

Research & Innovation projects supporting the Circular Economy Act

Focus area: Recycled and bio-based content and end-of-waste criteria



Independent Expert Report

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Focus area: Recycled and bio-based content and end-of-waste criteria

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Dr. Tom Vöge

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Executive Summary

The evidence from the project portfolio demonstrates that the EU has largely established the technical foundations for a high-performing circular economy. The key challenge now lies in scaling these solutions across the Single Market by addressing persistent regulatory fragmentation, weak demand signals, and misalignments at the waste–chemicals–product interface. The upcoming Circular Economy Act provides a critical opportunity to shift from pilot success to systemic deployment by aligning legal definitions, market incentives, and digital infrastructure.

A first priority is the harmonisation of End-of-Waste (EoW) criteria for high-value material streams such as textiles, plastics, composites, and WEEE. The absence of EU-wide criteria continues to create legal uncertainty, administrative burden, and barriers to cross-border trade, effectively treating secondary raw materials as waste rather than products. The Act should introduce material-specific EoW rules supported by harmonised technical standards, enabling a clear and uniform “legal identity” for high-quality recyclates. This would unlock the internal market for secondary materials and provide the certainty required for industrial uptake.

Second, the Act must establish strong market-pull mechanisms through progressive mandatory recycled content quotas. Evidence confirms that technical equivalence with virgin materials is achievable, but demand remains insufficient without regulatory drivers. Binding, sector-specific targets, starting e.g. at 10–20% by 2030, would create predictable demand and unlock investment in advanced sorting and purification infrastructure. These measures should prioritise high-value, closed-loop applications to avoid downcycling and preserve material quality.

Third, Digital Product Passports (DPPs) should be operationalised as the backbone of the circular economy framework. Beyond transparency, DPPs must function as a verified data infrastructure to enforce recycled content requirements, ensure chemical safety, and enable traceability across value chains. Standardised data architectures and differentiated access levels - for industry, regulators, and consumers - will be essential to balance usability with enforcement. In particular, DPPs should provide auditable information on material origin, recycled content, and the removal of hazardous substances, while also guiding consumers on repair, reuse, and return pathways.

Complementing these measures, economic instruments are required to address the persistent “green premium” associated with recycled materials. The eco-modulation of Extended Producer Responsibility (EPR) fees offers a direct mechanism to internalise environmental costs by penalising non-circular designs and rewarding the use of recycled content. Revenues from these schemes should be channelled into the development of national and regional sorting and purification hubs, which are essential to aggregate sufficient volumes and deliver industrial-grade secondary raw materials.

Addressing the waste–chemicals–product interface is another critical enabler. Current regulatory inconsistencies often prevent the market uptake of recycled materials due to strict substance restrictions, despite evidence that advanced technologies can remove the vast majority of contaminants. The Act should adopt a risk-based “safe-by-design” approach, including safe-use thresholds and testing protocols, while accelerating the phase-out of hazardous additives at the design stage. This would prevent the unnecessary loss of valuable materials to incineration while maintaining high safety standards.

Finally, the Act should strengthen the end-of-life phase through the institutionalisation of “design for divestment”. Products must be designed not only for durability and recyclability, but also for easy return and reintegration into material loops. This includes mandatory end-of-life

instructions embedded in digital product passports, as well as incentives for take-back schemes and product-as-a-service models that retain producer responsibility over materials.

Strategically, these measures point to a broader shift in EU circular economy policy, i.e. from volume to quality, from voluntary action to mandated demand, and from fragmented regulation to system-wide integration. Success should be measured not by recycling rates alone, but by the quality and reuse potential of secondary materials. By combining harmonised standards, enforceable demand, digital traceability, and targeted fiscal incentives, the Circular Economy Act can provide the necessary legal, economic, and technological framework to scale circularity, strengthening both EU competitiveness and resource resilience.

1. Scope and policy relevance

This report provides a synoptic analysis of selected key projects from various Horizon Europe and Horizon 2020 calls across several economic sectors, all of which address shared circular concepts or challenges. The primary objective of this evaluation is to identify common features of successful circular solutions that merit integration or support within the framework of the Circular Economy Act (CEA). By pinpointing these successful models, the report assists the Commission in fostering the ideal conditions for secondary resource markets and increasing the uptake of secondary raw materials across the Union.

The analysis consists of five reports structured around five specific intervention areas directly linked to the objectives of the Circular Economy Act. Namely, public procurement, recycling of the Waste Electrical and Electronic Equipment (WEEE) with a focus on critical raw materials, the uptake of recycled and bio-based content, trans-national or regional initiatives, and the refinement of extended producer responsibility schemes. Each of these themes has been analysed by a dedicated domain expert to ensure a comprehensive technical assessment. To ensure the findings are suitable for a formal Commission legislative impact assessment, every proposed solution is measured against its specific environmental, economic, and social impacts.

The evidence presented in this report is derived from a detailed review of project deliverables provided by DG Research and Innovation (DG RTD), supplemented by the experts' own professional insights. Where internal data has been augmented, the report provides valid references to published scientific literature and external research to maintain a robust evidence base. Ultimately, this synthesis serves as a foundation for evidence-based policymaking, ensuring that future legislative measures are informed by proven innovations in circularity.

1.1. Role of the 5 intervention areas

To bridge the gap between technical feasibility and market reality, the Circular Economy Act must activate specific regulatory levers. The five intervention areas analysed in the complete report represent the core pillars required to build a functioning, resilient market for secondary raw materials (SRMs) and bio-based alternatives:

- **Refinement of Extended Producer Responsibility (EPR):** EPR is the financial and operational engine of the circular transition. By moving beyond traditional waste-collection fees towards dynamic, data-driven eco-modulation, EPR internalises the environmental costs of products. This corrects a fundamental market failure—the "virginity trap," where virgin fossil materials remain artificially cheaper than secondary feedstock—and provides the necessary price signal to drive eco-design at the source.
- **Circular Public Procurement (CPP):** while EPR pushes supply, public procurement creates the required demand-side "pull." Leveraging the immense purchasing power of

European public authorities (accounting for approximately 14% of EU GDP¹), mandatory circular procurement criteria² can provide the "base load" demand needed to de-risk high-capital expenditure (CAPEX) investments in advanced recycling and bio-based manufacturing infrastructure.

