STRATEGIC RESEARCH AND INNOVATION AGENDA

Circular Economy

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Foreword

CLIC Innovation is an open innovation cluster focused on bioeconomy, circular economy, and energy. By bringing together industry and academia, CLIC manages collaborative RDI projects that accelerate the commercialisation of new knowledge. By driving sustainable circular business development, CLIC strives to create broader and quicker positive impact for the environment, society, and the planet as a whole. Jointly developed strategic research and innovation agendas (SRIAs) guide cluster partners toward shared RDI goals, and CLIC invites all stakeholders to join efforts in implementing the SRIA.

CLIC's circular economy (CE) cluster's SRIA sets out a framework for sustainable circular production & consumption. The main philosophy (Figure 1) for the circular activities is simple, the cluster aims to use different circular strategies to enable materials and products to loop continuously through the economy via cross-cutting industrial innovations, regenerative value chains and business models, and push for societal transitions with resilient supply systems. Yet beneath this seemingly straightforward philosophy lie highly complex systems, where material flows, technological pathways, business incentives, policy frameworks, and social behaviours must align in practice for circularity to truly function at scale.

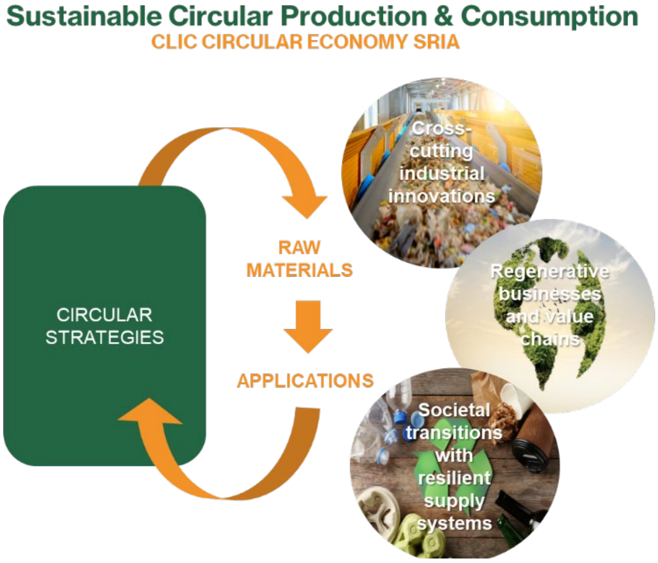

Figure 1. CLIC CE SRIA circular philosophy.

Because circularity is still far from mainstream, the lack of widely adopted practices, scalable solutions, and enabling conditions form major gaps for circularity transition that the CE Cluster aims to close through coordinated innovation, research, and systemic transition efforts. The main focus raw material areas are chemicals and polymers, critical and strategic materials, non-forest biobased raw materials, water and technical carbon.

Transitioning to a circular economy is both necessary and strategic in today's uncertain global environment. It offers substantial business opportunities for those who adapt quickly, but success depends on innovative cooperation across public and private sectors, cross-border teamwork, and resilient value chains. Redefining production, consumption, and governance systems requires a holistic approach, and although the process is complex, integrated efforts are essential for lasting sustainability and competitiveness.

Together, the Shareholders and partners of CLIC seek to reduce the global overuse of natural resources with novel technological and service solutions. CLIC Shareholders and partners (01/2026):

Industry partners

ABB, AFRY, ANDRITZ, BMH TECHNOLOGY, ELENIA, FCG, fortum, Gasum, HELEN, Kemira, KUUSAKOSKI RECYCLING, L&T, Metso, Metsä, Metsäteho, NEOVA, NESTE, NG Nordic, SSAB, storaenso, Sumitomo SHI FW, UPM BIOFORE BEYOND FOSSILS, VAISALA, Valmet, Vantaan Energia, WÄRTSILÄ

RTOs

Aalto University, SYKE Finnish Environment Institute, Ilmatieteen laitos Meteorologiska institutet Finnish Meteorological Institute, GTK, LUT Lappeenranta University of Technology, NLS National Land Survey of Finland, Luke Natural Resources Institute Finland, Tampere University, University of Eastern Finland, University of Helsinki, Jyväskylän yliopisto University of Jyväskylä, University of Oulu, University of Turku, Vaasan yliopisto University of Vaasa, VTT, Åbo Akademi

Associated partners

3Flash Finland, DURAT, LAB University of Applied Sciences, MIRKA, Tampere University Tampere University of Applied Sciences, vaasaETT

On behalf of the CLIC CE Cluster,
Anna Tenhunen-Lunkka
Head of Circular Economy
CLIC Innovation Ltd

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Executive summary

THE circular economy (CE) is more than a resource efficiency strategy; it is a transformative pathway to address the systemic nature of global challenges and redefines how value is created, delivered, and sustained across society. By decoupling economic growth from resource consumption and environmental degradation, CE directly supports the wellbeing of the environment and planetary boundaries, whilst ensuring business and societal development. CE taps into new opportunities for sustainability, innovation, competitiveness as well as resilience and security. To fully realize these benefits, systemic solutions are needed to respond to complex, often systemic, challenges.

Systemic challenges are those that arise from the interconnectedness of social, economic, and environmental systems. They are complex, multi-layered, and often resistant to simple solutions. Challenges such as climate change, biodiversity loss, resource scarcity, and social inequality are interconnected issues influenced by the structure and functions of existing economic and societal systems. The systemicity emerges from cross-sector dependencies, feedback loops, and entrenched patterns of production and consumption that span local to global scales. Systemic solutions require integrated approaches that consider the full lifecycle of materials, products, and services. At best, they need to be adaptive (*responding to new conditions and operational environments as well as new knowledge*), inclusive, multi-level and cross-sectoral. CE is embraced not just as a technical fix, but as a strategic approach to rethinking how systems operate; economically, socially, and environmentally.

This systemic approach aligns with the broader goals of CLIC leading collaboration for systemic transitions by integrating environmental, economic, and social dimensions into a cohesive strategy for long-term sustainability and resilience. This SRIA shows the shared commitment of CLIC partners; the companies and industry, universities, and research organizations, to tackle complex challenges together and co-develop novel circular solutions and scale circular economy.

The transition to a circular economy demands systemic transformation, combining innovative technologies, forward-looking policies, and shifts in both business practices and consumer behavior. Beyond improving material efficiency and developing sustainable alternatives, success hinges on new business models, such as product-as-a-service and resource recovery, and a cultural shift toward long-term value creation. Digitalisation plays a critical role by enabling real-time tracking of materials, enhancing transparency across value chains, and supporting data-driven decision-making. At the same time, the rise of regenerative business strategies and the growing emphasis on supply chain resilience offer new opportunities to align economic activity with ecological boundaries. Achieving these goals requires seamless collaboration between researchers, industry leaders, and policymakers, ensuring that innovation, regulation, and market incentives move in step toward a more circular and resilient future. In 2025, the shareholders of CLIC Innovation identified critical circular economy areas where research, development and innovation (RDI) activities are most needed. This strategic research and innovation agenda (SRIA) for Circular Economy presents these focus areas, which are:

» Chemicals and polymers
» Critical and strategic materials
» Non-forest biobased raw materials
» Water
» Technical carbon

The CLIC-level SRIA outlines cross-cutting themes that highlight the importance of integrating non-technical, multidisciplinary perspectives into research, innovation, and technology development. These themes address key areas such as industrial innovation through digitalization and AI to drive sustainability, the advancement of regenerative business models and value chain development, and the facilitation of societal transitions supported by resilient supply systems.

A central principle of the SRIA is the recognition that applications serve as powerful sources of novel and green growth. By linking research with concrete applications in industry and society, the agenda ensures that developments lead to scalable solutions with measurable impact. Applications act as both testbeds and accelerators, transforming R&D&I outputs into innovations that create new business opportunities, enable green growth, and reinforce the transition towards a circular economy.

1. Introduction: Circular economy operating within the planetary and legislative boundaries

THE circular economy (CE) has been shaped by legislation and different initiatives to be a transformative pathway to address the systemic nature of global challenges and redefines how value is created, delivered, and sustained across society. By decoupling economic growth from resource consumption and environmental degradation, CE directly supports the wellbeing of the environment and planetary boundaries, whilst ensuring business and societal development. CE taps into new opportunities for sustainability, innovation, competitiveness as well as resilience and security. To fully realize these benefits, systemic solutions are needed to respond to complex often systemic challenges.[1], [2]

Systemic challenges are those that arise from the interconnectedness of social, economic, and environmental systems. They are complex, multi-layered, and often resistant to simple solutions. These challenges, such as climate change, biodiversity loss, resource scarcity, and social inequality, are not isolated problems but deeply interconnected, driven by the structure and functions of the current economic and societal systems. The systemicity emerges from cross-sector dependencies, feedback loops, and entrenched patterns of production and consumption that span local to global scales.

The planetary boundaries framework defines the environmental limits within which humanity can safely operate. It identifies nine critical Earth system processes: climate change, biosphere integrity (such as biodiversity loss), land-system change, freshwater change, biogeochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and introduction of novel entities, such as chemical pollution or plastics, to the environment. These boundaries represent thresholds to maintain a stable and resilient planet. Crossing these boundaries increases the risk of triggering abrupt or irreversible environmental changes that could undermine the conditions for human development. Currently, 7 boundaries are crossed. [3]

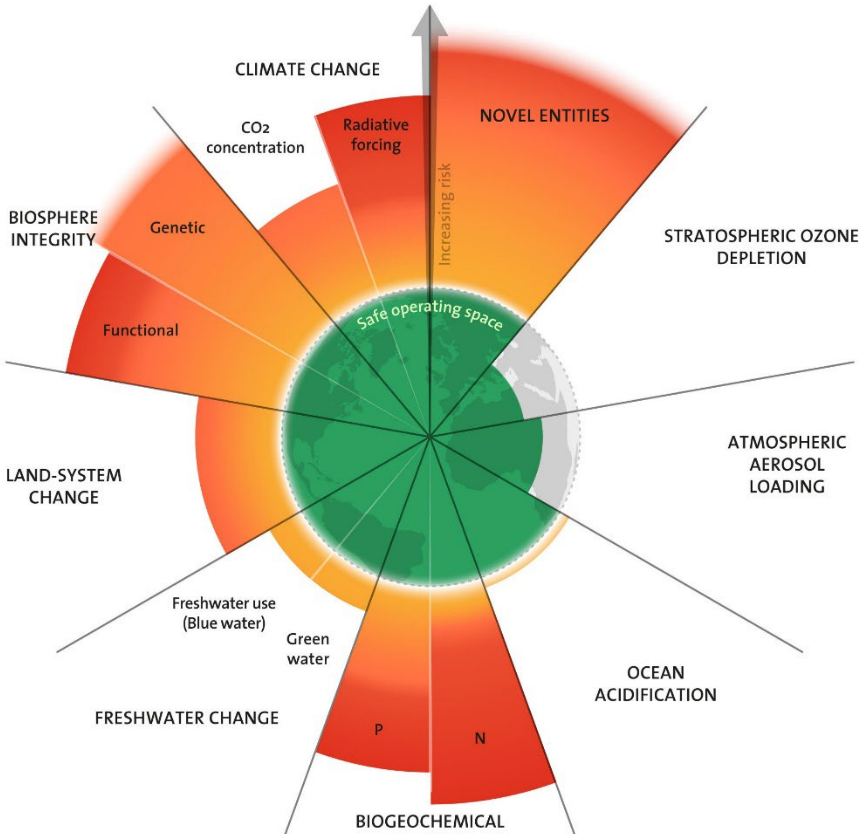

Figure 2. Planetary boundaries and their situation in 2025. Source: Stockholm Resilience Centre.

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[1] analysis_of_the_eu_circular_economy_action_plan_2020_web.pdf

[2] Regulatory landscape of the circular economy (pdf)

[3] Planetary boundaries - Stockholm Resilience Centre

When boundaries are transgressed, the consequences can be severe. For example, exceeding the climate change boundary can lead to rising sea levels, extreme weather events, and ecosystem collapse. Breaching the biodiversity boundary threatens food systems and natural resilience, while disruption of biogeochemical flows (like nitrogen & phosphorus cycles) can cause dead zones in oceans and freshwater systems. These impacts are not isolated; they interact and amplify each other, creating systemic risks that affect health, economies, and societies globally.[1]

The boundaries are interconnected, which makes the systemic approach essential. Tackling one issue in isolation can inadvertently worsen another. Circular economy is a systemic approach to tackle multiple global challenges by redesigning production and consumption systems to minimize waste, regenerate natural systems, and keep materials in use. This reduces pressure across multiple boundaries simultaneously and cutting emissions, conserving resources, and protecting ecosystems.[1]

To implement such solutions effectively, cross-sector and multi-stakeholder collaboration is crucial. Circularity cannot be achieved by a single actor alone - it requires collaboration across sectors, value chains, and disciplines. No company, municipality, or research organization can operate in a fully circular way in isolation, because circular systems depend on shared flows of materials, data, and value. It is characteristic of circular economy that progress depends on partnerships, co-creation, and systemic coordination. Governments must create enabling policies, businesses need to innovate and adopt sustainable models, scientists provide data and insights, and civil society ensures accountability and inclusivity as well as a fair transition.

In response to the global challenges, CE has been widely embedded in national strategies, international agreements, and businesses' innovation agendas. Central to EU's efforts in accelerating transition to circular economy is the Circular Economy Action Plan (CEAP), launched under the European Green Deal. CEAP outlines systemic measures across product design, waste prevention, and resource recovery, with targeted initiatives for high-impact sectors such as textiles, electronics, packaging, and vehicles. The new EC's Clean Industrial Deal is a strategic initiative aimed at strengthening the EU's industrial competitiveness while accelerating the transition to a low-carbon economy[4]. It focuses on turning decarbonisation into a growth driver by supporting energy-intensive industries and clean-tech sectors through affordable energy, circularity, and innovation.

