articles, the collection showcases innovative approaches to unlocking biomass potential – prioritizing sustainability, scalability, and technological innovation. Spanning green chemistry, synthetic biology, catalysis, and materials science, the research presented here demonstrates groundbreaking pathways for converting lignocellulosic biomass and waste streams into high-value chemicals, energy carriers, and functional materials. Together, these contributions pave the way for a more sustainable and resource-efficient future.

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Lignin valorization: from waste to wealth

A key theme of this collection is the integration of cutting-edge technologies to maximize the utilization of biomass composition and enhance the process efficiency. Lignin, nature's most abundant aromatic polymer, has long been underutilized due to its structural complexity. This collection features multiple breakthroughs in lignin conversion, emphasizing its potential as a feedstock for biofuels, polymers, and fine chemicals. For instance, transforming lignin into renewable jet-fuel cycloalkanes demonstrates how lignin-derived aromatics can replace petroleum-based aviation fuels (**https://doi.org/10.1039/D4GC02051K**). Microbial hosts like *Pseudomonas putida* and *Novosphingobium aromaticivorans* achieve high yields of 5-carboxyvanillic acid and 2-pyrone-4,6-dicarboxylic acid, respectively, from lignin derivatives (**https://doi.org/10.1039/D4GC06537A**; **https://doi.org/10.1039/D4GC01975J**). Meanwhile, technological advances in enzymatic strategies were explored to overcome lignin's structural complexity, enabling efficient depolymerization and conversion toward aromatic chemicals (**https://doi.org/10.1039/D4GC03567D**). The integration of artificial intelligence and protein engineering further accelerates the design of tailored biocatalysts, bridging the gap between laboratory innovation and industrial scalability.

Catalytic and microbial (enzymatic) conversion processes

Catalysis remains pivotal in biomass transformation. Rhenium-based catalysts demonstrate unique oxophilicity in deoxydehydration and lignin depolymerization for biomass conversion (**https://doi.org/10.1039/D4GC02925A**). A new strategy for decorating Pt/WO_x with mononuclear NbO_x improved both activity and stability for direct conversion of cellulose to ethanol (**https://doi.org/10.1039/D4GC03390F**). A catalyst-free method of photo-induced solvent-enabled selective bond cleavage is proven for lignin model compounds (**https://doi.org/10.1039/D4GC05578K**). A highly active and stable hydrogenolysis catalyst enables the reductive catalytic deconstruction of lignin into aromatic compounds (**https://doi.org/10.1039/D4GC05467A**).

Enzymatic innovations are equally prominent, while synthetic biology drives progress in bioconversion efficiency. Engineered yeast for flavanone derivatives and *P. putida* for *cis*,*cis*-muconic acid, highlight microbial platforms that are optimized for co-utilizing glucose and xylose, thus addressing feedstock heterogeneity (**https://doi.org/10.1039/D4GC05241B**; **https://doi.org/10.1039/D4GC03424D**). Engineered *Yarrowia lipolytica* strains co-ferment glucose and xylose to produce succinic acid (**https://doi.org/10.1039/D4GC04189E**). A sequential single-enzyme oxidation approach engineers a lanthanide-dependent dehydrogenase for high-yields of 2,5-furandicarboxylic acid (**https://doi.org/10.1039/D5GC00157A**), while chemoenzymatic strategies integrate cofactor regeneration systems to achieve high selectivity for furan carboxylic acids (**https://doi.org/10.1039/D4GC04735D**). Enzymatic cascades, such as photo-enzyme-coupled catalysis for 2,5-furandicarboxylic acid synthesis, demonstrate how hybrid systems overcome challenges in selective oxidation (**https://doi.org/10.1039/D4GC05475J**).