- **WEEE and critical raw materials (CRM) recovery:** the electrification of the European economy hinges on secure access to critical metals. Focusing on WEEE ensures that high-tech "urban mines" are properly exploited. By recovering magnet-grade and battery-grade materials, this intervention area directly supports European strategic autonomy, preventing valuable resources from leaking out of the Single Market through substandard processing or illegal export.
- **Uptake of recycled and bio-based content:** establishing horizontal, mandatory recycled content thresholds - combined with clear, EU-wide End-of-Waste (EoW) criteria - is vital for decoupling industrial growth from fossil extraction. This area guarantees off-take certainty for recyclers and incentivises the substitution of hazardous legacy substances with Safe-and-Sustainable-by-Design (SSbD) bio-based alternatives.
- **Trans-national and regional initiatives - industrial symbiosis:** the circular economy operates at the territorial level. Fostering trans-national and regional hubs ensures that by-products from one industry can become feedstock for another without being derailed by fragmented, cross-border waste shipment regulations. This area operationalises material loops by harmonising local governance and creating connected "circular valleys".

1.2. Link to CE Act objectives and related EU legislation

The regulatory backbone for recycled content and end-of-waste (EoW) criteria in the forthcoming Circular Economy Act is already largely defined by existing EU waste and product legislation. Central is the Waste Framework Directive, which establishes the legal concept of end-of-waste under Article 6, defining when a material ceases to be waste and becomes a secondary raw material based on criteria such as market demand, technical compliance, and absence of adverse environmental impacts. This Directive also empowers the Commission to adopt EU-wide EoW criteria for specific streams (e.g. metals, glass, and increasingly plastics and textiles), which are critical for creating a functioning Single Market for secondary raw materials.

On the recycled content side, product-specific legislation is becoming increasingly important. The Packaging and Packaging Waste Regulation introduces binding targets for recycled content in packaging and requirements to reduce reliance on virgin materials, while sectoral rules such as the End-of-Life Vehicles Regulation set mandatory recycled material targets (notably plastics) in manufacturing. Together with implementing acts under existing legislation (e.g. for plastics recycling and food-contact materials), these instruments are expected to be consolidated and streamlined under the Circular Economy Act to align recycled content obligations with harmonised EoW criteria, thereby strengthening demand and supply for secondary raw materials across the EU.

¹ European Parliament. *Public procurement*. European Parliamentary Research Service (EPRS). PE 775.896. September 2025.

² The Circular City Centre – C3. "Circular Public Procurement in Cities." ACR+. October 14, 2025.

2. Methodology and analytical framework

The CEA must be grounded in scalable market realities and requires translating cutting-edge Research and Innovation (R&I) directly into actionable EU policy. This section details our assessment framework.

We applied a strict policy-readiness lens to filter the Horizon 2020 and Horizon Europe portfolios. By triangulating project data, stakeholder input, and market dynamics, we isolated solutions based on three core criteria: systemic impact, technological maturity, and regulatory viability. The objective of this methodology is straightforward: to advance only proven, high-impact circular models as concrete legislative recommendations for the CEA.

2.1. Analytical logic

The analytical logic deployed in this report is fundamentally outcome-driven and impact-assessment oriented. Rather than simply cataloguing technological achievements, the methodology is designed to perform a synoptic analysis of Research and Innovation (R&I) projects to identify scalable, transferable circular solutions that can directly inform the regulatory mechanisms of the forthcoming CEA.

The approach combines both qualitative and quantitative assessments to evaluate the environmental, economic, and social effects of each solution. The workflow followed a rigorous, multi-stage policy formulation process:

1. **Scoping and alignment:** initial requirements gathering through DG RTD instructions to align technical research with current political and market demands.
2. **Purposive sampling:** a broader portfolio analysis followed by a purposive sample selection tailored to the specific intervention area.
3. **Iterative drafting:** structuring the analysis matrix, drafting expert contemplations, and refining the findings through iterative consultations with the DG RTD to ensure final group alignment and policy coherence.

2.2. Sources and evidence

The analysis draws upon published project data as the core evidence, extracted from official project deliverables, periodic reports, and milestone achievements accessed via the European Commission's SYGMA portal and CORDIS database, supplemented by data from the official project websites.

2.3. Project portfolio attribution and assessment method

The initial project portfolio was attributed by DG RTD, providing a baseline of Horizon 2020 and Horizon Europe projects targeting circularity and resource efficiency. However, to ensure strict relevance to the focus area, the portfolio underwent a rigorous expert validation and filtering process.

3. R&I Project Portfolio scope and overview

3.1. Portfolio overview

Projects and sectors

#	Project Number	Project Name	Sector
1	101058670	PRecycling	Advanced Materials
2	101057067	PRIMUS	
3	101058487	INCREASE	
4	101091801	DigInTraCE	Energy-Intensive Industries
5	101138789	WOOD2WOOD	
6	101096306	HEFT	Transport CRMs
7	101060814	CHEERS	Bio-Based
8	101081823	SUSTRACK	
9	101135562	SYMBA	
10	101135166	SYMBIO	
11	818309	LEX4BIO	CBE JU
12	101023280	CIRCULAR BIOCARBON	
13	730323	FiberEUse	Composites (REA)
14	101003883	MERLIN	Plastics
15	820895	NONTOX	
16	821087	PLAST2BCLEANED	
17	101082068	CIRC-BOOST	Construction
18	101003806	CIRCULAR FOODPACK	Plastics
19	101060343	T-REX	Textiles
20	101003906	SCIRT	

Project references:

- DigInTraCE
 - D5.1: Secondary materials quality characterization for recycle, reuse upgrade
 - D6.1: Waste streams mapping
- INCREASE
 - D5.1: State-of-the-art inventory of (A) barriers and drivers to societal demand for recycled plastics and (B) (design for) divestment research
- PRIMUS
 - D1.1: Report on enhancing systemic actions to boost the circularity of target waste streams
 - D1.2 Guidance Report)
 - D7.2: PRIMUS Best Practice Book and Policy Recommendations
- PRecycling
 - D1.1: Inventory and characterization of the EoL PWS (for the different applications

- D1.2: Review of the best practices used in industry/ EU countries for calculating, verifying and reporting of recycled plastic content in products
- WOOD2WOOD
 - D16.4: Policy recommendations for developing a circular and sustainable process industry
- CIRCULAR FoodPack
 - Policy Brief: Can Flexible Food Packaging Go Circular?
- Circ-Boost
 - D2.2 Interim Policy Brief: Cooperation with and recommendations to regional and European policymakers
- SCIRT
 - D5.5: Set of guidelines and recommendations on key policy interventions
- T-REX
 - White Paper: Advancing Textile Circularity: Policy Recommendations for Implementing ESPR (Ecodesign for Sustainable Products Regulation) in the EU
- CIRCULAR BIOCARBON
 - D1.1: Report on the definition of technical requirements, barriers and solutions
 - D1.2: Legal framework of the MSW and SS-based biorefineries in Europe: law of application to materials and processes and future trends in Europe
- PLAST2bCLEANED
 - D1.1: Limitations, barriers, standards for using recycled polymers
 - D6.13: Route map for recommendations to the consortium and the stakeholders across the whole value chain
- NONTOX
 - D1.1: Publishable report on plastics recycling, featuring recycling with legacy additives from C&DW, ELV, WEEE; testing of plastic materials, including scrap & recycle
 - D5.3: Report on enhancing actions to reach a circular plastic economy
- MERLIN
 - D5.5: Policy recommendation toolbox for policymakers (preliminary)
 - D6.2: Guidelines on increasing the recyclability and circularity of plastic packaging: Learnings from collected good practices
- Project: FiberEUse
 - D7.6: Legislation boundaries and recommendations for policy makers
- CHEERS
 - D1.3: Report on the bio-based products regulatory and market uptake barriers
 - D6.6: Policy Brief
- HEFT
 - D6.1: Report on the resource efficiency, recyclability, and criticality of the supply chain
- LEX4BIO
 - D7.6: Policy brief with a clear concise summary of policy recommendations
 - D8.5: Policy Roadmap
- SUSTRACK
 - D1.3: Report on the prioritisation of the identified limits, as well as the preliminary guidelines and policy recommendations
 - D5.1: Mid-term policy brief: policy priorities to support the sustainable transition and examples of good policies
- SYMBA
 - D5.4: Policy Brief 1
- SYMBIO
 - D3.3: Policy overview and recommendations

3.2. Portfolio characterisation

3.2.1. Distribution Across Technology Readiness Levels (TRLs)

The portfolio spans a broad TRL spectrum, strategically balanced between technological validation and near-market deployment:

- High-Maturity Deployment (TRL 6–8):

The most advanced tier of the portfolio is led by **CIRCULAR BIOCARBON**, which aims to reach **TRL 8** by operating a first-of-its-kind flagship commercial-scale biorefinery. Other high-maturity initiatives, such as **FiberEUse** and **LEX4BIO**, bridge the gap to commercialization (TRL 5–7) by demonstrating large-scale circular value chains and validating agricultural performance for bio-based fertilizers.

- Medium-Scale Innovation (TRL 4–7):

A significant cluster of projects operates within the **TRL 4 to 7** range, focusing on moving from laboratory validation to system demonstration.

- **HEFT**, **SCIRT**, and **T-REX** are notable for targeting a high end-maturity of **TRL 7**, addressing complex sectors like EV motor recyclability and closed-loop textile recycling.
- Projects like **DigInTraCE**, **WOOD2WOOD**, and **CHEERS** focus on the mid-range (**TRL 4–6**), integrating digital traceability and upcycling brewery side-streams.
- **CIRCULAR FoodPack** specifically targets the production of high-purity recycled PE for food-contact applications, moving from a TRL 4 to a 5–6 range.

- Foundational and Early-Stage Validation (TRL 3–6):

The portfolio also captures essential early-stage innovation. **PLAST2bCLEANED** and **NONTOX** begin at **TRL 3**, focusing on the dissolution and extraction processes to remove hazardous additives from plastics. **MERLIN** similarly bridges foundational work into practical application, starting at **TRL 3/4** to advance AI-driven sorting and delamination for multi-layer packaging.

Project Name	Start TRL	End TRL**	Key Maturity Objective
CIRCULAR BIOCARBON	6	8	Build and operate a first-of-its-kind flagship commercial-scale biorefinery for organic waste (OFMSW and sewage sludge).
FiberEUse	5	7	Demonstrate large-scale circular economy value chains for the reuse and remanufacturing of end-of-life fibre-reinforced composites.
LEX4BIO	5	7	Optimize bio-based fertilizers and validate agricultural performance.
CHEERS	4	6	Upcycle brewery side-streams into novel non-plant feedstocks.
HEFT	4	7	Develop a high-power density, recyclable motor for mass-market EVs.
DigInTraCE	4	6	Integrate digital traceability for secondary raw material quality.