Different new or amended key legislative instruments to implement the CEAP include, for example, the Ecodesign for Sustainable Products Regulation (ESPR), which promotes circularity and applies to any physical goods that are placed on the market or put into service, including components and intermediate products. Further impacts are expected through the expansion of Extended Producer Responsibility (EPR) schemes, particularly in textiles and packaging, further shifts lifecycle responsibility to producers, incentivizing sustainable design and end-of-life management. For packaging, a key legislation driving circularity has been the 2025 Packaging and Packaging Waste Regulation (PPWR), which pushes for waste reduction, and higher reuse and recycling. In parallel, the Circular Economy Monitoring Framework was revised in 2023 to include indicators on material footprint and resource productivity, reinforcing the EU's commitment to climate neutrality by 2050. Waste Electrical and Electronic Equipment (WEEE) is under evaluation and recent progress report highlights that nearly half of the WEEE is not collected at all, critical raw materials are lost, and the recycling rates remain rather low around 40 %.[5,2]

Despite the circularity boom and set legislation, the circularity transition is still slow and even declining. Globally, the UN Sustainable Development Goals (SDGs) continue to emphasize circularity, particularly in Goal 12: Responsible Consumption and Production. However, the 2025 SDG Report warns that only 17% of targets are on track, underscoring the urgency of scaling up circular solutions[6]. According to the Global Circularity Gap report, the global circularity has declined as only 6.9% of materials entering the global economy are reused, down from 7.2% in 2024. This indicates a widening circularity gap despite growing awareness and efforts.[7] Businesses are increasingly seen as key actors to reverse this trend by redesigning products, rethinking supply chains, and investing in reuse and recycling systems. A survey of 420 executives across 10 industries found that while only 40% considered circularity important three years ago, 75% do today, and 95% expect it to be critical within three years[8]. Circularity has shifted to drive economic value by enabling revenue growth,

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[4] Clean Industrial Deal - European Commission

[5] Circular economy action plan - European Commission

[6] SDG Indicators

[7] 2025 The Global Circularity Gap Report | Deloitte Global

[8] The circular transformation of industries: Unlocking economic value | World Economic Forum

cost reduction, greater resilience against supply chain shocks, and progress in sustainability and emissions reduction.

According to the European Environment Agency's Circularity Metrics Lab[9], businesses are undergoing a significant transformation toward circular operating models, aiming to decouple profitability from environmental degradation. This shift is driven by changing consumer expectations and the need to reduce resource dependency. Key indicators highlight both progress and challenges: EU Ecolabel certifications have surged by 121% since 2014, reflecting growing adoption of circular products; 32% of SMEs now offer green products or services; and 4.3 million people are employed in circular economy sectors across the EU. The Repairability Index has assessed over 1,400 products, especially smartphones, promoting longer product lifespans. However, the increased production and consumption of chemicals, up by 8%, signals that cleaner material cycles still face hurdles. These metrics underscore both the momentum and complexity of embedding circularity into business practices.

Systemic solutions require integrated approaches that consider the full and multiple lifecycles of materials, products, and services. At best, CE solutions need to be adaptive (*responding to new conditions and operational environments as well as new knowledge*), inclusive, multi-level and cross-sectoral. CE is embraced not just as a technical fix, but as a strategic approach to redesign how systems operate - economically, socially, and environmentally. To fully realize these benefits, systemic change is needed, supported by policy frameworks, financial instruments, and education. Multi-stakeholder collaboration is essential: governments must set enabling conditions, businesses must lead innovation, and citizens must be engaged as active participants in the transition.

This systemic approach aligns with the broader goals of CLIC leading collaboration for systemic transitions by integrating environmental, economic, and social dimensions into a cohesive strategy for long-term sustainability, security and resilience.

This SRIA shows the shared commitment of CLIC partners - the companies and industry, universities, and research organizations tackle together complex challenges and co-develop novel circular solutions and scale circular economy.

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[9] Circularity Metrics Lab

2. CLIC Strategic research and innovation agendas

2.1. CLIC high-level SRIA

AT the CLIC level, the high-level SRIA is anchored in three interconnected themes; Bioeconomy, Circular Economy, and Future Energy Systems, that together drive sustainable transformation. These themes are reinforced by three cross-cutting layers that ensure both technological progress and societal impact as well as CLIC's open ecosystems 4R and GreenE2. Cross-cutting layers are industrial innovations, business and value chain development, and societal transitions with resilient supply systems. The *industrial innovations* integrate digitalisation, AI, and industrial carbon cycling to accelerate sustainable production and resource efficiency. *Business and value chain development* focuses on scaling regenerative industries and supporting circular, performance-based business models that embed social responsibility, inclusivity, and fair value distribution across supply chains. Finally, *societal transitions with resilient supply systems* ensure that the transformation is both sustainable and just, by linking urban resilience with secure, equitable access to energy, food, water, transport, and materials.

The 4R Innovation Ecosystem SRIA and the CLIC Circular Economy SRIA are deeply interconnected, each reinforcing the other's impact and reach. The 4R ecosystem, with its focus on plastics and polymer circularity (*circular packaging, technical plastics & composites, and textiles*), acts as a specialized, action-oriented platform within the broader CE SRIA framework. It demonstrates how targeted, sectoral innovation ecosystems can accelerate systemic change and deliver tangible results in high-impact value chains. The 4R Innovation Ecosystem is a great example of how the CE SRIA's systemic vision can be realized in practice. By aligning sectoral innovation platforms like 4R with the broader CE SRIA, CLIC ensures that breakthroughs in plastics circularity contribute to and benefit from the wider transition to a circular, resilient, and sustainable economy.

The CE SRIA provides the overarching strategic framework setting a common vision, cross-cutting themes, and systemic circularity across the different material and application flows, value chains, and sectors. It emphasizes the need for integrated approaches, cross-sectoral collaboration, and the valorisation of diverse material sources, including processing residues, side streams, and waste streams. The CLIC high-level cross-cutting themes steer the CE SRIA from a sectoral roadmap to a systems-level strategy. The cross-cutting themes ensure that RDI efforts are future-proof, interconnected, and aligned with broader EU and global goals, such as the Green Deal, Bioeconomy Strategy, and Digital Transition and the UN SDGs.

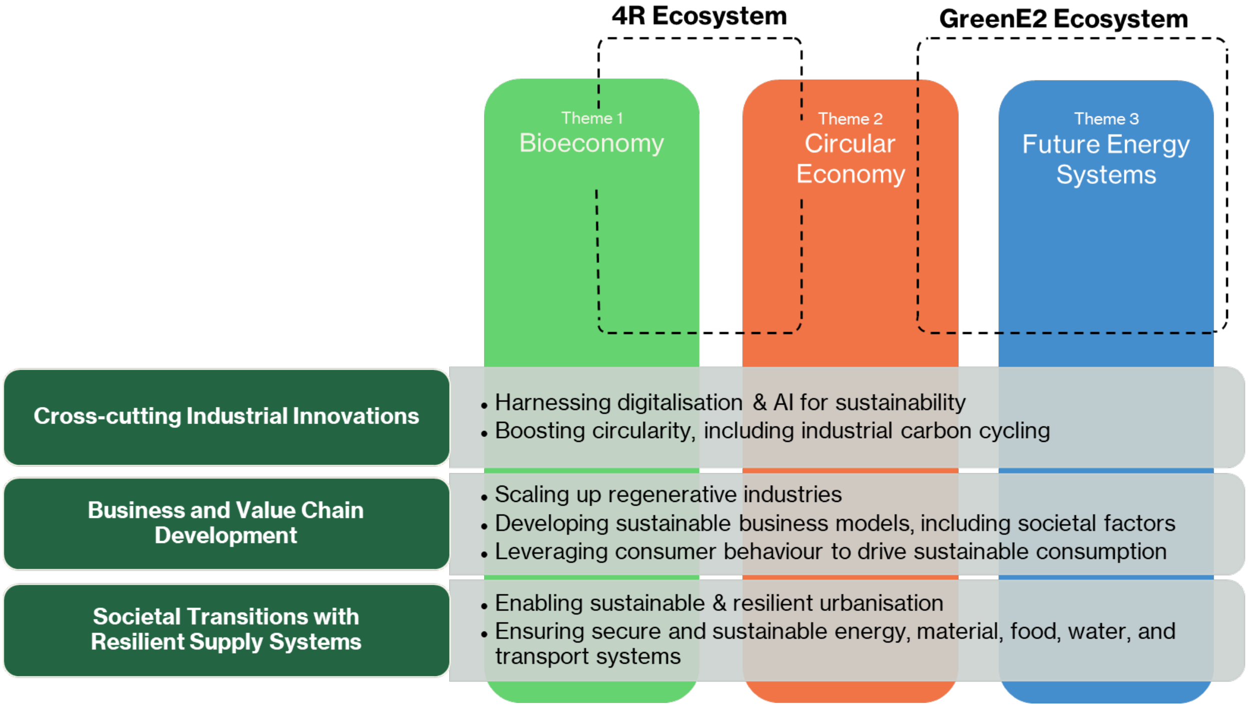

Figure 3. CLIC high-level SRIA.

2.2. Circular Economy SRIA

THE Circular Economy SRIA defines CLIC's strategic framework to accelerate the transition towards sustainable circular production and consumption. It positions circularity not as an isolated objective, but as a systemic enabler of industrial and societal transformation, compete-tiveness, and resilience across value chains and sectors.

The framework is built around **three interconnected pillars** (Figure 4):

1. **Circular strategies** that shift production and consumption patterns
2. **Strategic raw material focus areas** reflecting partner priorities
3. **Application domains** where circular solutions are implemented and scaled

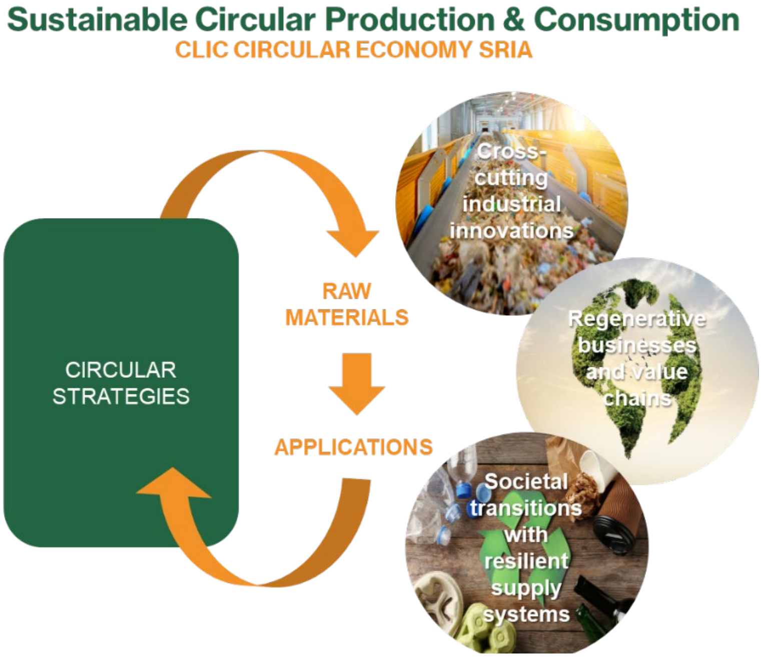

Figure 4. CLIC CE SRIA's main principles

At its core, the SRIA integrates the full spectrum of circular strategies (Refuse–Recover), including higher perceived circularity-value retention approaches such as refuse, rethink, reduce, reuse, and repair, while ensuring efficient recycling and material recovery where needed. This hierarchy supports a transition from linear resource use toward value-preserving, closed-loop systems. The circular strategies are often referred to as the 10 R-strategies, arranged from most to least impactful in terms of resource efficiency:

- *Refuse, Rethink, Reduce*: Avoiding excessive use of resources and unnecessary consumption.
- *Reuse, Repair, Refurbish, Remanufacture, Repurpose*: Extending product lifetime and functionality.
- *Recycle, Material Recovery:* Recovering materials at the end of life for a new lifetime, and processing residues, industrial side streams, and different waste streams.

RAW MATERIAL FOCUS AREAS AND CIRCULAR PRODUCTION

THE CE SRIA focuses on five strategic raw material domains (Figure 5) : **chemicals and polymers, critical and strategic materials, non-forest bio-based raw materials, water, and carbon**. These together represent the core resource base for circular transformation across industries and society. These domains reflect the **industrial and research strengths of CLIC's partner network**, spanning process industries, technology providers, municipalities, and research organisations. Forest-based raw materials are the focus of CLIC's bioeconomy cluster.

Chemicals and polymers underpin a wide range of industrial applications within the partner base but require redesign for circularity; critical and strategic materials are essential for energy, digital, and manufacturing sectors represented in the network, yet face supply and resilience challenges; non-forest bio-based materials build on strong bioeconomy capabilities, enabling renewable and regenerative solutions; water connects industrial and urban systems as both a resource and a carrier of materials and energy; and carbon links emissions-intensive sectors with emerging circular carbon value chains. Together, these domains reflect where **CLIC partners can jointly drive impact**, using their complementary roles across value chains to close material loops, enable substitution, and scale circular solutions across sectors.

Regarding sustainable circular production, industrial side streams and waste fractions are a central lever for scaling circularity from pilots to industrial deployment. Beyond end-of-life products, the SRIA prioritises the valorisation of production residues, by-products and waste fractions as circular feedstocks across sectors. This requires (i) systematic characterisation and digital traceability of streams, (ii) safe and sustainable upgrading and purification technologies, (iii) industrial symbiosis models that enable cross-sector utilisation, and (iv) market-creating measures such as standards, certification and long-term offtake mechanisms.

