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Introduction to the circular economy themed collection

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The global transition to a circular economy represents one of the most pressing challenges of our time, requiring a fundamental shift in how we design, use, and manage materials and resources. At its heart, the circular economy is a systems approach to economic development that aims to decouple growth from the consumption of finite resources.[1,2] By prioritising waste minimisation, material reuse, and sustainable innovation, the circular economy[3] promises not only environmental benefits but also new opportunities for economic growth and social equity.

In this themed collection, we bring together cutting-edge research and thought leadership to advance the principles and practice of the circular economy. The collection spans a wide range of topics, including innovations in materials science, advancements in resource recovery technologies, and frameworks for systemic change.[4] Together, these contributions provide a comprehensive look at the state of the art in circular economy research and offer actionable insights for stakeholders across academia, industry, and policy. Central to these efforts is the pivotal role of chemistry,[5] which underpins many of the innovations necessary to drive the transition to a sustainable future.

Innovation in materials and design

A key pillar of the circular economy is rethinking materials—designing them for longevity, recyclability, and minimal environmental impact. Several contributions in this collection showcase innovative pathways for sustainable materials. The development of bio-based, chemically recyclable epoxy thermosets (**https://doi.org/10.1039/d4su00382a**) represents a significant step towards sustainable composite materials, offering a viable alternative to traditionally non-recyclable plastics. Similarly, the upscaled synthesis of pinene-derived monomers (**https://doi.org/10.1039/d4su00210e**) demonstrates how bio-based building blocks can replace fossil-derived polymers in coatings, improving sustainability without compromising performance.

Beyond polymer innovation, this collection highlights lignocellulosic biomass valorisation (**https://doi.org/10.1039/d4su00342j**), which reviews methods for transforming agricultural residues into valuable chemical feedstocks. While bio-based materials are often discussed in the context of energy applications, this study underscores their broader potential in high-value chemical production and materials science. Furthermore, keratin–chitin bio-composite films (**https://doi.org/10.1039/d4su00179f**) demonstrate how waste-derived biopolymers can be repurposed for wastewater treatment, providing an innovative approach to sustainability.

These studies collectively highlight how chemistry enables material innovation, reducing reliance on virgin resources while advancing circular economy principles. By integrating renewable feedstocks and designing materials for end-of-life circularity, researchers are paving the way for sustainable industrial transformation.

Advancements in resource recovery

Closing the material loop requires efficient and scalable resource recovery solutions. Papers in this collection explore novel approaches to battery recycling, including microwave-assisted lithium recovery (**https://doi.org/10.1039/d4su00202d**), which offers a more energy-efficient alternative to traditional processes. "Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes" (**https://doi.org/10.1039/d3su00142c**) highlights advancements in recovering lithium, cobalt, and nickel from spent batteries, critical for

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ensuring long-term material security in clean energy technologies.

Chemical recycling also plays a crucial role in closing resource loops. "Chemical recycling of PET to value-added products" (**https://doi.org/10.1039/d3su00311f**) presents innovative depolymerisation strategies that allow PET plastic waste to be transformed into fine chemicals and monomers, reducing reliance on virgin petrochemicals. Additionally, new catalytic pathways for polymer upcycling (**https://doi.org/10.1039/d4su00233d**) provide insights into making plastic waste a viable feedstock for high-performance materials.

Precious metal recovery is another area where chemistry is enabling circularity. "Recovery of Palladium from Waste Fashion Items Through Food Waste By-Products" (**https://doi.org/10.1039/d3su00242j**) introduces a green chemistry approach to extracting valuable metals from discarded jewellery, demonstrating the potential of alternative, bio-based solvents in sustainable metal recycling. These advancements illustrate how interdisciplinary research can turn waste into valuable resources, strengthening the case for circular economy principles in high-value materials recovery. The strategies to recover critical materials for energy storage (**https://doi.org/10.1039/d3su00142c**) have the potential to reduce reliance on mining. Meanwhile, palladium recovery from waste jewellery (**https://doi.org/10.1039/d3su00242j**) introduces a green chemistry approach to recovering valuable metals using food waste by-products. These advancements illustrate how interdisciplinary research can turn waste into valuable resources, strengthening the case for circular economy principles in high-value materials recovery.