DigInTraCE	4	6-7	Develop a digital traceability framework to improve the sorting and upgrading of secondary raw materials (PET, wood, resins) for reuse.
WOOD2WOOD	4	6	Implement a wood-to-wood cascade upcycling approach using Digital Product Passports to enhance the valorisation of waste wood.
CIRCULAR FoodPack	4	5-6	Produce high-purity recycled PE from flexible packaging waste suitable for food-contact applications through advanced sorting and deinking.
SCIRT	4	7	Demonstrate a systemic, textile-to-textile recycling system for post-consumer garments, covering natural, synthetic, and blended fibres.
T-REX	4	6-7	Create a harmonized EU blueprint for closed-loop textile recycling, moving from household waste collection to new garment production.
PLAST2b CLEANED	3	5/6	Develop a dissolution process to remove hazardous additives (e.g. BFR) and recover high-purity ABS/ HIPS polymers from WEEE.
NONTOX	3	5	Increase recycling rates of WEEE, ELV, and C&DW plastics by removing legacy hazardous substances using dissolution and extraction.
MERLIN	3/4	6	Increase the quality and recycling rate of multi-layer plastic packaging through advanced AI sorting and delamination techniques.
INCREASE	4-5	6-7	Increase the uptake of recycled plastics in added-value products through digitized circularity and improved consumer acceptance.
PRIMUS	4-5	6-7	Standardise the quality and safety of recyclates to enable their use in high-demand applications like food contact materials.
PRecycling	4-5	7	Develop methods for verifying and reporting recycled plastic content while improving mechanical properties for home appliances, toys, and textiles.
Circ-Boost	4-5	6-7	Establish a digital building platform and pilot projects to demonstrate circular solutions for construction and demolition waste recovery.
SYMBA	N/A*	N/A*	Establish a methodology for bio-based industrial symbiosis.
SUSTRACK	N/A*	N/A*	Identify limits of fossil-based systems and draft policy roadmaps.
SYMBIO	N/A*	N/A*	Foster regional bio-based symbiosis through stakeholder engagement.

*) Note: These projects are "Coordination and Support Actions" (CSA). These focus on methodologies, policy, and networking rather than developing specific hardware/ software through TRL stages; however, they aim to bring industry systemic maturity to a level where commercial adoption (comparable to TRL 9) becomes feasible.

**) Note: Where projects have been finalised, these are the actual achieved values; for project, which are still ongoing, these are the projected values, based on the ambition of the respective projects.

3.2.2. Sectors and Materials Most Represented

The following section provides a comprehensive overview of the primary industrial sectors and material streams addressed by this project cluster. By focusing on areas with high environmental impact and technical recycling challenges, these initiatives aim to move the global economy toward a more circular and sustainable model.

- Plastics, Packaging, and WEEE:

Plastics represent the most significant material focus across the portfolio, particularly regarding the challenge of using recycled content in high-performance or sensitive applications. Projects such as CIRCULAR FoodPack, PRIMUS, INCREASE, PRecycling, DigInTraCE, Merlin, and NONTOX target materials like Polyethylene (PE), Polyethylene Terephthalate (PET), and various resins. A primary objective is achieving food-grade quality for post-consumer recycled (PCR) content in flexible packaging and consumer goods. Furthermore, a specialized focus on Waste Electrical and Electronic Equipment (WEEE) is evident in projects like PLAST2BCLEANED and NONTOX, which work to recover High Impact Polystyrene (HIPS) and ABS. These efforts are specifically designed to remove legacy hazardous substances, such as brominated flame retardants, ensuring that recycled electronics plastics meet modern safety standards.

- Critical Raw Materials in the Transport Sector:

The transport sector represents a primary driver of demand for Critical Raw Materials (CRMs), particularly regarding the rare earth elements essential for the permanent magnets used in electric vehicle traction motors. The HEFT project focuses on the transition toward a circular automotive industry by developing a novel class of low-cost, high-power-density, and highly efficient recyclable motors for mass-produced electric vehicles. By evaluating four distinct e-motor prototypes designed for compact and family car segments, the project addresses the critical challenge of permanent magnet recovery, particularly for rare earth elements (REEs) like Neodymium and Dysprosium. The initiative utilizes the Product Circularity Indicator (PCI) to demonstrate that motors incorporating 100% recycled or reused magnets can achieve significantly higher circularity scores (up to 59.78%) compared to those using virgin materials.

- Textiles, Wood, and Composites:

The textile and forestry sectors are undergoing a transition from traditional linear models to sophisticated "closed-loop" and "cascade" systems. The textile industry is a major pillar of this research, with projects like SCIRT, T-REX, and PRecycling addressing the technical and economic hurdles of "textile-to-textile" recycling for cotton, wool, polyester, and complex fibre blends. Similarly, the wood and forestry sector, supported by WOOD2WOOD and DigInTraCE, emphasizes the hierarchical reuse of timber and wood-based composites in furniture and construction before they are relegated to energy recovery. Complementing these materials is the study of fibre-reinforced polymers; the FiberEUUse project specifically tackles the mechanical challenges of recycling glass-fibre and carbon-fibre composites used in demanding industrial applications.

- Construction, Infrastructure, and Mineral Waste:

Addressing one of the largest waste streams in the EU, the construction and infrastructure sector focuses on the recovery of value from demolition waste. The Circ-Boost project leads this effort, focusing on the reuse of concrete, bricks, glass, and mineral-based materials. These initiatives explore the integration of recycled aggregates and industrial by-products, such as fly ash and slag, into new structural components and infrastructure. By turning construction and demolition waste (CDW) into secondary raw materials, these projects aim to reduce the industry's reliance on virgin minerals and lower the carbon footprint of the built environment.

- Bio-based Economy and Organic Valorisation:

The transition to a circular bio-based economy (CBBE) is represented by projects that convert organic waste into high-value products. CircularBiocarbon and CHEERS focus on valorising municipal solid waste, sewage sludge, and brewery side-streams like spent grain to produce biopolymers, biofertilizers, insect protein, and specialty chemicals. This work is supported by cross-sectoral projects such as SUSTRACK and SYMBA, which provide the overarching policy frameworks and systemic strategies needed to manage diverse biomass feedstocks. Together, these projects ensure that biological resources are managed sustainably throughout their lifecycle, from initial production to final recovery.

3.2.3. Typology of Solutions Developed

The portfolio moves beyond simple technology fixes to provide a holistic suite of circular enablers. Technological solutions include advanced sensor-based sorting using NIR and FTIR, molecular-level purification, chemical recycling pathways, and the development of high-performance mono-material structures. These are complemented by governance and regulatory solutions, such as the development of harmonised End-of-Waste criteria, protocols for by-product reclassification, and alignment frameworks for the complex interface between chemicals, waste, and product legislation.