Figure 5. Strategic raw material focus areas of the CLIC CE SRIA.

CIRCULAR APPLICATIONS

THE SRIA targets a broad and evolving range of applications, understood as material integration platforms across key industrial and societal systems. These include, but are not limited to, packaging, construction, mobility, energy systems, electronics, textiles, food and feed, water infrastructure, and industrial processing, where multiple raw material streams converge. Applications are prioritised based on their ability to embed and circulate primary, secondary, and bio-based feedstocks, particularly in areas with high material throughput, strategic relevance, or strong potential for loop-closing, substitution, and cross-sectoral value creation.

The SRIA does not define a closed list of applications, but focuses on those that act as scalable entry points for circularity, enabling continuous reconfiguration of materials and value chains as technologies, markets, and partner capabilities evolve. These applications are inherently dynamic, evolving as new material combinations, processing technologies, and circular business models emerge, thereby continuously expanding the scope and impact of circular solutions.

In circular systems, applications and products function as active nodes of material circulation, where raw materials are combined, retained, and later recovered. By closing loops, they enable the sourcing and re-sourcing of embedded materials across lifecycles, transforming products into temporary material banks rather than end points. As such, applications are key leverage points for scaling circularity, ensuring that material compatibility, traceability, and recoverability are embedded from the outset.

CROSS-CUTTING ENABLERS

MANAGING trade-offs between environmental impact, economic viability, and system complexity is inherent to circularity. The SRIA therefore promotes a systems-thinking approach, supported by cross-sector collaboration and multidisciplinary integration. The SRIA emphasises that circularity requires more than technological innovation. It demands simultaneous progress in three domains:

- Technological breakthroughs, including digitalisation, artificial intelligence and advanced processing
- Business model innovation, such as product-as-a-service and circular value chains
- Behavioural and societal change, enabling adoption and systemic impact

The CE SRIA highlights the importance of advancing intelligent material circulation**,** valorization of diverse material sources**,** and the development of added value and closed-loop systems. These efforts are embedded within a broader framework that promotes cross-sector collaboration, systems thinking, and the integration of circular principles into innovation ecosystems, policy frameworks, and industrial strategies. Applications are at the heart of this systemic framework, acting as sources of novel and green growth. By linking systemic approaches with concrete applications, the CE SRIA ensures that RDI outputs can be piloted, scaled, and translated into industrial practice, unlocking new value chains, fostering innovation-driven business opportunities, and accelerating societal transitions.

To be effective, CE must be deployed across multiple levels of transition: from macro-level policy and regulatory frameworks to meso-level industrial ecosystems and value chains, down to micro-level business models and consumer behavior. Its principles, designing out waste, keeping materials in use, and regenerating natural systems, must be woven into innovation ecosystems, governance structures, and industrial strategies. However, translating these principles into practice involves navigating complex trade-offs, such as balancing environmental impact with economic viability, or aligning global supply chains with local circular solutions. This complexity is essential to CE's systemic nature and must be embraced through a holistic, collaborative, and adaptive approach.

Broader interdisciplinarity and cross-cutting themes; such as digitalisation, artificial intelligence, systems thinking for managing complex interdependencies, value chain development and transformation, comprehensive sustainability assessment, and the integration of diverse disciplinary perspectives, are needed to ensure a holistic approach to technical, sustainability, social, and policy readiness. These include disciplines such as social sciences and humanities (especially behavioral and consumer research), governance and policy development - each contributing essential insights into behavioral patterns, institutional dynamics, spatial development, and regulatory frameworks to ensure relevance, inclusivity, and societal impact.

To boost innovation scale-up, the SRIA prioritises:

- Industrial symbiosis and cross-sector collaboration
- Shared piloting and innovation infrastructures
- Standardisation, certification, and market mechanisms for secondary materials
- Digital traceability and data-driven decision-making

Aligned with Finland's circular economy strategy and EU policy frameworks, the SRIA also has a clear market-shaping function. It drives demand for circular solutions, supports investment environments, and strengthens the position of Finnish industries as providers of globally scalable circular innovations.

By fostering co-creation among academia, industry, and policymakers, and promoting shared piloting and innovation infrastructures, the CE-SRIA provides a practical and flexible roadmap to embed CE into system-level transitions and unlock scalable impact.

HOLISTIC CLIC CE SRIA

Strategic Research and Innovation Agenda (Figure 6) of CLIC's Circular Economy cluster reflects the shared vision of CLIC Innovation's owners and partners on the research, development, and innovation efforts needed to accelerate the transition to a circular economy. It positions circularity not as a standalone goal, but as a systemic enabler of sustainable transformation across industries, value chains, and society. The SRIA emphasizes that the sustainable use of resources are driven by scientific and technological breakthroughs as well as by new business models and behavioral shifts.

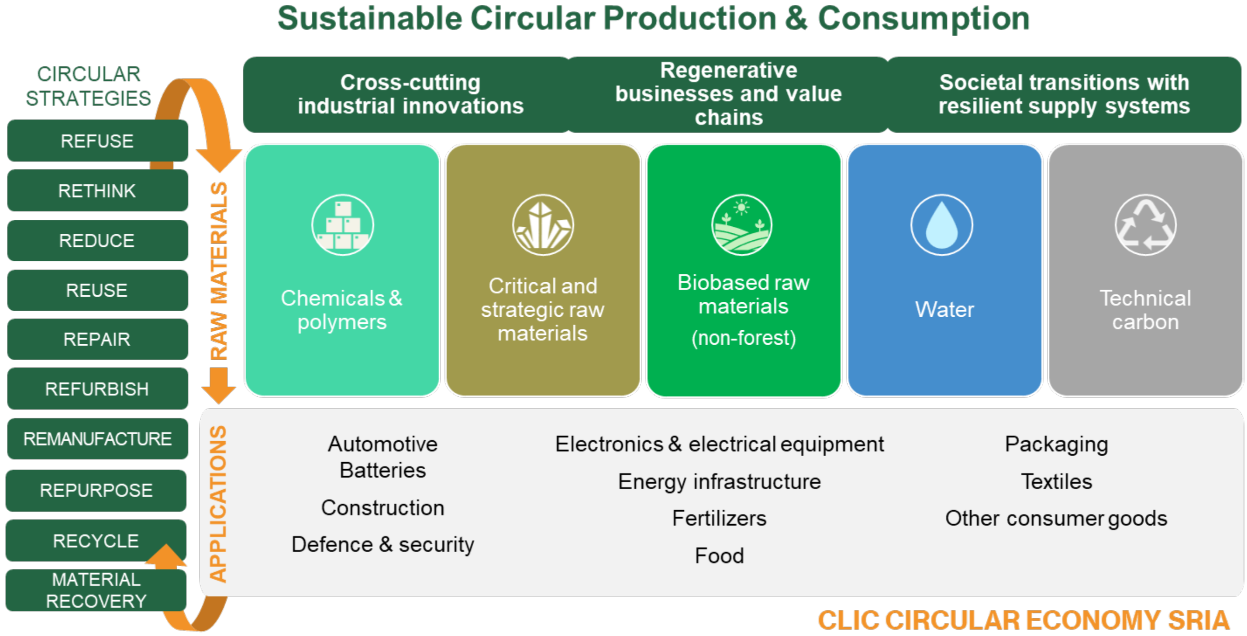

Figure 6. CLIC Circular Economy thematic area SRIA.

The CLIC CE SRIA is directly aligned with Finland's 2035 vision of a carbon-neutral circular economy society, ensuring that RDI actions contribute to keeping raw material consumption within sustainable limits while doubling resource productivity and circularity[10]. By advancing intelligent material circulation, bio-based feedstocks, industrial carbon cycling, and closed-loop systems, it supports national targets on resource efficiency, climate neutrality, and systemic resilience. The cross-cutting layers, digitalisation, business and value chain transformation, and societal transitions, mirror Finland's emphasis on innovation, smart regulation, and fair welfare, while also strengthening inclusivity and just transitions.

Crucially, the CE SRIA has strong market-shaping potential, as it drives demand for sustainable products, creates incentives for new business models, and fosters investment environments that accelerate adoption. In this way, it positions Finnish industries and research ecosystems to export advanced solutions, technologies, and business models, reinforcing Finland's role as a frontrunner in shaping international circular economy markets.

2.3. 4R Innovation Ecosystem SRIA

The 4R ecosystem (formerly 4Recycling) is Finland's leading open innovation platform lead by CLIC for accelerating the circular economy of plastics in its path to stop plastic waste. Since 2019, 4R has grown into a recognised collaboration hub with more than 300 organisations engaged, preparing RDI projects worth over €150 million and positioning Finland as a frontrunner in bio-based alternatives, plastic recycling, and circular materials.

New EU regulations (PPWR, ESPR, textiles EPR) mandate waste prevention, reuse, recyclability, and traceability, while public concern about plastics pollution and climate change continues to rise. At the same time, global markets for sustainable packaging, composites, and textiles are expanding rapidly. These developments create both a challenge and a major opportunity, the must to comply can be turned into a competitive advantage and international growth. Taken the operational environment changes

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[10] Uusi suunta: Ehdotus kiertotalouden strategiseksi ohjelmaksi - Valto

and new circularity targets into consideration, the 4R innovation ecosystem is focused on three spearheads with the highest business and circularity potential:

1. Circular Packaging – PPWR-compliant renewable, reusable, recyclable systems.
2. Technical Plastics & Composites – Design for extended lifecycles and advanced recycling.
3. Textiles – Renewable, repairable, recyclable fibres and systems.

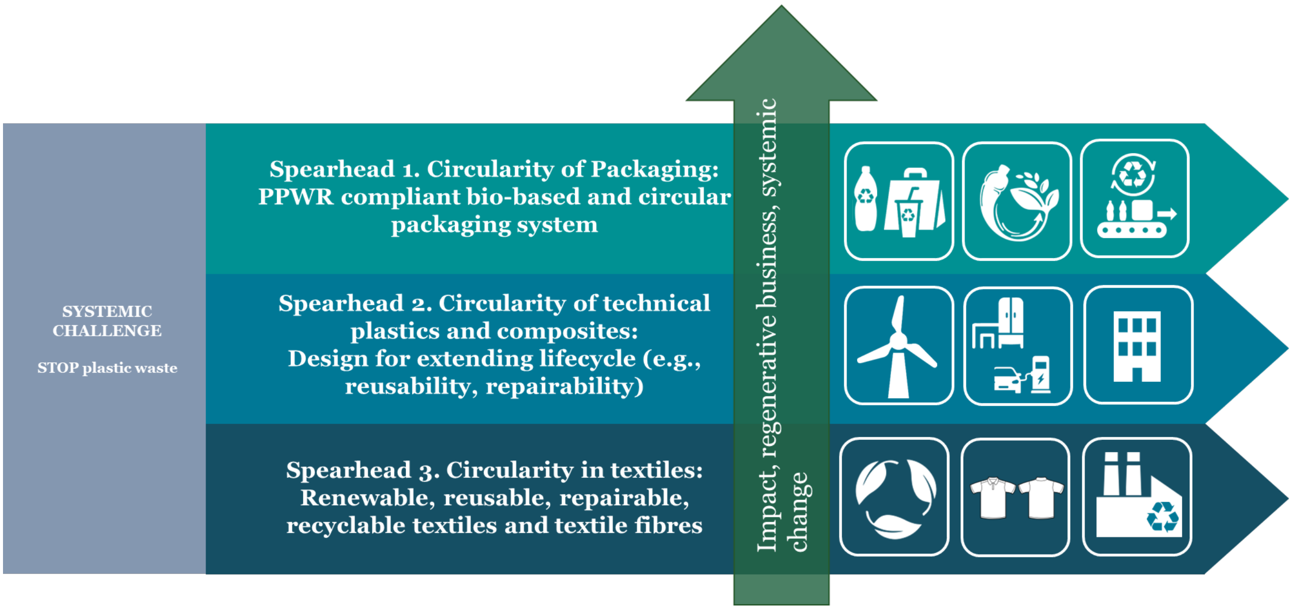

Figure 7. 4R Innovation Ecosystem SRIA.

3. Strategic opportunity areas for circular research, development and innovation

THE transition to a circular economy requires focusing RDI efforts on high-impact resource flows, material systems, and value chains where circularity can be realised at scale. This chapter presents the strategic opportunity areas identified by CLIC Innovation and its partners, highlighting domains where collaborative RDI efforts are most likely to drive systemic change and unlock scalable solutions.

3.1. Chemicals and polymers and related applications

CHEMICALS and polymers are foundational to virtually every industrial value chain, making their transformation essential to the success of a circular economy. The chemical industry plays a dual role, as both a provider of enabling technologies and a sector requiring deep systemic change. By redesigning chemical processes and products to be safer, more sustainable, and easier to recover, the industry can significantly reduce environmental impacts and unlock new circular business models.