Green solvents and sustainable processes

Sustainable processes and green solvents are critical to minimizing environmental footprint. The quest for environmentally benign solvents underpins several studies. Deep eutectic solvents and ionic liquids feature prominently, as seen in a "lignin-first" biorefinery, which achieves high-purity lignin extraction with preserved β-O-4 bonds under mild conditions (**https://doi.org/10.1039/D4GC05498A**; **https://doi.org/10.1039/D4GC02874K**; **https://doi.org/10.1039/D4GC02083**). Similarly, multi-scale computational screening of cyclic amines identifies novel solvents for biomass pretreatment, balancing efficiency with reduced environmental impact (**https://doi.org/10.1039/D5GC00924C**; **https://doi.org/10.1039/D4GC05891G**). Thymol as a green solvent, can pioneer membrane fabrication for energy-efficient separations (**https://doi.org/10.1039/D4GC01961J**). These efforts align with green chemistry principles, minimizing energy consumption and toxic waste while enhancing process economics.

Innovative biomass-derived products and functional materials

The collection also underscores the critical role of biomass in fostering green chemistry and carbon-efficient systems, showcasing breakthroughs in transforming biomass into high-value bio-based products. From biodegradable materials to chemicals, biomass-derived products are redefining industries toward a circular bioeconomy. Biodegradable copolymers of lignin-*graft*-polyester with enhanced thermal stability for packaging and construction have been synthesized (**https://doi.org/10.1039/D4GC03558E**).

3D photocatalysts from lignin help design solar-driven antimicrobial materials for environmental remediation (**https://doi.org/10.1039/D4GC01246A**), while sudden supercritical water hydrolysis of tomato peel unlock rigid cutin networks for bio-based polymers (**https://doi.org/10.1039/D5GC00375J**).

Multifunctional reinforced bioplastics are innovatively designed by crosslinking cellulose nanofibrils and polyhydroxybutyrate, with computational modeling, guiding enhanced thermal stability, mechanical strength, and accelerated biodegradation (**https://doi.org/10.1039/D4GC02440K**). Diacid-superbase ionic liquids for the efficient dissolution of cellulose are described, and a variety of high-performance cellulosic materials are prepared (**https://doi.org/10.1039/D4GC02083A**). Innovations such as biochar-integrated urban green infrastructures and food waste valorization for lactic acid and carbon dot production, exemplify circular economy principles, transforming agricultural and industrial waste into functional products while enabling carbon sequestration (**https://doi.org/10.1039/D4GC03071K**; **https://doi.org/10.1039/D4GC01890G**).

Sustainable biorefinery systems and green metrics

The transition to a bio-based economy demands not only scientific innovation but also economic viability and environmental stewardship. Beyond technical innovation, this collection emphasizes sustainability assessments. Contributions like *Path2Green* – 12 principles for green extraction – provide frameworks to evaluate environmental and economic viability (**https://doi.org/10.1039/D4GC02512A**). Technoeconomic analysis of C-lignin biorefineries demonstrates a pathway to produce bio-catechol by reducing the carbon footprint (**https://doi.org/10.1039/D4GC06090C**). Life cycle analyses reveal pathways to reduce greenhouse gas emissions for bio-based adipic acid, underscoring the dual imperative of scalability and sustainability (**https://doi.org/10.1039/D4GC03424D**). Novel integrated biorefineries can reduce 5-hydroxymethyl furfurals production costs through waste-stream valorization, which aligns with economic and environmental sustainability (**https://doi.org/10.1039/D4GC04270K**). These frameworks provide actionable guidance for policymakers and industries to adopt greener practices, enabling the transition toward a circular bioeconomy through sustainable biorefinery systems.

This collection not only captures the dynamism of carbon-efficient biomass research but also underscores the pressing need to accelerate the transition toward bio-based and circular economies. By bringing together excellent global expertise, it offers a strategic roadmap for tackling climate change, resource depletion, and environmental pollution. Positioned at the crossroads of green chemistry and sustainable development, the insights presented here serve as a catalyst for continued innovation, collaboration, and meaningful action toward a resilient, carbon-neutral future.

This collection features numerous valuable contributions that could not be covered in this editorial due to space constraints. We extend our gratitude to the contributors whose groundbreaking research enriches this collection. Their dedication to advancing carbon-efficient solutions underscores the collective effort required to achieve a sustainable future. We are also grateful to the editorial office of *Green Chemistry*, especially Dr Kieran Nicholson, Dr Andrea Carolina Ojeda Porras, and Dr Zhiyuan Zhu for their guidance and support throughout the preparation of this collection.