Business model innovations within the portfolio include the prototyping of Product-as-a-Service models, the establishment of regional material hubs, and the design of circular procurement strategies for public authorities. Digital and standardisation tools are also prominent, featuring the creation of DPPs, standardised Technical Data Sheets for recyclates, and BIM-integrated material cadastres to ensure traceability and market trust. Social and behavioural interventions round out the portfolio, involving research into design for divestment, consumer acceptance of recycled content in sensitive applications, and storytelling strategies designed to increase the market value of secondary raw materials.

3.3. Key challenges addressed

3.3.1. Market Failures

The transition to circularity is fundamentally hindered by the economic disparity between sustainable materials and traditional linear models. Projects such as DigInTraCE, INCREASE, and PLAST2bCLEANED highlight a persistent price gap where the low cost and stable supply of virgin, fossil-based plastics frequently displace recycled content, while Circ-Boost notes that the construction sector consistently prioritizes cheaper, new materials over recycled demolition waste. This is compounded by high financial risks during the "valley of death" phase, the precarious transition from research to full-scale commercial deployment identified by MERLIN, which often deters private investment. Furthermore, WOOD2WOOD identifies a lack of economies of scale for waste wood, while CHEERS and CIRCULAR BIOCARBON describe a "chicken-and-egg" problem where novel bio-based products struggle because distribution infrastructure and downstream demand are not yet synchronized. In high-tech sectors like HEFT and SYMBIO, market failure manifests as a dangerous reliance on critical raw material imports and volatile bio-based feedstock prices, exposing European supply chains to significant geopolitical risks.

3.3.2. Regulatory Fragmentation

A major obstacle across all sectors is the lack of a harmonized legal landscape, which creates a disjointed market and administrative uncertainty. DigInTraCE, PRIMUS, FiberEUse, CHEERS, and CIRCULAR BIOCARBON all point to the "bottleneck" caused by the lack of standardized "end-of-waste" status and the slow, case-by-case reclassification of by-products. This fragmentation is exacerbated by the complex overlap between waste management laws

and chemical safety regulations like REACH, POPs, and CLP, which PRecycling and NONTOK note creates significant uncertainty for manufacturers of toys and home appliances. Furthermore, T-REX and SCIRT emphasize that the transition for textiles is slowed by the lack of a unified EU framework for the Ecodesign for Sustainable Products Regulation (ESPR), while LEX4BIO points to fragmented organic waste collection rules that prevent a unified European market for bio-based fertilisers.

3.3.3. Technical Barriers

Technical hurdles remain the most direct challenge to high-quality circularity, ranging from material performance to the complexities of data traceability. For plastic and electronic waste projects like PRecycling, NONTOK, and PLAST2bCLEANED, the primary difficulty lies in the sophisticated sorting and purification required to remove hazardous legacy additives and contaminants to meet strict safety levels, a challenge echoed by CIRCULAR FoodPack regarding food-contact materials. In the bio-based sector, New Wave and LUCRA face challenges with the heterogeneity of organic feedstocks, which often contain twice the impurities of industrial streams, making it difficult to scale processes like delamination or hydrogenation. These physical challenges are matched by digital ones; WOOD2WOOD, Circ-Boost, and NONTOK address the infrastructure needed for Digital Product Passports (DPP) and IoT platforms to track material quality, while HEFT struggles with material loss in complex electronic components and SUSTRACK identifies analytical errors in current decision models that make it difficult to prioritize circularity efforts.

3.3.4. Fiscal Measures

Economic uptake is slow largely because current financial incentives and tax structures are insufficient to bridge the "green premium" gap. SCIRT, T-REX, MERLIN, and CIRCULAR BIOCARBON advocate for the eco-modulation of Extended Producer Responsibility (EPR) fees to provide a tangible financial incentive for producers to design for recyclability, noting that current schemes often fail to effectively penalize non-recyclable designs. DigInTraCE notes that reaching high-performance levels with secondary materials is inherently "techno-economically" expensive, while PRIMUS highlights the need for systemic actions where the price gap is too wide for market forces to bridge alone. Additionally, PLAST2bCLEANED identifies high administrative costs for cross-border waste shipments as a hidden barrier. For primary producers, LEX4BIO notes that farmers lack the financial support to transition to bio-based fertilizers, especially when rising energy prices increase the operational costs of the biorefineries themselves, despite the public infrastructure investments mentioned by SYMBA.

3.3.5. Social and Behavioural Barriers

The success of the circular economy depends heavily on the "human element," including consumer trust and established industrial habits. INCREASE identifies "disgust sensitivity" and the fear of contamination as major psychological barriers to the acceptance of recycled plastics, while PRecycling emphasizes that maintaining high safety levels is the only way to build consumer trust for sensitive categories like children's toys. Beyond the consumer, LEX4BIO points to a lack of knowledge-sharing that prevents farmers from adopting new technologies. SCIRT calls for a broader shift away from "fast fashion" toward long-term stewardship, but this is hindered by what SYMBA calls "path dependency," where regions invested in traditional waste-to-energy systems resist moving toward higher-value upcycling. Finally, CIRCULAR BIOCARBON and SUSTRACK emphasize the need for cultural change to foster collaboration across siloed sectors and manage the social trade-offs inherent in shifting the agri-food chain.

4. Outcomes and impacts across the portfolio

4.1. Tangible results and knowledge generated

4.1.1. Technologies Validated

The project portfolio has successfully transitioned critical circular technologies from experimental pilot phases to validated industrial applications. This progress is particularly evident in sectors previously characterized by high unrecyclability risks. In the field of high-purity purification and sorting, the PLAST2bCLEANED and NONTOX projects have validated sensor-based sorting using near-infrared and Fourier-transform infrared spectroscopy, alongside dissolution-based recycling for waste electrical and electronic equipment plastics.