A circular approach to chemicals involves minimizing hazardous substances, improving lifecycle management, and ensuring that materials can be safely reused or recycled. This is particularly important in sectors like textiles, electronics, and packaging, where legacy chemicals can disrupt recycling streams or pose health risks. The EU’s chemicals legislation, including REACH and the Chemicals Strategy for Sustainability, supports safe material cycles and helps prevent the reintroduction of harmful substances into the economy. The EU’s chemicals policy is undergoing a major transformation to address growing concerns about chemical pollution, health risks, and sustainability. The Chemicals Strategy for Sustainability (CSS), launched in 2020 under the European Green Deal, outlines 85 actions aimed at reducing harmful chemical exposure, promoting innovation, and strengthening the competitiveness of the EU chemicals sector. While progress has been made—such as revising the Classification, Labelling and Packaging (CLP) Regulation and the Industrial Emissions Directive—key actions like the REACH Regulation revision and export bans on hazardous substances remain pending. The sector faces significant challenges, including high energy costs, global competition, and regulatory fragmentation. Persistent pollutants like PFAS ("forever chemicals") continue to pose serious health and environmental risks, prompting the EU to consider phased restrictions and essential-use exemptions.[11]

Looking ahead, the EU is aligning chemical regulation with broader industrial and sustainability goals. The **Chemicals Industry Action Plan**, launched in July 2025, aims to modernize the sector, reduce administrative burdens, and support clean innovation through fiscal incentives and trade defense measures. Future trends include stronger market surveillance, increased border controls, and the establishment of a **Critical Chemicals Alliance** to secure supply chains. The EU is also preparing a **Circular Economy Act** to promote chemical recycling and reduce reliance on fossil-based materials. While these initiatives signal a robust commitment to sustainability, their success hinges on timely implementation, stakeholder engagement, and coherent governance across overlapping strategies.[12]

Polymers, especially plastics, are among the most visible challenges and opportunities in the circular transition. Plastics remain essential to modern life, yet they pose a growing global challenge. As of 2025, global plastic waste generation is projected to exceed 460 million tonnes annually, with over 20% leaking into the environment, including oceans, where plastic pollution continues to escalate[13],[14]. Furthermore, 99 % of the plastics made is based on fossil resources. Despite increased awareness and policy action, only about 9% of plastic waste is effectively recycled worldwide, while the rest is incinerated, landfilled, or mismanaged.[13]

Despite notable progress in Europe, plastics circularity is improving slowly according to the Circularity Metrics Lab data by the EEA. Mechanical recycling capacity has grown significantly: from 2 million tonnes in 1996 to over 13 million tonnes in 2023. However, many recyclers are challenged with high energy prices and low oil prices. While mechanical recycling capacity and the use of recycled plastics are increasing, the overall share of secondary plastics remains low. In 2020, only 8.1% of total plastic material consumption in the EU came from recycled plastics. Total plastics consumption by end-users in the EU27+3 decreased slightly from 58.3 Mt in

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[11] Targeted scrutiny of the EU chemicals strategy for sustainability

[12] Plan for stronger EU chemical industry - European Commission

[13] Plastic waste worldwide - statistics & facts | Statista

[14] Global push to end plastic pollution gains ground in Nice | UN News

2018 to 55.2 Mt in 2022, equivalent to 105 kg per capita per year. Marine litter remains a major issue, especially in the Mediterranean and Black Seas. The top five beach litter items in 2022 were all plastic-based. The packaging and construction sectors are the largest consumers, followed by automotive, electronics, houseware, agriculture, and textiles. Despite the slight dip, plastics consumption is expected to double by 2060, though at a slower rate than global averages.[15]

The EU Waste Framework Directive (WFD) sets the overarching principles and requirements for waste management in the EU, including plastics. It establishes the "waste hierarchy," which prioritizes prevention, followed by reuse, recycling, other recovery (such as energy recovery), and disposal as the last resort. For plastics, this means that EU Member States must take measures to prevent plastic waste generation, promote reuse and recycling of plastics, and minimize landfilling and incineration. The WFD also sets targets for preparing for reuse and recycling of waste materials, including plastics, with a minimum of 50% by weight from households by 2020, and higher targets for municipal waste in subsequent years (55% by 2025, 60% by 2030, and 65% by 2035).[16]

The Directive introduces the "polluter pays principle" and "extended producer responsibility" (EPR), requiring producers of plastic products to take responsibility for the entire lifecycle of their products, including waste collection, sorting, and recycling. It also provides definitions for waste, recycling, and recovery, and clarifies when waste ceases to be waste and becomes a secondary raw material. The WFD is complemented by more specific legislation for plastics, such as the Single-Use Plastics Directive and the Packaging and Packaging Waste Regulation, but it remains the foundational legal framework guiding how plastics are managed as waste in the EU.

The EU Single-Use Plastics Directive (SUP) aims to reduce the environmental and health impacts of certain plastic products, particularly those most commonly found as marine litter. The legislation targets a range of single-use plastic items by introducing market bans for products with readily available alternatives (such as cutlery, plates, and straws), setting consumption reduction goals for items without alternatives, and mandating design changes like tethered caps for bottles. Key targets include achieving a 77% separate collection rate for plastic bottles by 2025 (rising to 90% by 2029) and requiring PET beverage bottles to contain at least 25% recycled plastic by 2025 and 30% by 2030. The directive also strengthens extended producer responsibility, requiring producers to cover the costs of waste management, clean-up, and public awareness campaigns.[17]

The Packaging and Packaging Waste Regulation (PPWR) is designed to minimize packaging waste, increase reuse and recyclability, and reduce the presence of harmful substances in packaging across all sectors and materials. The regulation sets ambitious targets, including making all packaging recyclable in an economically viable way by 2030, introducing minimum recycled content requirements for plastic packaging, and mandating reuse and refill systems for consumers. It also bans unnecessary packaging, such as single-use condiment portions and pre-packed fruit under 1.5 kg and prohibits the use of PFAS ("forever chemicals") in packaging.

Waste Electrical and Electronic Equipment (WEEE) Directive covers plastics as a significant component of electronic waste, which is one of the fastest-growing waste streams in the EU. Plastics make up about 25% of WEEE by weight. The Directive requires the separate collection, proper treatment, and recycling of WEEE and sets targets for weight-based collection and recovery targets. Around 44% of plastics from WEEE are sent to material recovery, while 45% go to energy recovery, and the rest to landfill. The Directive also mandates extended producer responsibility (EPR), making producers responsible for the collection and recycling of plastics in electronics. However, only about 40% of all WEEE is recycled in the EU, and challenges remain in improving the quality and quantity of recycled plastics, especially due to hazardous substances and lack of harmonized standards.[18]

Plastics are included as a material stream within Construction and Demolition Waste (CDW) , which accounts for over a third of all waste generated in the EU. The Waste Framework Directive sets a target of at least 70% (by weight) of non-hazardous CDW (including plastics) to be prepared for reuse, recycled, or otherwise recovered. The EU promotes selective demolition and sorting to enable the removal and recycling of plastics

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[15] EU circularity of plastic materials | Circularity Metrics Lab

[16] Waste Framework Directive - European Commission

[17] Packaging waste - European Commission

[18] Waste from Electrical and Electronic Equipment (WEEE) - European Commission

and other materials. Guidelines and protocols encourage pre-demolition audits to identify and separate plastics for high-quality recycling, supporting the circular economy and reducing landfill.[19]

End-of-Life Vehicles (ELV) Directive aims to maximize the recovery and recycling of materials from vehicles. It sets targets for reuse, recycling, and recovery of ELVs and restricts the use of hazardous substances in new vehicles. The latest proposals of the new ELVD require that 25% of plastics in new vehicles come from recycled sources, with at least a quarter of that from closed-loop systems (i.e., recycled back into automotive applications). The Directive also encourages design for disassembly and recycling, and mandates that plastics and other materials from ELVs are properly treated to avoid environmental harm. Despite high overall recycling rates for ELVs, the recycling rate for plastics remains low, and scaling up closed-loop recycling is a key challenge for the sector.[20]

3.1.1. Market opportunities and application areas

THE transition to a circular economy is unlocking significant global market opportunities in the chemical and polymer sectors. As waste management systems remain underdeveloped or inefficient in many regions, there is growing demand for affordable, scalable, and clean technologies for waste collection, sorting, recycling, and material recovery. AI-powered sorting systems, chemical recycling innovations, and digital platforms for material traceability are attracting investment and reshaping the recycling landscape.[21]

While the global plastic recycling market is projected to grow from $44.88 billion (€38.08 billion) in 2024 to $67.58 billion (€57.33 billion) by 2029, the European recycled plastics market alone is estimated at around €18-19 billion in 2025, with annual growth expected at 7% through 2031. This is especially evident in packaging, construction, and automotive sectors, where circular design and stricter content requirements are creating new business prospects. Europe's ambition to boost the market for recycled plastics to 10 million tonnes annually by 2025 underpins this momentum.[22],[23] .

Meanwhile, bio-based and biodegradable plastics are gaining traction as complementary solutions. The bioplastics market is expected to reach $16.8 billion in 2025, with strong uptake in European markets due to

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[19] Construction and demolition waste - European Commission

[20] End-of-Life Vehicles - European Commission

[21] Top 10 Growth Opportunities in the Circular Economy Market

[22] The Drivers Shaping the Plastics Industry in 2025 | Pall Corporation

[23] Europe Recycled Plastics Market Size | Industry Report 2030

policy support and consumer demand. [24] Biodegradable plastics, valued at $5.36 billion, are growing rapidly supported by bans on single-use plastics and emerging compostable packaging standards. Although bio-based plastics still represent a modest share of the market, advances in PLA, PHA, and starch-based blends are enhancing performance and scalability[25].

The circular economy is fostering innovative business models, such as product-as-a-service, reverse logistics, and regenerative packaging, while opening up substantial investment and growth opportunities across the whole chemical and polymer value chains.

The application possibilities of circular economy solutions in chemicals and polymers span across technological, business, and systemic dimensions. On the technological side, closed-loop recycling systems integrating advanced sorting, chemical depolymerization, and solvent-based purification can enable high-quality recovery of even complex, multi-material plastics, making them suitable for reuse in packaging, automotive, or construction applications. Bio-based and CO_2-derived polymers open pathways for fossil-free material substitution, while smart additives and self-healing functionalities extend product lifetimes and simplify repair and reuse. From a business perspective, product-as-a-service models and reverse logistics can transform traditional linear sales into regenerative value chains, supported by digital traceability platforms and plastic credit systems that reward sustainable practices. On the systemic level, industrial symbiosis offers opportunities to valorize chemical by-products across sectors, while urban mining and smart city recycling infrastructures can position municipalities as hubs for material recovery.

3.1.2. Focus areas for research and innovation

Innovations in the circular economy for chemicals and polymers are accelerating through advanced technologies, sustainable design, and policy-driven transformation. RDI efforts are increasingly aligned with the 10Rs, Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, and Recycle, reshaping how materials are created, used, and reintegrated across their lifecycle.

From non-toxic catalysts and bio-based polymers that eliminate harmful substances, to AI-optimized production and modular materials that extend product life, the sector is embracing regenerative models. Industrial symbiosis and chemical recycling are unlocking new value from waste, while digital traceability ensures transparency and efficiency. Together, these approaches are laying the foundation for a resilient and circular chemical and polymer ecosystem, where innovation meets sustainability to redefine material value. To tackle the plastic challenge, innovation must focus on enhancing reusability and recyclability, extending product lifecycles, developing fossil-free alternatives, and enabling systems that support material cascading and behavioral shifts.

To accelerate the circular economy for chemicals and plastics, the integration of CLIC cross-cutting themes offers a multidimensional approach that merges digital innovation, sustainability leadership, and behavioral engagement. Harnessing digitalization and AI technologies, eg. intelligent waste sorting, enhances transparency and efficiency across the plastic value chain. Embedding circularity into carbon management,

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[24] Bio-plastics Market Growth & Trends, 2025 to 2035

[25] Biodegradable Plastic Market Size, Share, and Trends 2025 to 2034

through carbon capture, advanced recycling, and closed-loop supply chains, can help transform emissions into valuable feedstocks. Regenerative business models are further supported by digital marketplaces, innovative financing, and platforms that empower consumers to participate in sustainable practices. On the societal front, aligning behavioral science with recycling incentives, perception studies, and educational campaigns can foster a culture of conscious plastic consumption. Cities play a pivotal role by integrating urban circularity hubs and smart recycling infrastructure, turning waste into valuable urban resources. Finally, secure and sustainable supply systems, backed by standardized certifications, material flow databases, and resilient supply chains, ensure that recycled plastics meet quality benchmarks while reinforcing supply resilience.

Examples of RDI Topics for CE SRIA in Chemicals & Polymers

1. Smart & efficient recycling technologies

Focus: Improve system efficiency, recyclability, and material quality.

- AI-driven waste sorting: Intelligent systems for accurate material separation and contamination minimization.
- Advanced on-line analytics: Real-time, cost-effective monitoring tools for sorting plastic streams.
- Novel imaging/spectroscopic tools: Identification of hard-to-sort plastics (black, colored, multilayered films).
- Blockchain for traceability: Secures transparent, accountable plastic lifecycle tracking.
- Purification & hazardous substance removal: Eliminates toxic additives and legacy chemicals from recyclates.
- Hybrid recycling techniques: Synergistic mechanical, chemical and biological recycling for diverse streams.
- Microwave-assisted depolymerization: Speeds chemical conversion into reusable polymers.
- Recycling of complex, multi-material plastics: Expands recovery from packaging and electronic waste.
- Chemical recycling technologies: Converts difficult-to-recycle plastics into base molecules.
- Solvent-based purification: Restores polymer purity for high-value applications.
- Urban mining for plastics: Recovers polymers from electronics and consumer goods.
- Smart additives for Recyclability and Repairability for easier sorting, disassembly, and in-situ repair of polymer-based products.

2. Bio-Based & High-Performance Material Innovation

Focus: Design fossil-free, recyclable, and high-functionality alternatives.

- Bio-based mono-materials: Derived from forest biomass for applications like food packaging.
- Bio-based and CO_2-derived chemical building blocks
- Algae-based bioplastics: Marine-based solutions for biodegradable plastic alternatives.
- Nano-enhanced biodegradable plastics: Improved mechanical performance and compostability.
- Self-healing polymers: Extend product life and reduce waste through auto-repair capabilities.
- Optimized material properties: Tailor strength, durability, and recyclability for demanding applications.
- System-compatible bio-alternatives: Ensure recyclability in existing infrastructure.
- Multi-material bio-composites: Support durable, repurposable use in construction, agriculture, and transport.