Systems thinking and policy

Technological advancements must be accompanied by systemic shifts in regulation, policy, and economic models. This collection includes a review of 20 years of e-waste regulation in the EU (**https://doi.org/10.1039/d4su00548a**), highlighting gaps and opportunities for more effective circular economy policies. Similarly, Safe and Sustainable by Design (SSbD) principles for nanomaterials (**https://doi.org/10.1039/d2su00101b**) emphasise the need to integrate safety and circularity considerations into emerging materials. These contributions underscore the importance of policy frameworks that incentivise sustainability while ensuring long-term environmental and economic benefits.

Furthermore, industrial symbiosis emerges as a key strategy for achieving sustainability at scale. "Towards flexible large-scale, environmentally sustainable methanol and ammonia co-production using industrial symbiosis" (**https://doi.org/10.1039/d4su00647j**) explores how integrating green hydrogen and carbon capture into production processes can significantly reduce emissions. These findings illustrate the potential of systemic industrial collaborations to drive circular economy principles in heavy industry. Technological advancements must be accompanied by systemic shifts in regulation, policy, and economic models. This collection includes a review of 20 years of e-waste regulation in the EU (**https://doi.org/10.1039/d4su00548a**), highlighting gaps and opportunities for more effective circular economy policies. Similarly, Safe and Sustainable by Design principles for nanomaterials (**https://doi.org/10.1039/d2su00101b**) emphasise the need to integrate safety and circularity considerations into emerging materials. These contributions underscore the importance of policy frameworks that incentivise sustainability while ensuring long-term environmental and economic benefits.

Community and global perspectives

The transition to a circular economy must be inclusive and globally relevant, addressing diverse regional and industrial challenges. A significant theme in this collection is the importance of regionally adapted recycling systems. "A review on spent lithium-ion battery recycling: from collection to black mass recovery" (**https://doi.org/10.1039/d3su00086a**) outlines key barriers to effective LIB recycling across different economic contexts, reinforcing the need for localised strategies. Similarly, "Recovery of palladium from waste fashion items through food waste by-products" (**https://doi.org/10.1039/d3su00242j**) demonstrates how bio-based approaches can enable sustainable precious metal recovery. "Mapping the end-of-life of chemicals for circular economy opportunities" (**https://doi.org/10.1039/d4su00517a**) further highlights how regional waste management variations influence circularity outcomes, underscoring the need for adaptable, policy-driven solutions.

Complementing industrial symbiosis strategies, this collection also features innovative uses of underutilised waste streams. "One-pot synthesis of carbon dots from neem resin and their application in Fe(II) detection and photocatalytic degradation of toxic dyes" (**https://doi.org/10.1039/d3su00404j**) showcases how natural biomass can contribute to environmental monitoring and pollution remediation, illustrating the role of emerging materials science in circular economy applications. Similarly, "Valorisation of lignocellulosic biomass" (**https://doi.org/10.1039/d4su00342j**) presents scalable bio-based solutions for waste-to-energy pathways, while biopolymer-based keratin–chitin films (**https://doi.org/10.1039/d4su00179f**) offer sustainable alternatives for wastewater treatment. Additionally, carbon-supported copper catalysts from citrus waste (**https://doi.org/10.1039/d4su00463a**) exemplify the potential of food waste valorisation in clean energy applications.

These studies highlight how regionally adaptable, bio-based, and systemic approaches can play a key role in closing material loops across various industries while ensuring equitable benefits from circular economy transitions.

Looking ahead

As the research in this collection demonstrates, the circular economy is not a distant goal but an achievable and necessary transformation. However, realising its full potential will require sustained investment in research, innovation, and collaboration. Despite progress, only about 7.2% of materials were cycled globally in 2023, a decline from 9.1% in 2018.[6] Meanwhile, global material consumption has surged, with over 500 billion tonnes used in the past five years—nearly equal to the total consumption during the entire 20th century. If this trend continues, material use is expected to double again by 2050,[6] exacerbating environmental and resource challenges. The urgency for circularity has never been greater.

The challenge now lies in translating research into systemic change. This includes fostering innovation, scaling sustainable solutions, and integrating circular principles into industrial practice and policy. Advancing these efforts will not only enhance material stewardship but also significantly contribute to the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Embedding circular economy principles within these broader sustainability frameworks will be critical for achieving long-term economic and environmental resilience.

The papers in this collection provide a strong foundation for continued progress and highlight the immense opportunities ahead. Chemistry will remain a cornerstone of these efforts, driving advancements in materials, processes, and systems thinking. We extend our gratitude to all the authors, reviewers, and editors who contributed to this themed collection. Your efforts have helped illuminate the path towards a more sustainable and circular future. We hope this collection inspires further innovation and dialogue as we collectively work to transform economic systems and safeguard our planet for generations to come.

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