These technological interventions achieved a removal rate of over 99% for hazardous contaminants, such as brominated flame retardants, producing secondary resins like ABS and HIPS that comply with stringent safety standards. The innovation is particularly relevant for plastics arising from waste electrical and electronic equipment (WEEE), especially ABS and HIPS from appliance housings and mixed shredder fractions containing legacy brominated flame retardants. Within the WEEE Directive, this could be reflected by:

- Strengthening requirements for the selective treatment and separation of plastic fractions containing hazardous additives.
- Shifting policy emphasis from overall recycling tonnage to the quality of plastic recovery, i.e. recovery as polymer-grade material rather than energy recovery.
- Introducing qualitative performance benchmarks for contaminant removal in recycled plastic streams.

This would support the market uptake of high-purity secondary resins and better align WEEE implementation with circularity and chemicals objectives.

Structural performance equivalence was addressed through the Circ-Boost project, which validated the use of up to 100% recycled aggregate concrete. Pilots conducted across diverse European climates, specifically in Prague and Norway, confirmed that secondary materials can meet the mechanical and durability requirements established for virgin structural concrete.

To ensure structural performance equivalence and promote the uptake of recycled aggregates based on the Circ-Boost project, requirements should focus on technical standardisation and the elimination of regulatory barriers. Technical recommendations include mandating rigorous quality control to manage the variability in composition and contamination of recycled materials. Standardised Technical Data Sheets should be required to provide manufacturers with the statistical confidence needed to compare secondary aggregates against virgin benchmarks. Additionally, the integration of material data into Building Information Modelling (BIM) via material passports should be mandated to track structural assets throughout their lifecycle, ensuring they remain "bankable" for future recovery.

In the area of advanced barrier packaging, the Circular FoodPack initiative validated the application of double functional migration barriers in flexible food packaging. This utilises a "double migration barrier" system to safely incorporate up to 30% post-consumer recycled polyethylene (PE PCR) into food packaging. By sandwiching the recycled layer between functional barriers (such as coextruded EVOH or thin SiOx layers) the design effectively blocks contaminants and prevents "set-off migration" during storage. This "Design4Recycling" approach ensures the packaging remains compliant with EFSA safety standards while supporting the transition toward a circular, mono-material-based economy. This technological

breakthrough enables a 30% uptake of post-consumer recycled polyethylene in food-contact applications, representing a significant contribution toward the targets set by the Packaging and Packaging Waste Regulation (PPWR). Furthermore, the CHEERS project demonstrated the successful validation of bio-refining side-streams, transforming brewery residues into high-value precursors such as insect protein for animal feed and ectoine for the cosmetics industry.

4.1.2. Business and Governance Models Tested

The portfolio has prototyped the institutional and governance arrangements required to establish the economic viability of circular systems. Within the textile sector, the T-REX and SCIRT projects tested governance models for enhanced producer responsibility. These models utilise eco-modulation fees designed to bridge the current green premium price gap, with a typical range of 20-30%, between recycled and virgin fibres, according to the SCIRT project's analysis of the economic hurdles facing textile-to-textile recycling. This mechanism acts as a fiscal lever to internalize the environmental costs of virgin materials and reward circular design. The system creates a financial "reward and penalty" structure to equalize market prices:

- **Penalties for Linear Design:** Manufacturers of products that are difficult to recycle or made from virgin content are charged higher fees, essentially penalizing non-circular choices.
- **Subsidies for Circularity:** The revenues collected from these fees can be used to fund the development of national and regional sorting and purification hubs.
- **Market Alignment:** By implementing fee structures that reward verified post-consumer content, the "green premium" is neutralised, providing the economic "pull" signal needed to make recycled materials competitive.

In the textile industry, recycled fibres currently face a structural disadvantage because they are 20-30% more expensive than fossil-based virgin fibres. Under an eco-modulated EPR model tested by projects like T-REX and SCIRT, a brand using virgin polyester would pay a higher fee at market entry. These fees are designed to bridge the price gap, ensuring that garments made from recycled fibres can compete with cheaper, non-circular alternatives.

In the construction sector, the projects examined regional material cadastres. These models utilise digital marketplaces and regional hubs to facilitate the efficient exchange of secondary aggregates, marking a transition away from fragmented, project-specific waste management toward a systemic approach. Industrial symbiosis was further advanced through the CircularBiocarbon and CHEERS projects. These initiatives established governance frameworks that allow biorefineries to utilize municipal solid waste and industrial by-products as feedstock, thereby fostering necessary cross-industry collaboration between waste management entities and chemical producers.

Based on the recommendations and project findings, eco-modulation of Extended Producer Responsibility (EPR) fees is a mechanism designed to internalize environmental costs and close the "green premium" gap where virgin materials remain cheaper than recycled alternatives.

Concrete example of how this would function, drawing from the Textile and Plastic Packaging sectors are outlined below:

i. Textile Sector Example (SCIRT Set of guidelines and recommendations on key policy interventions)

In this scenario, a clothing brand pays a per-unit EPR fee for every garment placed on the market. The fee is "modulated" based on specific sustainability criteria:

- **Base Fee:** A standard rate applied to garments made from 100% virgin fossil-based polyester.
- **Fee Reduction (Bonus):** The brand receives a significant reduction in the fee if the garment contains a high percentage of textile-to-textile recycled content (e.g., recycled from old clothes) rather than non-textile sources like PET bottles.
- **Fee Reduction (Design for Circularity):** Additional discounts are applied if the garment is designed for durability and repairability or avoids "problematic fibre blends" that currently hinder high-quality recycling.
- **Fee Increase (Malus):** The brand pays a higher fee if the garment is difficult to recycle due to complex trims or chemical finishes that do not meet safety standards like REACH or OEKO-TEX.

ii. Plastic Packaging Example (CIRCULAR FoodPack Policy Brief "Can Flexible Food Packaging Go Circular?")