3. Industrial health, safety & process sustainability

Focus: Minimize risk in recycling and manufacturing environments.

- Safe handling of chemicals and feedstocks
- Pollution management

4. New business models & incentives for circularity

Focus: Support material efficiency and secondary material markets.

- Plastic credit systems: Rewarding companies for circular practices
- Service-based and performance-based business models: Promoting leasing, product-as-service, and modularity
- Material efficiency in product design: Reduce raw material use and encourage reuse loops
- Eco-design for modular and reconfigurable polymer products to support easy upgrading, repurposing, and remanufacturing.

5. Policy instruments & systemic collaboration

Focus: Enable structural change, data integration, and consumer engagement.

- Databases on streams, volumes, and value chains: Foundations for systemic analysis and planning
- Recycled material classification & standards: Ensure market confidence and consistent quality
- Behavioral economics in recycling: Nudge consumer habits toward reuse and better disposal
- Consumer behavior & acceptance: Improve trust in recycled products and foster low-waste lifestyles
- Cross-sectoral collaboration: Engage industries, governments, and academia in systems change

Table 1. 10R principles and RDI Focus areas for chemicals and polymers and related applications.

R Principle	RDI Focus Areas
Refuse -Rethink -Reduce	• Eliminating harmful and hazardous substances and chemicals. • Shifting away from fossil feedstocks by advancing bio-based, recycled and CO_2-derived building blocks. • Designing chemicals and products for multi-R lifecycle compatibility. • Developing service-based business models (e.g., polymers-as-a-service). • Substituting harmful and hazardous substances and chemicals. • Optimizing processes and systems using AI and digitalization. • Designing processes and material-efficient products to minimize chemical and material use.
Reuse – repair – refurbish – remanufacture - repurpose	• Reuse of textiles, packaging, and other consumer goods. • Reuse in components (OEMs) of automotive and construction sectors. • Developing smart additives and coatings that enable repairability and easy dismantling. • Creating self-healing polymers for extended lifetimes in e.g., electronics, coatings, and infrastructure. • Designing modular, upgradable polymer components in electronics and automotive. • Retrofitting existing infrastructure. • Products are designed so that parts can be easily replaced or upgraded. • Innovative depolymerization and solvent purification for reuse. • Reuse, repair and repurpose products, e.g., electronics, car seats.
Recycle	• Higher utilization of secondary raw materials, processing side and waste streams. • Increased end-of-life product collection and recycling. • High-quality recyclates and secondary raw materials. • Safe use of secondary raw materials.
Recover	• Recovering substances, components, nutrients and energy. • Thermal valorisation of non-recyclable streams thermally with emission capture. • Removing and recovering legacy additives safely.

3.2. Critical and strategic materials and related applications

CRITICAL and strategic raw materials (CRM and SRM) are the backbone of the European Union's industrial competitiveness and its path toward a green and digital transition. These materials, vital in sectors ranging from renewable energy and electric vehicles to defense, electronics, and space, are increasingly vulnerable to geopolitical, economic, and environmental pressures. The EU currently identifies 34 CRMs, including high-risk but essential inputs such as cobalt, lithium, tungsten, and antimony. Cobalt and lithium are key to battery technologies, yet are challenged by ethical sourcing, concentrated supply chains, and rapidly accelerating demand. Tungsten and antimony face similar constraints, with production dominated by a small number of global actors.[26] [27], [28], [29]

Strategic raw materials are singled out for their indispensable role in meeting Europe's climate neutrality, digital leadership, and defense goals. Among them are rare earth elements, such as neodymium, gallium, and germanium, which are at the core of semiconductors, wind turbines, electric motors, and advanced communications. Their constrained availability and concentration in geopolitically sensitive regions represent growing supply chain threats.[27]

The sharp rise in global demand has heightened material scarcity and price volatility, prompting a rethinking of resource strategies. European industries are now prioritizing alternative material development, substitution, material efficiency, and design-for-reuse principles. Governments and businesses are increasingly deploying measures such as long-term procurement agreements, strategic reserves, and enhanced recycling and recovery capabilities to reduce exposure to supply disruptions. Circularity, urban mining, and domestic extraction, are gaining policy and industrial traction. Waste streams, including electronic waste, industrial residues, and end-of-life components, are being tapped for valuable secondary raw materials. Technological advances, such as hydrometallurgical processing, eco-design integration, and bio-based material recovery, are enabling more sustainable, low-impact access to critical resources. These trends are mirrored by evolving regulatory frameworks, including the EU Critical Raw Materials Act and international trade policies, which are redefining access, sustainability criteria, and traceability obligations across global supply chains.[27, 30]

Resilience and sustainability are becoming the defining principles of CRM and SRM management. Companies are embedding lifecycle thinking and circular principles into product development, while national strategies are supporting localized processing, data-driven supply chain monitoring, and regional collaboration. In this context, the circular economy is not merely a complementary approach but a strategic imperative. By extending product lifespans, maximizing resource efficiency, and closing material loops, CE reduces dependency on primary raw materials and mitigates environmental impacts. It fosters innovation in design, manufacturing, and end-of-life recovery, while enhancing Europe's autonomy and competitiveness. As climate challenges, strategic dependencies, and geopolitical shifts reshape global dynamics, securing critical materials through sustainable, circular, and innovative means is now a central pillar of the EU's industrial and technological future.[27]

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[26] RMIS - Critical and strategic materials

[27] Understanding dynamic availability risk of critical materials: The role and evolution of market analysis and modeling | MRS Energy & Sustainability | Cambridge Core.

[28] Mahnoor, M., Chandio, R., Inam, A. & Ahad, I. 2025. Critical and Strategic Raw Materials for Energy Storage Devices. Batteries 2025, 11, 163. https://doi.org/10.3390/batteries11040163.

[29] Laneridi, O., Sahoo, A.R., Limbeck, A., Naghdi, S., Eder, D., Eitenberger, E., Csendes, Z., Schürch, M. & Bica-Schröder, K. 2021. Toward the recovery of platinum group metals from spent automotive catalysts with supportedionic liquid phases-ACS Sustainable Chemistry Engineering 9:375-386. Toward the Recovery of Platinum Group Metals from a Spent Automotive Catalyst with Supported Ionic Liquid Phases

[30] European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M. and Veeh, C., *Study on the critical raw materials for the EU 2023 – Final report*, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2873/725585

3.2.1. Market opportunities and application areas

CRITICAL and strategic materials, such as rare earths, lithium, cobalt, and antimony, are essential to Europe's industrial base, clean energy transition, and digital infrastructure. Europe currently consumes over 25% of global critical raw materials, yet produces only a small fraction domestically, exposing the region to significant supply risks [26], [31]. For example, the EU is nearly 100% dependent on imports for heavy rare earths and platinum group metals, with key suppliers concentrated in countries facing governance or trade challenges.[32]

The need for these materials is accelerating rapidly indicating that by 2030, Europe could need up to 18 times more lithium and 5 times more cobalt to support electric mobility and energy storage systems, rising to nearly 60 times more lithium by 2050. 1 This underscores the urgency of developing domestic extraction, processing, and recycling capacities. Under the EU Critical Raw Materials Act, targets have been set for 10% extraction, 40% processing, and 15% recycling of strategic materials within the EU by 2030. Without strategic investment and circular innovation, Europe risks economic vulnerability, industrial disruption, and delayed climate goals.[32]

The shift toward a circular economy in critical and strategic raw materials is transforming industries and creating new value chains. As demand for materials such as lithium, cobalt, rare earths, and gallium accelerates, driven by electric vehicles, renewable energy systems, semiconductors, and defense technologies, industries are investing in alternative sourcing, materials innovation, and circular business models. Companies specializing in waste valorization, recycling infrastructure, and advanced recovery technologies are gaining commercial traction, particularly in recovering secondary raw materials from electronic waste, end-of-life batteries, and industrial byproducts. Efficient, low-impact processes such as hydrometallurgy and bioleaching are helping meet both sustainability goals and regulatory requirements.[29]

Urban mining and closed-loop manufacturing systems are enabling more localized and resilient supply chains, where high-value materials are continuously recirculated within regional industrial ecosystems. Digital innovation is unlocking new frontiers in transparency and compliance. Traceability tools, blockchain systems, and AI-enabled diagnostics are improving visibility across material flows and supporting alignment with emerging regulations such as the EU Critical Raw Materials Act. Startups and SMEs developing solutions for material substitution, eco-design, and resource-efficient manufacturing are becoming pivotal actors in circular value networks. At the same time, policy instruments like green public procurement and carbon border adjustments are creating favorable market conditions for climate-smart material solutions.[33], [34], [35]

Cross-sector collaboration among mining, manufacturing, recycling, and technology providers is evolving into a strategic advantage. Platform-based models that connect material flows, data, and services are reshaping industrial ecosystems and enabling more integrated approaches to resource management. These dynamics reflect not only new opportunities for commercial growth but also the strategic imperative of securing raw material sovereignty in an increasingly multipolar and resource-constrained world. The integration of circular economy principles into the raw materials sector is no longer peripheral, it is becoming central to industrial strategy, environmental stewardship, and geopolitical resilience.[30]

Critical and strategic materials also play an essential role in nutrient cycling, particularly within agricultural and ecological systems. Phosphorus-bearing minerals such as phosphate rock are vital for fertilizer production and directly support the phosphorus cycle that underpins plant growth and ecosystem productivity. Rare earth elements and metal catalysts like molybdenum and cobalt are increasingly used in bio-catalysts that accelerate microbial processes, including nitrogen fixation and organic matter decomposition. As global demand intensifies, sustainable management of these resources is crucial not only for food security and biodiversity but also for reducing environmental degradation linked to mining and overuse. Their role in nutrient cycles reveals a deeper layer of interconnection between geology, technology, and life—underscoring the systemic importance of circularity across both industrial and ecological domains.[36]

The application potential on critical and strategic materials spans the entire industrial value chain, addressing both supply risks and sustainability challenges. In mining and extraction, urban mining platforms, microwave-

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[31] Supply risk evolution for critical raw materials | Circularity Metrics Lab

[32] The European Union and Critical Raw Materials: Juggling Geopolitical and Economic Realities

[33] European Critical Raw Materials Act - European Commission

[34] What is urban mining and how does it help the planet? | World Economic Forum

[35] aaa_20190506-d3-jrc-science-for-policy-recovery_of_rm_from_mining_waste_and_landfills_4_07_19_online_final.pdf

[36] European Commission – Critical Raw Materials and Circular Economy Report. Slide 1

assisted mineral refinement, and algae-supported processing enable more sustainable and regenerative access to scarce resources. Manufacturing and product design benefit from biomimetic CRM-free alloys, modular and repairable design approaches, and innovation hubs focused on reducing material dependency. In waste management and recycling, AI-powered sorting, hybrid metallurgical processes, and advanced recovery of platinum group metals help close material loops, while toxic residue neutralization ensures environmental safety. The chemical and metallurgical industry is advancing with zero-discharge refining, hydrometallurgy, bioleaching, and soil-enhancing by-products. In energy and mobility, closed-loop battery recovery and leasing models for CRM-intensive systems support resource efficiency, while substitution strategies reduce reliance on scarce elements. Electronics and IT see opportunities in rare earth recovery, sensor-integrated disassembly, and blockchain-enabled supply chain traceability. The construction sector can extract and recycle CRMs from buildings and infrastructure through modular urban mining hubs and demolition recovery. Cross-sectoral applications such as CRM credit trading, lifecycle data platforms, quality standards for recycled materials, and consumer engagement strategies create systemic conditions for a sustainable and inclusive transition.

3.2.2. Focus areas for research and innovation

To respond to growing pressures around critical raw material supply, the research and innovation must focus on improving material recovery, extending lifecycle performance, developing strategic substitutes, and enabling systems that support circularity, resource resilience, and behavioral change.

Incorporating CLIC cross-cutting themes into CE for critical and strategic materials brings transformative value across multiple sectors. Digitalisation and AI fuel predictive modeling and traceability for material flow, optimizing resource use and waste reduction. Regenerative industries foster systems where extraction and manufacturing not only minimize damage but actively restore ecosystems, crucial when working with materials like bauxite or cadmium. Sustainable business models, aligned with societal needs, enable stakeholder-driven innovation and enhance market readiness for recycled or repurposed strategic materials. By understanding consumer behavior, businesses can better tailor products and services that encourage sustainable consumption and lower dependence on rare materials. Societal transitions toward resilient supply systems allow adaptation to global shocks, be it geopolitical tensions or climate risks, ensuring steady access to vital resources. Resilient urbanization offers fertile ground for urban mining, material recovery, and CE hubs, while securing sustainable energy, water, and transport infrastructures create an enabling environment for scalable CE ecosystems.

1. Smart & efficient circular technologies for critical materials
Focus: Enhance recovery efficiency, purity, and lifecycle traceability.

- **AI-powered CRM sorting systems:** Advanced machine vision and robotics to separate complex metal streams from e-waste and industrial scraps.
- **Sensor-integrated real-time analytics:** Monitor quality and contamination levels of material flows during disassembly and recycling.
- **Traceability via digital twins & blockchain:** Track CRM origins, transformations, and ownership through product lifecycles.
- **Hazardous and toxic element separation and neutralization:** Develop technologies to safely extract and stabilize cadmium, antimony, and other hazardous elements.
- **Hybrid metallurgical recycling:** Combine pyrometallurgical and hydrometallurgical methods for efficient CRM recovery.
- **Microwave-assisted mineral refinement:** Accelerate breakdown of ore composites like bauxite or rare earths.
- **Urban mining platforms for SRMs and CRMs:** Map and extract valuable materials from buildings, vehicles, and infrastructure.
- **Secondary platforms for SRMs and CRMs:** Map and extract valuable materials from underutilized or non-utilised industrial side and waste streams.