For a producer of flexible food packaging, the EPR fee is adjusted to incentivize the transition from waste management to high-quality secondary raw material production:

- **Base Fee:** Applied to complex, multilayer plastic packaging which is difficult to sort and often ends up in incineration.
- **Fee Reduction (Material Simplicity):** The fee is lowered if the producer switches to mono-material structures (like 100% Polyethylene) that are compatible with advanced mechanical and chemical recycling.
- **Fee Reduction (Safety and Tech):** Reductions are granted for using deinkable inks and removable adhesives, which achieve >99% purity in the recycling process.
- **Strategic Reinvestment:** modulated fees are a critical tool to finance advanced sorting and purification infrastructure (e.g., tracer-based sorting) required to produce food-grade recycled content.

The goal of these „policy correction mechanisms" is to shift the market so that incineration is no longer the cheapest option compared to circular recycling. By increasing fees for hard-to-recycle products and lowering them for circular designs, the system creates the long-term regulatory certainty brands need to invest in recycled material capacity.

4.1.3. Tools, Standards, Methodologies, and Data developed

The research projects have delivered the essential digital and regulatory infrastructure required to operationalize circularity across diverse value chains. A primary output involves the development and testing of DPP prototypes. These tools ensure the comprehensive traceability of material origin, chemical safety in compliance with the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), and the verification of recycled content percentages.

To address persistent market mistrust, the many of the projects in the portfolio developed standardised technical data sheets for recyclates:

PRIMUS: The PRE 1000 Standard:

The PRIMUS project focused on PRE 1000, which is described as a unified EU standard to determine the quality and general product safety of recyclates.

- Deliverable 1.2 serves as a guidance report for this standard, providing a structured way to document the properties of recycled plastics.
- This is particularly critical for bridging the gap between general safety and Food Contact Material (FCM) status, ensuring that recyclate properties are communicated transparently across the value chain.

DigInTraCE: SRM Quality Characterisation:

The DigInTraCE project developed standardized formats for characterizing materials under Deliverable 5.1.

- It provides a "Secondary materials quality characterization" framework designed for the upgrade of materials for recycle and reuse.
- These documents act as technical data sheets that map the properties of secondary raw material (SRM) streams, such as those from the brewery or electronics industries, to ensure they meet the specific requirements of industrial processes.

PRecycling: Material Inventory and Characterisation:

The PRecycling project produced Deliverable 1.1, which provides an "Inventory and characterization of the EoL PWS (End-of-Life Plastic Waste Streams)."

- These documents function as technical data sheets for recycled plastics used in home appliances, toys, and textiles.
- They ensure that the secondary materials are characterized accurately enough to comply with safety and chemical regulations (like REACH and CLP) for sensitive consumer applications.

WOOD2WOOD: Digital Product Passports (DPP):

While specific to the wood sector, WOOD2WOOD (Deliverable 16.4) developed technical descriptors for Digital Product Passports.

- These passports serve as a "digital data sheet," capturing the technical specifications and quality of waste wood to ensure it remains a "bankable asset" for cascading upcycling rather than being downcycled.

This infrastructure provides manufacturers with the data necessary to compare secondary materials against virgin benchmarks with high levels of statistical confidence. Additionally, for the built environment, tools were developed to integrate material passports directly into building information modelling. This enables a digital twin approach to life-cycle management, allowing for better tracking of materials throughout the lifespan of a structure.

4.1.4. Knowledge on environmental and socio-economic assessment and deployment possibilities generated

Comprehensive assessments were generated to provide a roadmap for the deployment of circular solutions. Life cycle assessment research quantified the environmental dividends of circularity, highlighting for example, that:

- Replacing virgin polyethylene with high-quality post-consumer recycled content in flexible packaging can achieve a 56% reduction in carbon dioxide emissions (CIRCULAR FoodPack).
- That using 100% recycled aggregates in structural concrete significantly reduces primary raw material extraction and diverts massive waste volumes from landfills while maintaining mechanical parity with virgin concrete (CircBoost).
- High-purity recovery of technical plastics, ABS and HIPS, via advanced purification removes over 99% of hazardous legacy substances, preventing the incineration of contaminated electronics waste (DigInTraCE and PRecycling).
- That transforming industrial side-streams, such as brewery residues, into high-value precursors for animal feed and cosmetics maximizes carbon savings compared to using primary biomass (DigInTraCE).
- That molecular-level recovery of construction materials ensures that secondary resources remain "bankable assets" within a circular loop rather than being downcycled into lower-value applications (Circ-Boost).

Socio-economic research identified deep-seated behavioural barriers, specifically the consumer perception gap regarding the safety of recycled materials in food-contact and construction applications. The findings suggest that transparency regarding molecular-level purification processes is essential for securing market acceptance. Finally, strategic mapping through the SUSTRACK and CircularBiocarbon initiatives identified specific geographic and industrial clusters within the Union where bio-based and recycled material production can be most efficiently scaled, providing a clear evidence base for future regional investment.

4.2. Impact assessment

4.2.1. Environmental Impacts

The projects offer quantified evidence of the environmental benefits derived from shifting from linear to circular systems, primarily through the reduction of resource extraction and the mitigation of carbon emissions. Life cycle assessments conducted under the Circular FoodPack project demonstrate that substituting virgin polyethylene with high-quality post-consumer recycled content in flexible packaging results in a 56% reduction in greenhouse gas emissions.

Regarding waste diversion and resource efficiency, the Circ-Boost project demonstrated significant potential for diverting construction and demolition waste from landfills by utilising 100% recycled aggregates. This practice substantially reduces the demand for primary raw materials in structural applications.

Furthermore, the management of legacy substances has been improved through projects like PLAST2bCLEANED and NONTX, which remove over 99% of hazardous substances from the plastic stream, thereby preventing the recirculation of toxins. While the shift toward bio-based feedstocks in the CHEERS and CircularBiocarbon projects serves as a lever to reduce fossil carbon reliance, the findings emphasize that land use impacts must be mitigated by prioritising industrial side-streams over primary biomass.

4.2.2. Economic Impacts

The assessment identifies a tension between the creation of long-term markets and immediate challenges to competitiveness. A significant economic barrier remains the green premium, where recycled fibres in the textile sector face a 20-30% price gap compared to virgin alternatives. Without the implementation of economic levers such as eco-modulated producer responsibility fees, circular products remain at a distinct disadvantage.