2. Regenerative & bio-based material innovation
Focus: Develop high-performance, low-impact materials that restore ecosystems.

- **Biomimetic CRM-free alloys:** Design substitutes for rare earths and cobalt using nature-inspired microstructures.
- **Algae-supported mineral processing:** Use algal biomass to concentrate or detoxify heavy metals during ore treatment.
- **Soil-enhancing CRM by-products:** Convert CRM residues into nutrient-supportive soil amendments post-mining.

3. Industrial health, safety & process sustainability

Focus: Ensure ethical and safe production and recycling of strategic materials.

- **Zero-discharge CRM refining systems:** Develop closed-loop water and waste treatment for CRM processing facilities.
- **Safe handling of CRM nanoparticles and residues:** Address emerging risks in advanced metallurgy and reuse.

4. Circular business models & incentives

Focus: Facilitate market uptake, modularity, and reuse systems for CSMs.

- **CRM credit trading systems:** Rewarding companies that recover or reuse strategic materials.
- **Leasing models for CRM-heavy systems:** Apply product-as-a-service concepts to magnets, batteries, or turbines.
- **CRM-efficient product design innovation hubs:** Support modularity, repairability, and upgrade pathways across industries.

5. policy instruments & systemic collaboration

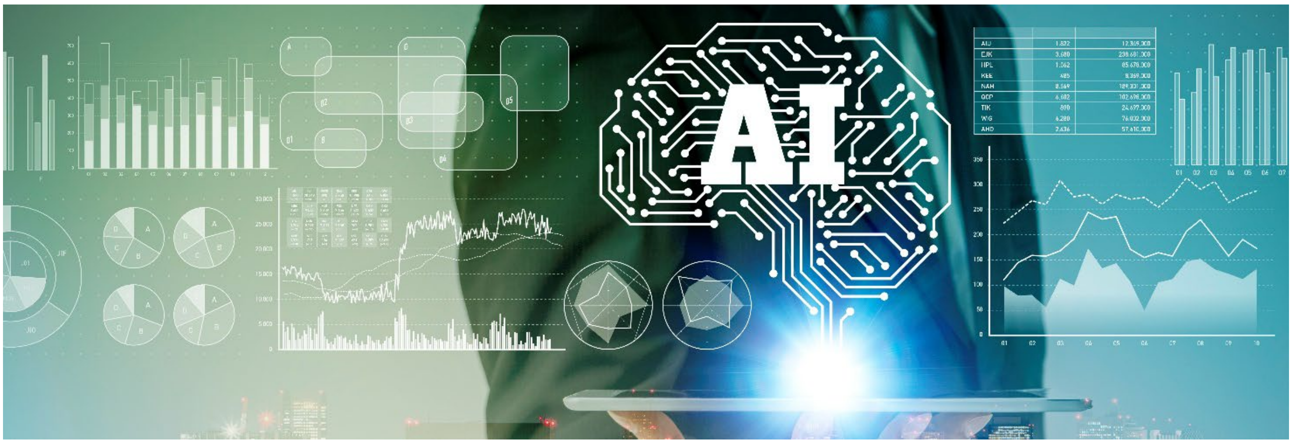
Focus: Enable cross-sector coordination, standardization, and data integration.

- **Global CRM lifecycle data platforms:** Standardized tracking of material volumes, transformations, and hotspots.
- **Quality standards for recycled strategic metals:** Ensure usability and confidence in secondary materials.
- **Consumer engagement strategies for CRM reuse:** Increase awareness, traceability, and participation in CE transitions.
- **Transdisciplinary CRM CE roadmaps:** Foster research-industry-government collaborations with shared metrics.
- **Cross-sector CRM recovery agreements:** Link mining, construction, and electronics industries through shared CE goals.

Table 2. 10R Principles and RDI focus areas for critical and strategic materials and related applications.

R Principle	RDI focus areas for critical and strategic materials
Refuse - rethink	• Avoiding reliance on high-risk CRMs through substitution and CRM-free design. • Developing zero-waste mining and processing concepts. • Establishing material-sharing platforms across industries. • Developing multifunctional CRM substitutes (e.g., biomimetic alloys). • Creating materials-as-a-service models for products containing magnets, batteries, turbines, but also for the raw materials.
Reduce – reuse – repair – remanufacture – remanufacture - repurpose	• Deploying AI-powered sorting and robotics for e-waste/scraps. • Developing low-energy hybrid metallurgical systems. • Implementing modular, decentralized processing to minimize transport inefficiencies. • Enabling direct reuse of CRM and SRM containing products, (e.g., through secondhand phones, repurposing end-of-life ELV batteries as grid energy storage systems) • Enabling direct reuse of recovered CRMs in batteries, alloys, and electronics. • Integrating reuse streams with remanufacturing hubs. • Developing repairable CRM-intensive devices (magnets, sensors, storage). • Applying coatings and modular design to extend product lifetimes. • Retrofitting industrial plants with CRM recovery modules. • Upgrading legacy refining units with digital monitoring and modular processing. • Rebuilding catalysts and separation membranes used in CRM processes. • Repurposing end-of-life batteries and magnets into secondary feedstocks. • Converting CRM-rich by-products into soil amendments or construction inputs.
Recycle	• Increasing collection and recycling of products containing CRMs and SRMs. • Innovative recycling processes. • Applying electrochemical recycling for rare earths, lithium, cobalt. • Using bioleaching and enzymatic processes for eco-efficient metal recovery. • Operating urban mining platforms for CRMs in buildings, vehicles, infrastructure.

Recover	• Recovering energy from metallurgical and recycling processes. • Applying advanced sorbents and thermal refinement for CRM recovery from flue gases and residues. • Stabilizing hazardous elements (e.g., cadmium, antimony).



3.3. Bio-based raw materials (non-forest) and related applications

NON-FOREST bio-based materials, ranging from agricultural residues and dedicated lignocellulosic crops to macroalgae, food system by-products, and urban biowaste, are increasingly recognized as strategic feedstocks in the transition toward a circular bioeconomy. Rather than reiterating their composition, the focus shifts to their functional integration across industrial value chains. These materials offer a renewable alternative to fossil-based inputs in sectors such as chemicals, polymers, textiles, and energy, while enabling systemic circularity through cascading use, valorization of side streams, and end-of-life biodegradability. Beyond their role in industrial inputs, food and feed systems are emerging as central arenas for circular innovation. Valorization of food system side streams, such as fruit peels, cereal husks, spent grains, dairy residues, and fish by-products, can generate new materials, proteins, and nutrients while reducing food loss and waste. This not only strengthens resource efficiency but also directly supports food security and soil health by closing nutrient loops and enabling carbon recycling. Biorefineries are increasingly designed to integrate food- and feed-grade recovery alongside bio-based chemical production, linking sustainable material flows with nutrition, climate goals, and land-use optimization.[37].

Their deployment supports multiple CE objectives, such as reducing dependency on finite resources, decarbonizing production systems, and enhancing resource efficiency. Moreover, their versatility allows for tailored applications, from platform chemicals and bio-based composites to nutrient recovery and soil amendments, depending on regional biomass availability, technological maturity, and policy frameworks.
At the policy level, the European Union has taken significant steps to support the development of non-forest bio-based materials within CE frameworks. Technological advancements are also shaping the landscape, particularly through the development of second-generation biorefineries. These facilities are designed to process agricultural residues and non-food biomass into high-value products. In Europe, biorefinery models are evolving to include starch/sugar-based, oilseed-based, and lignocellulosic pathways, each offering unique advantages in terms of feedstock availability and product diversity.[5, 40, 41.]

Despite these promising developments, several challenges remain. Land-use competition is a persistent concern, especially in regions with limited arable land. The debate over food security continues, with experts calling for nuanced, evidence-based assessments rather than blanket restrictions on biomass use. Additionally, logistical and economic barriers, such as the cost and complexity of biomass collection, transportation, and processing, still hinder large-scale adoption.[38] The bioeconomy sector requires close collaboration and innovation to ensure the upscaling of bioeconomy and reduce dependance on fossil feedstock. With increasing policy support, innovation funding, and recognition of their climate benefits, bioeconomy is critical in the

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[37] Ingle, A & Saxena, S. (2025) Production of biomaterials and biochemicals from lignocellulosic biomass through sustainable approaches: current scenario and future perspectives. Biotechnology for Sustainable Materials (2025) 2:3 https://doi.org/10.1186/s44316-025-00025-2.

[38] Muscat, E.M. de Olde, I.J.M. de Boer, R. Ripoll-Bosch (2020) The battle for biomass: A systematic review of food-feed-fuel competition. Global Food Security 25 (2020) 100330

sustainable industrial transformation. Integrated value chains are being developed to ensure efficient resource use, and new business models are emerging to support circularity across sectors.

3.3.1. Market opportunities and application areas

THE market potential for non-forest bio-based materials is expanding rapidly, driven by sustainability imperatives, technological innovation, and supportive policy frameworks. Valued at USD 32.84 billion in 2024 and projected to reach USD 41.38 billion in 2025, the global bio-based materials market is expected to grow to USD 283.81 billion by 2033, with a CAGR of 26.02%. This surge is fueled by the shift toward sustainable materials across packaging, construction, automotive, textiles, and increasingly, food and feed valorization.[39]

Packaging is moving toward biodegradable and recyclable solutions, construction is adopting bio-based insulation and structural materials from agricultural waste and fungi, while automotive sectors are integrating lightweight bio-composites to cut emissions. Textiles are turning to algae- and wood-based fibres as alternatives to synthetics. At the same time, food systems are emerging as a critical frontier for scaling bio-based materials. Agricultural residues and food industry by-products, such as fruit peels, cereal husks, dairy whey, and fish processing waste, are being upcycled into edible and compostable food packaging, nutraceuticals, animal feed, and biofertilizers. Biorefineries are developing multi-product platforms where food- and feed-grade proteins, fibers, and specialty ingredients can be recovered alongside chemicals and bioenergy, creating new value chains that link food security with climate goals. Algae and microbial biomass offer additional pathways to renewable proteins, lipids, and specialty food ingredients, while reducing pressure on arable land and freshwater. These opportunities align with the EU's bioeconomy strategy and food waste reduction targets, creating strong synergies between climate action, sustainable diets, food security, and industrial competitiveness[40]. Digitalization and traceability tools, such as AI-based biomass forecasting, smart logistics, and blockchain certification, further enhance transparency, consumer trust, and market uptake. By embedding circular principles into both material innovation and food systems, Europe can accelerate a sustainable, resilient, and inclusive transition toward a circular bioeconomy. EU policy is accelerating market development through initiatives and embedding targets in legislation that aim to raise the bio-based share in chemical production to 25% by 2030 and harmonize bio-based waste markets.[40], [41], [42].

Non-forest bio-based raw materials, including agricultural residues, macroalgae, food system by-products, and urban biowaste, open a wide range of application possibilities across industries. In packaging, biodegradable, fibre-based, and edible solutions derived from cereal husks, fruit peels, and starch-based blends provide sustainable alternatives to plastics. In construction, bio-based insulation, fungal composites, and mycelium-derived panels enable low-carbon, circular building materials. The automotive and transport sectors increasingly integrate lightweight bio-composites from agro-residues and natural fibres to reduce emissionsIn

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[39] https://www.businessresearchinsights.com/market-reports/bio-based-materials-market-118204
[40] Bioeconomy strategy - European Commission
[41] Bio-based products - European Commission

[42] Actions to boost biotechnology and biomanufacturing in EU

textiles, algae-based and cellulose fibres replace synthetics, offering biodegradability and reduced microplastic pollution. Food and feed systems present unique opportunities: dairy whey, fish residues, and spent grains are being upcycled into nutraceuticals, protein-rich feed, biofertilizers, and soil amendments, strengthening food security while closing nutrient loops. The chemical and polymer industries are using lignocellulosic biomass and microbial pathways to produce platform chemicals, biopolymers, and safe-by-design materials. Finally, energy applications include biogas, biofuels, and modular biorefineries that valorise side streams into energy carriers alongside proteins and bio-based chemicals. Together, these applications illustrate the versatility of non-forest bio-based resources in driving sustainable, circular, and resilient industrial ecosystems.

3.3.2. Focus areas for research and innovation

STRATEGIC RDI should focus on feedstock diversification, process innovation, regulatory alignment, and cross-sectoral collaboration. Embedding circular economy principles and digitalization, especially within food systems, will be vital to achieving sustainable industrial transformation and global leadership in next-generation materials.

CLIC's cross-cutting themes provide critical added value to the transition toward sustainable non-forest bio-based materials by linking innovation, value chains, and societal resilience. Industrial innovations such as modular biorefineries, AI-based biomass forecasting, and safe-and-sustainable-by-design polymers accelerate the efficient use of agricultural residues, algae, and food by-products, while enabling new high-performance applications. Business and value chain development strengthens integration across agriculture, food, chemical, and textile industries, fostering circular business models where side streams are valorized into feed, nutraceuticals, packaging, and composites. Meanwhile, societal transitions with resilient supply systems ensure that the scaling of bio-based materials supports food security, soil health, and inclusive access to sustainable products.

Priority RDI Actions

- A promising direction involves the **valorisation of underutilised biomass sources**, including secondary agricultural residues, macroalgae, insects, fungi, and microbial biomass. These feedstocks offer high potential for producing bio-based materials, food and feed ingredients, and biologically active compounds, while reducing pressure on land and biodiversity. Research should focus on developing cultivation systems such as biofermentors and mixotrophic platforms, optimizing growing conditions, and improving extraction and conversion technologies to enhance resource efficiency and circularity.
- Another emerging topic is the **development of circular-by-design bio-based packaging**, particularly fibre-based solutions with enhanced barrier properties and recyclability. This includes integrating biodegradable coatings and smart functionalities to meet performance standards while reducing environmental impact. RDI should address material innovation, end-of-life strategies, and compatibility with existing recycling infrastructure.
- The **retrofitting of existing industrial plants** to accommodate bio-based production processes is also gaining traction. This involves integrating modular bioprocessing units, upgrading feedstock handling systems, and implementing digital monitoring tools to enable flexible, low-carbon manufacturing. Research should explore techno-economic feasibility, lifecycle impacts, and business model innovation.
- In the context of sustainable agriculture, there is growing interest in **bio-based and biodegradable delivery systems for fertilisers and soil amendments**. These systems aim to reduce microplastic pollution and improve soil health by replacing conventional polymer carriers with bio-based alternatives. RDI should focus on material formulation, controlled-release mechanisms, and field validation under diverse agroecological conditions.
- The **scaling-up of nutritional proteins from alternative sources**, such as macroalgae, microbial biomass, and agro-industrial side streams—is another high-impact area. This supports food system resilience and circularity by valorising non-food biomass into high-value ingredients. Research should address process optimisation, safety and regulatory compliance, and consumer acceptance.
- Finally, the **development of SSbD (Safe and Sustainable by Design) bio-based polymers and copolymers** is critical for unlocking new market applications in textiles, coatings, and consumer goods. RDI should integrate toxicological assessment, circularity metrics, and performance benchmarking to ensure materials are both safe and scalable.

1. Feedstock diversification and valorisation

- Develop scalable technologies for converting agricultural residues, food waste, and algae into high-value materials.

- Advance microbial and enzymatic processes for precision bioconversion.
- Explore underutilized biomass sources (e.g. seaweed, sugar beet pulp, mushroom mycelium) for novel applications.

2. Advanced material design and functionalization

- Engineer bio-based polymers with enhanced mechanical, thermal, and barrier properties.
- Create multifunctional materials (e.g. antimicrobial, self-healing, conductive) for high-performance sectors.
- Integrate digital design tools (e.g. AI-driven material discovery) to accelerate prototyping.

3. Circular processing and manufacturing

- Innovate low-energy, low-emission processing techniques (e.g. fermentation, green chemistry).
- Develop modular biorefineries adaptable to regional feedstock availability.
- Enable closed-loop manufacturing systems with traceable material flows.

4. End-of-Life solutions and circularity

- Design materials for biodegradability, compostability, or chemical recycling.
- Develop sorting and recovery technologies for bio-based composites and blends.
- Create standards and certification schemes for circular bio-based products.

5. Cross-sector integration and systems innovation

- Foster synergies between agriculture, industry, and waste management sectors.
- Pilot regional bioeconomy hubs with integrated supply chains and innovation ecosystems.
- Model systemic impacts using life cycle assessment (LCA) and techno-economic analysis (TEA).

6. Investment pathways

- Public-Private Partnerships
- Expand funding under Horizon Europe, CBE JU, and national bioeconomy programs.
- Incentivize co-investment from industry through innovation clusters and demonstration projects.

7. Infrastructure and scale-up support

- Invest in pilot plants, testing facilities, and shared R&D infrastructure.
- Support SMEs and startups in scaling bio-based innovations through grants and venture capital.

8 . Market development and procurement

- Use green public procurement to create demand for bio-based products.
- Establish market incentives for premium bio-based goods (e.g. tax breaks, ecolabels).

Table 3. 10R Principles and RDI focus areas for non-forest bio-based raw materials and related applications.

R Principle	RDI Focus Areas for non-forest bio-based raw materials
Refuse	• Avoiding unsustainable biomass sourcing (deforestation, monocultures). • Eliminating hazardous chemicals in bio-based production.
Rethink	• Developing circular-by-design bio-based packaging and polymers. • Creating multifunctional materials (antimicrobial, self-healing, conductive). • Exploring product-service systems for bio-based products.
Reduce	• Improving biomass processing efficiency via green chemistry and enzymatic conversion. • Optimizing cultivation systems (biofermentors, mixotrophic algae platforms). • Using digital tools (AI-based biomass forecasting) for reducing input and waste.
Reuse	• Reusing side streams from industry in cross-sectoral symbiosis (e.g., dairy whey → nutraceuticals). • Reusing catalysts, enzymes, and microbes in biorefinery cycles.
Repair	• Developing bio-based coatings and smart additives for extending product lifetimes. • Creating recyclable fibre composites with repairable barrier layers.
Refurbish	• Retrofitting industrial plants for modular bio-based production. • Upgrading feedstock handling and digital monitoring in existing facilities.
Remanufacture	• Remanufacturing biocomposites and polymers into new applications.

Repurpose	• Repurposing agricultural residues into soil amendments and biofertilizers. • Using side streams (e.g., fish waste, fruit peels) for nutraceuticals and specialty ingredients.
Recycle	• Developing biodegradable and compostable bio-based materials. • Applying chemical recycling of biopolymers. • Setting standards for compostability and recyclability. • Upcycling food and agricultural by-products into feed, fertilizers, and biomaterials.
Recover	• Recovering nutrients (N,P,K) from bio-waste streams. • Recovering energy via anaerobic digestion or biochar.

3.4 Water and related applications

WATER plays a pivotal role in circular systems, not simply as a resource, but as a carrier of materials and energy. It transports nutrients like phosphorus and nitrogen, enables energy recovery through wastewater treatment, and facilitates reuse and recycling in both industrial and municipal processes.

Globally, the importance of water in circular systems is growing, yet challenges persist. Urbanization and climate change are increasing water scarcity, and currently, less than five percent of water is reused worldwide. Nevertheless, wastewater reuse is on the rise, especially in agriculture and industrial sectors, and there is a growing interest in integrating water, energy, and material systems to create more sustainable urban and industrial environments.[43], [44]

The European Circular Economy model outlines six key principles for handling water and wastewater: reducing water use and pollution at the source, reclaiming water through the removal of pollutants, reusing treated wastewater for non-potable applications, recycling water back to potable standards, recovering valuable resources such as nutrients and energy from wastewater, and rethinking how society and industries engage with water overall. Finland has embraced water as a strategic resource in its transition to a circular economy, targeting in reducing water consumption, improving wastewater treatment, and recovering valuable resources like nutrients and energy from water systems.[45], [46]

Innovation in water treatment technologies, like reverse osmosis and biorefineries, alongside better policy alignment across sectors and stronger public-private partnerships, could accelerate the transition to truly circular water use. Water, once regarded simply as a utility, is increasingly being recognized as a strategic asset essential to building resilient systems.

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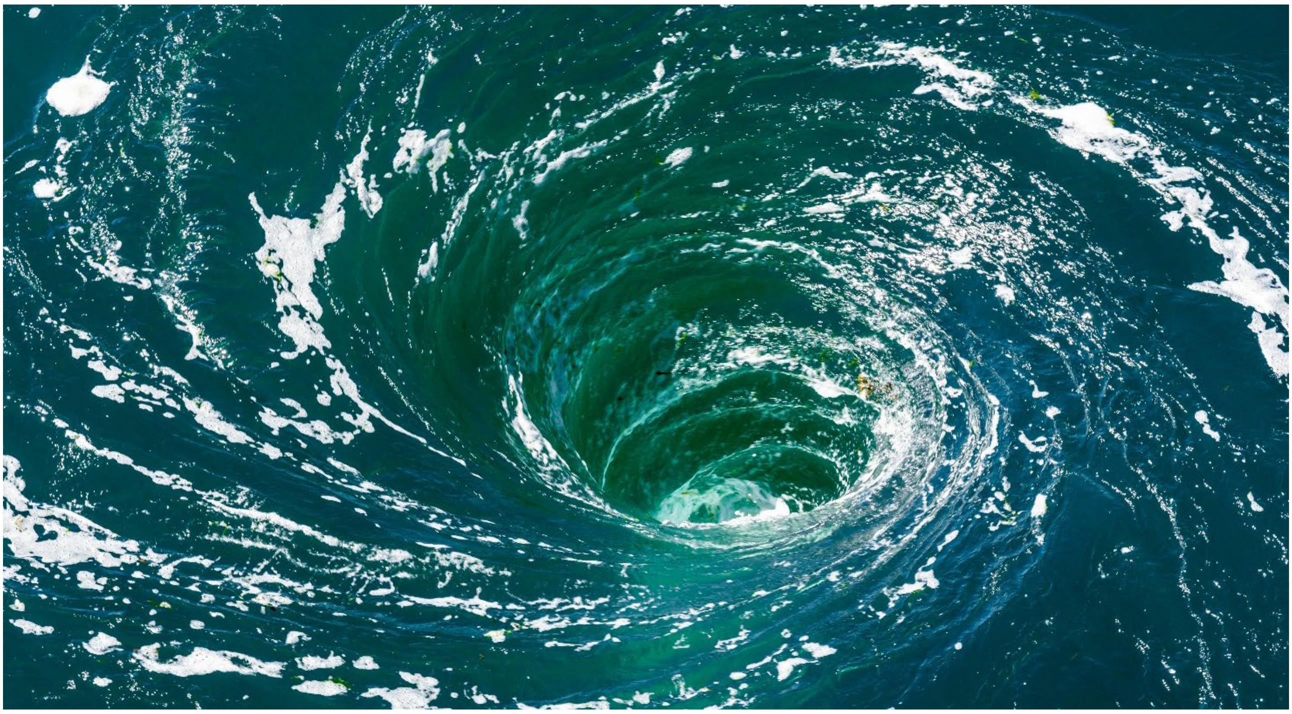
[43] Finnish road map to a circular economy 2016-2025 - Sitra

[44] Peydayesh, M. & Mezzenga, R. (2024) The circular economy of water across the six continents. Chem. Soc. Rev. 2024 53: 4333. DOI: 10.1039/d3cs00812f

[45] Smol, M., Adam, C. & Preisner, M. (2020) Circular economy model framework in the European water and wastewater sector. Journal of Material Cycles and Waste Management (2020) 22:682–697 https://doi.org/10.1007/s10163-019-00960-z

[46] Government+resolution+on+the+Strategic+Programme+for+Circular+Economy+8.4.2021.pdf



3.4.1. Market opportunities and application areas

The rapidly expanding market for circular water systems is focused on reuse, recycling, and resource recovery. It is projected to grow from €4.2 billion in 2024 to €10.8 billion by 2034, with a compound annual growth rate of nearly 10 percent. This expansion is driven by rising water scarcity, climate change, and increased demand for sustainable resource management across industrial, municipal, agricultural, and residential sectors.[47].

Industries are adopting circular water technologies not only to reduce operational costs but also to meet tightening environmental regulations. Solutions such as advanced filtration, desalination, biological treatment, and smart water management using IoT are transforming traditional systems into regenerative ones. These innovations allow businesses to recover nutrients, generate energy, and reuse water, creating entirely new revenue streams from resources once treated as waste.[48],[49].

Regional growth is strongest in Asia-Pacific, Europe, and North America. Asia-Pacific's momentum comes from urbanization and industrial expansion, while Europe's leadership stems from robust sustainability policies and infrastructure investment. In North America, the combination of regulatory frameworks and technological innovation is accelerating market uptake.[44].

There is also rising interest in decentralized water treatment systems, which offer flexible, scalable solutions in both urban and rural contexts. Digital platforms for real-time monitoring and predictive analytics are emerging, transforming water data into actionable insights. Additionally, public-private partnerships and green financing models are modernizing infrastructure and attracting investment, particularly for projects that demonstrate circular value creation. As water increasingly becomes a strategic asset rather than a passive utility, companies that can deliver cost-effective, scalable, and sustainable solutions will be at the forefront of this transformation.[50],[51].

Water in the circular economy is central to industrial and societal transitions with application possibilities spanning across multiple sectors. In municipal systems, advanced treatment and reuse technologies transform

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[47] The Rise of Circular Water Economy Systems: Market Trends & Sustainability Solutions - LinkeWire

[48] Karkou, E & al. (2024) Industrial circular water use practices through the application of a conceptual water efficiency framework in the process industry. Journal of Environmental Management, volume 370.

[49] circular-water-economy-faqs-2.pdf

[50] Dada, M., A. et al. (2024) Review of smart water management: IoT and AI in water and wastewater treatment. World Journal of Advanced Research and Reviews, 2024, 21(01), 1373–1382.

[51] Unlocking the Potential of Innovative Financing for Sustainable Water Infrastructure | by Robert C. Brears | Mark and Focus | Medium

The Rise of Circular Water Economy Systems: Market Trends & Sustainability Solutions wastewater into a source of reclaimed water for irrigation, cooling, and urban greening. In industry, circular water technologies such as closed-loop cooling, smart water management, and nutrient recovery from effluents reduce costs and environmental footprints while creating new revenue streams. Agriculture benefits from reclaimed water for irrigation and bio-based fertilizers derived from wastewater, reducing dependence on freshwater and synthetic inputs. In the energy sector, biogas recovery from sewage sludge and water-integrated bio-refineries provide renewable energy options. The chemical and resource industries can valorize waterborne side streams for nutrient recovery (phosphorus, nitrogen) and rare material extraction. In digital and infrastructure domains, IoT-enabled monitoring, predictive analytics, and decentralized treatment systems open opportunities for resilience, inclusivity, and localized water autonomy. By positioning water as a strategic asset, circular water applications support climate adaptation, food security, industrial competitiveness, and sustainable urbanization.

3.4.2. Focus areas for research and innovation

Emerging research, development, and innovation needs in the water circular economy are evolving rapidly as cities, industries, and governments seek to close water loops and build resilience. CLIC's cross-cutting themes bring added value to water circularity by positioning it as a systemic enabler rather than a standalone utility. Through industrial innovations, digital twins, IoT-based monitoring, and advanced treatment technologies make water reuse, recycling, and resource recovery more efficient and scalable. Business and value chain development fosters circular business models such as water-as-a-service, nutrient and energy valorization markets, and cross-sectoral industrial symbiosis, turning wastewater into a strategic asset. Finally, societal transitions with resilient supply systems integrate water into broader sustainability frameworks, linking urban resilience, food security, and energy-water-material nexus strategies. These themes ensure that water management evolves from efficiency gains to a transformative driver of sustainable, inclusive, and climate-resilient systems.

1. Decentralized water treatment systems for flexible, scalable solutions
2. Digital platforms for real-time monitoring and predictive analytics
3. Integrated urban water frameworks
    1. Design infrastructure that combines circular principles with climate resilience
    2. Promote inclusive access, waste elimination, and ecosystem regeneration
    3. Reuse treated wastewater for non-potable purposes
    4. Recover water for potable use
    5. Minimize water use and pollution at the source
4. Technological Innovation
    1. Develop advanced treatment technologies: membrane bioreactors, constructed wetlands, oxidation processes
    2. Pair treatment systems with digital tools like real-time monitoring and predictive analytics
    3. Extract nutrients and energy from wastewater
5. Governance & policy alignment
    1. Address fragmented regulations and low public acceptance
    2. Create harmonized standards, circularity metrics, and co-designed solutions with communities
6. By-product valorization
    1. Recover and commercialize outputs from wastewater such as nutrients, biogas, and biosolids
    2. Ensure environmental and health safety in reuse applications
7. Nature-based & decentralized solutions
    1. Implement ecologically beneficial systems to tackle water stress
    2. Integrate flexible, scalable solutions into mainstream infrastructure and financing strategies

Table 4. 10R Principles and RDI focus areas for water and related applications.

R Principle	RDI focus areas for water and related applications
Refuse – Rethink – Reduce	• Eliminating water-intensive production processes. • Phasing out harmful chemicals, pollutants and microplastics at source. • Zero-discharge systems in industries. • Integrating urban water frameworks linking climate resilience with circularity. • Developing new governance models for inclusive water access and equity. • Creating circular-as-a-service models for water utilities.

	• Minimizing freshwater withdrawals through efficiency technologies. • Using digital twins and AI for predictive leak detection and demand optimization. • Implementing low-energy treatment processes.
Reuse	• Reusing municipal and industrial wastewater for irrigation, cooling, and sanitation. • Reusing greywater reuse in households and buildings. • Establishing decentralized water loops for agriculture.
Repair	• Maintening and repairing water infrastructure using digital monitoring. • Applying smart coatings and sensors to extend pipe and membrane lifetimes. • Developing repairable modular treatment units.
Refurbish	• Retrofitting treatment plants with advanced filtration and energy recovery systems. • Upgrading existing infrastructure with modular solutions to accommodate new standards.
Remanufacture	• Remanufacturing pumps, filters, and membranes for extended use. • Reconditioning bioreactor components for multiple treatment cycles.
Repurpose	• Repurposing wastewater into industrial inputs (e.g., process water for cooling, textiles). • Using biosolids as soil amendments or construction materials.
Recycle	• Recycling wastewater into potable water using membrane bioreactors, advanced oxidation, and RO. • Nutrient recycling from effluents for fertilizers. • Closed-loop water recycling in industrial parks.
Recover	• Recovering nutrients (N, P, K) from municipal and agricultural wastewater. • Recovering energy via biogas and microbial fuel cells. • Valorizing by-products such as biopolymers, biosolids, and recovered heat.

3.5. Carbon cycling and related applications

CARBON cycling is at a pivotal moment currently. Despite major strides in renewable energy, global greenhouse gas emissions continue to climb, reaching over 40.8 billion metric tons of CO_2-equivalent in 2024. Sectors such as energy, industry, transport, land use, agriculture, and waste must now go beyond eliminating emissions and begin implementing net-negative carbon strategies to meet global climate commitments. At the same time, the atmosphere remains a vast and largely untapped source of simple carbon compounds like carbon dioxide, methane, and carbon monoxide, valuable feedstocks for circular production systems. Innovations in carbon capture and utilization (CCU) are becoming increasingly feasible, particularly when carbon is captured at industrial point sources. These technologies allow recovered carbon to be transformed into fuels, chemicals, materials, and even soil amendments. Synthesizing carbon-based products from emissions is closely tied to the hydrogen economy, as hydrogen is often required to convert CO_2 into usable compounds. This connection reinforces the need for clean energy expansion, including wind, solar, hydro, and bioenergy, to power hydrogen production and carbon transformation processes. [52], [53]

Circular economy and 10Rs present a systemic framework for addressing carbon cycling challenges and opportunities. Applying circular principles enables a shift from carbon as a pollutant to carbon as a resource, keeping it in productive circulation and reducing dependence on fossil sources. Whether through repairing carbon-intensive infrastructure, repurposing captured carbon into synthetic products, or recycling waste streams into biochar and low-emission materials, CE-driven strategies present scalable, cost-effective, and environmentally sound pathways to transform carbon cycling into a pillar of global resilience and resource sufficiency.[52, 53]

3.5.1. Market opportunities and application areas

THE transition to a carbon-neutral circular economy is accelerating across Europe, driven by declining renewable energy costs, stricter climate policies, and growing industrial interest in carbon valorization. CO_2 and other C1 compounds are increasingly viewed as strategic feedstocks for producing fuels, chemicals, and food. Technologies such as synthetic biology, agile biorefineries, and carbon capture and utilization (CCU) are enabling this shift, particularly in hard-to-abate sectors like steel, cement, and chemicals. Economically, the overall circular economy market is projected to grow from approximately €480 billion in 2025 to over €740 billion by 2029, with a compound annual growth rate (CAGR) of 11–12%. Carbon credit markets are also expanding, with direct air capture and biochar technologies generating offsets valued between €80–€150 per tonne of CO_2 removed, depending on verification standards and permanence.[54], [55], [56]

RDI plays a pivotal role in unlocking these opportunities. The circular carbon economy is no longer a niche concept but rather becoming a mainstream industrial strategy. Public-private partnerships are essential to scale up pilot projects, reduce technology costs, and build infrastructure for CO_2 transport and storage. RDI also supports the development of robust measurement and verification systems, which are critical for market credibility and investor confidence.

Carbon cycling is rapidly shifting from climate liability to a strategic industrial opportunity. Across energy, industry, transport, agriculture, construction, and waste management, carbon capture, utilization, and recycling open pathways to embed circularity at scale. In the energy sector, carbon capture and storage (CCS) and carbon-to-fuel conversion link emissions management with renewable hydrogen systems. Heavy industries like steel, cement, and chemicals are adopting CCU processes to convert CO_2 into synthetic fuels, methanol, polymers, and construction materials. Agriculture and land use benefit from biochar, soil amendments, and carbon-rich fertilizers derived from captured carbon and waste streams. In construction, CO_2 curing of concrete and the use of CO_2-derived composites reduce emissions while enhancing material performance. Transport and mobility sectors are experimenting with synthetic fuels and carbon-based additives to cut fossil dependence. Waste management is increasingly treating carbon-rich gases as resources, enabling pyrolysis, fermentation, and microbial pathways to recycle or recover carbon. Finally, digital and

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[52] s41598-025-97810-w.pdf

[53] Marian Antohi, M: & Zlati, M.L. (2025) Approaches and perspectives on the transition to the circular economy in Euroepan Union. Front. Environ. Sci., 04 March 2025. Volume 13. https://doi.org/10.3389/fenvs.2025.1533776

[54] EU Climate Law: new way to reach 2040 targets - European Commission

[55] Europe Carbon Credit Market Size & Outlook, 2030

[56] EU Emissions Trading System (EU ETS) - European Commission

policy frameworks, such as carbon credits, lifecycle digital twins, and industrial carbon-sharing platforms, are transforming carbon from pollutant into tradable, verifiable, and circular value streams. Together, these applications demonstrate that carbon cycling is becoming a foundation of a climate-neutral, resource-efficient, and resilient industrial economy.

3.5.2. Focus areas for research and innovation

TO accelerate the shift toward a carbon-neutral circular economy, strategic investments in viable and scalable solutions for carbon recycling are urgently needed. The utilization of single-carbon compounds, such as CO2 and methane, as core feedstocks for producing sustainable chemicals, fuels, and materials represents a critical pathway forward. Research and innovation efforts should prioritize cutting-edge technologies that enhance capture efficiency, enable resource-smart conversion, and foster the development of high-value, circular carbon products across industrial sectors.

CLIC's cross-cutting themes strengthen carbon cycling by embedding it into a broader systems-level transition. Industrial innovations such as digital twins, AI-optimized bioreactors, and modular CCU retrofits ensure capture and utilization processes are efficient and scalable. Business and value chain development drives new models like carbon-sharing platforms, carbon-as-a-service, and verified carbon credit markets, helping turn emissions into economic assets. Finally, societal transitions with resilient supply systems connect carbon utilization to sustainable urbanization, food security, and energy-water-material nexus strategies. Together, these themes elevate carbon cycling from a technological fix to a transformative enabler of a just, inclusive, and climate-resilient transition.

Novel RDI topics on carbon cycling

1. **Next-generation carbon-negative materials** – Development of industrial materials designed to eliminate fossil-based inputs and provide net-negative carbon footprints.
2. **Digital carbon avoidance systems** – Deployment of digital twins and AI lifecycle modeling to simulate and prevent CO2 generation at design and production stages.
3. **Carbon symbiosis platforms** – Establishment of industrial symbiosis networks where CO2 and other C1 compounds act as shared feedstocks across sectors.
4. **CO2-derived multifunctional polymers** – Design of adaptive materials with tunable properties derived directly from captured carbon.
5. **AI-optimized bioreactors** – Creation of bioreactor systems that integrate AI for minimal energy and resource input in CO2 conversion.
6. **Carbon-enhanced infrastructure** – Use of CO2 curing and carbon-based composites in construction to improve durability and reduce emissions.

7. **Self-healing carbon materials** – RDI into composites, coatings, and devices with repairable or regenerative carbon-based functionalities.
8. **Circular carbon retrofit technologies** – Retrofitting legacy industrial facilities with modular carbon capture, utilization, and valorization units.
9. **Catalyst remanufacturing** – Development of remanufacturing cycles for catalysts used in CCU, ensuring sustainable supply and performance consistency.
10. **Biochar & soil carbon valorization** – Large-scale repurposing of CO_2-derived and carbon-rich waste streams into soil amendments and biochar.
11. **Electrochemical carbon-to-chemicals pathways** – Scaling electrochemical recycling routes to produce methanol, ethylene, and formic acid from CO_2.
12. **Synthetic microbiology for carbon valorization** – Engineering microbes for targeted bioconversion of CO_2 and CH_4 into high-value chemicals and fuels.
13. **Carbon composite recycling** – Circular processing of carbon-based composites through pyrolysis, solvent, or enzymatic technologies.
14. **Thermal carbon recovery** – Gasification and advanced heat-integration systems to recover carbon and energy from biomass and industrial flue gases.
15. **Decentralized carbon energy systems** – Repurposing CO_2 capture and storage infrastructure as nodes for localized renewable energy and storage hubs.

Table 5. 10R Principles and RDI focus areas for carbon cycling and related applications.

R Principle	**Examples of RDI focus areas for carbon cycling and related applications.**
Refuse	• Designing carbon-negative materials. • Eliminate the need for fossil-based inputs. • Developing zero-carbon industrial process design to avoid CO_2 generation at source. • Using digital twins for carbon avoidance in product lifecycle simulations.
Rethink	• Establishing carbon-sharing platforms for industrial symbiosis (e.g., CO_2 as a shared feedstock). • Developing multi-functional carbon-based materials (e.g., CO_2-derived polymers with adaptive properties). • Circular-as-a-service models for carbon utilization technologies.
Reduce	• Developing low-energy carbon capture membranes with tunable selectivity. • Optimizing bioreactor systems with AI for minimal resource input. • Implementing carbon-efficient additive manufacturing using CO_2-derived feedstocks.
Reuse	• Reusing captured CO_2 directly in greenhouses, algae farms, and fermentation systems. • Applying CO_2 reuse in concrete curing to enhance material strength and reduce emissions. • Reusing carbon-rich industrial gases in closed-loop chemical synthesis.
Repair	• Developing self-healing carbon-based composites for infrastructure and aerospace. • Creating repairable CO_2 sensors and capture modules to extend device lifespans. • Applying carbon-based coatings that enable repairability of high-performance surfaces.
Refurbish	• Refurbishing legacy CCU systems with modular upgrades. • Retrofitting industrial plants with circular carbon valorization units. • Refurbishing bioreactors for new microbial strains targeting CO_2 conversion.
Remanufacture	• Remanufacturing catalysts used in CO_2 conversion processes. • Upcycling carbon capture modules from decommissioned systems. • Remanufacturing carbon-derived materials into new product forms.
Repurpose	• Turning organic waste streams into soil amendments or biochar. • Repurposing hydrogen capture infrastructure for integrated energy storage.
Recycle	• Recycling captured atmospheric or industrially sourced gases. • Recycling biomass waste streams via engineered microbes. • Converting captured gases into sustainable fuels and chemicals.
Recover	• Recovering carbon thermally from biomass and waste via gasification. • Recovering energy recovery from CO_2 conversion byproducts. • Recovering carbon from flue gases using advanced sorbents and heat integration.

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