However, the report notes that mandatory recycled content quotas under the ecodesign and packaging regulations provide the regulatory certainty necessary to unlock private investment in advanced sorting and purification infrastructure. Conversely, administrative burdens arising from regulatory fragmentation regarding end-of-waste criteria and by-product status continue to impose high costs and legal risks, particularly for small and medium-sized enterprises. Despite these hurdles, new value chains are emerging, as seen in the CHEERS project, which demonstrates the economic valorisation of brewery side-streams into high-value precursors, creating fresh revenue streams within the bioeconomy.

4.2.3. Social and Behavioural Impacts

The social dimension of the circular transition centres on trust, transparency, and the divestment phase of the product lifecycle. A documented perception gap exists regarding the safety of recycled materials in packaging and construction. Policy officer insights suggest that clear communication regarding the sophistication of molecular-level purification is vital for shifting social acceptance.

The research also advocates for a paradigm shift in the customer journey by focusing on the divestment phase. Rather than centring exclusively on purchase and use, companies must treat the way a consumer parts with a product as an integral social behaviour that requires incentives through design. Furthermore, consumer choice architecture research indicates that behavioural responses are varied; while some consumers respond well to storytelling regarding a product's past identity, others prefer a silent green approach where circularity is treated as a background quality standard. Finally, the transition necessitates a shift in the labour market toward circular skillsets in areas such as advanced sorting, chemical recycling, and digital material tracking.

In conclusion, while the environmental gains are technically validated and substantial, economic feasibility remains contingent upon legislative interventions, such as quotas and taxation, to correct existing market failures. The success of these measures is fundamentally linked to social acceptance and the successful harmonisation of the regulatory interface between waste, chemicals, and product safety.

5. Success and failure analysis

5.1. Enabling factors

5.1.1. Conditions Enabling Successful Circular Solutions

The analysis identifies several critical conditions that allow circular projects to move from pilot phase to market-ready applications. Technical performance equivalence is a primary requirement, as success is predicated on the ability of secondary raw materials to meet or exceed virgin material benchmarks. For instance, the Circ-Boost project demonstrated that 100% recycled aggregate concrete can achieve structural parity with traditional concrete, while Circular FoodPack proved that 30% PE PCR is technically viable for food-contact packaging when paired with functional migration barriers.

Traceability and data transparency also act as foundational success factors. The implementation of DPPs and standardised Technical Data Sheets mitigates the trust deficit by providing verifiable data on material origin, chemical safety in compliance with REACH, and recycled content percentages.

Furthermore, operational scalability is often linked to the creation of regional material cadastres or hubs. In the construction and bio-based sectors, these hubs aggregate supply and demand, ensuring that recyclers have a consistent volume of feedstock, and that off-takers have a reliable supply of secondary materials. Finally, consumer engagement in the divestment phase is essential. Projects that treat the end-of-life phase as a core part of the customer journey, designing specifically for how a consumer parts with a product, see higher recovery rates. Success here is driven by a design for divestment approach, making the return or collection process as frictionless as the initial purchase.

5.1.2. Regulatory, Market, Technological, Organisational Drivers

The portfolio identifies specific drivers across four domains that catalyse the uptake of recycled and bio-based content. From a regulatory perspective, binding recycled content targets under the Ecodesign for Sustainable Products Regulation (ESPR) and PPWR are cited as the single most effective driver, providing the regulatory certainty required to unlock long-term capital investment. The establishment of EU-wide End-of-Waste criteria is a primary driver for the transboundary movement of materials, effectively turning waste into a tradable commodity.

Additionally, green public procurement serves as a lead market driver, particularly in construction, by mandating the use of recycled aggregates in infrastructure projects.

Market and economic drivers include eco-modulated producer responsibility fees, which act as a critical fiscal driver by rewarding design for recycling and penalizing difficult-to-recycle products. This helps bridge the 20-30% price gap between recycled and virgin fibres. The internalization of externalities, such as the anticipation of a fossil carbon tax, also drives companies to switch to bio-based and recycled feedstocks to future-proof supply chains against rising carbon costs.

Technological drivers are centred on advanced sorting and purification. Technologies such as NIR or FTIR sensor-based sorting and dissolution-based recycling allow for the removal of over 99% of contaminants and legacy substances, enabling the use of post-consumer waste in high-performance or food-grade applications. Parallel to this, mono-material innovation simplifies the recycling process and improves the quality of the resulting recyclate.

Organisationally, success depends on industrial symbiosis and cross-sectoral alignment, where waste managers, chemical producers, and brand owners synchronize their operations. Communication strategies have also shifted from generic sustainability claims to storytelling or silent green approaches that focus on performance to better align circular offerings with specific consumer segments.

5.2. Hindering factors

5.2.1. Factors Limiting Performance, Uptake, or Scalability

A series of systemic drags prevent circular solutions from reaching industrial scale or competing effectively with linear models. The green premium remains a primary barrier, with recycled fibres and plastics often costing 20-30% more than virgin alternatives. In the absence of fossil carbon taxes, these materials remain economically unattractive for mass-market applications. Contamination and the presence of hazardous legacy substances, particularly in the electronics and construction sectors, severely limit the volume of material that can be safely recirculated, as high-purity purification remains energy-intensive and costly.

Infrastructure disconnects also persist, with a notable lack of advanced, high-efficiency sorting and purification facilities within the Union. While mechanical recycling is mature, it often results in downcycling, and the high-value chemical or molecular recycling required for food-grade quality currently lacks necessary scale. Furthermore, quality inconsistency and perceived technical risk cause manufacturers to revert to primary materials to ensure production stability. This is compounded by supply chain fragmentation and a lack of standardized Technical Data Sheets, which leads to information asymmetry and stalls the development of a transparent market.

5.2.2. Legislative Burdens and Implementation Gaps

Current regulatory frameworks often unintentionally act as barriers due to fragmentation and a lack of coherence. The lack of harmonized EU-level End-of-Waste criteria for complex materials is a major systemic bottleneck, as materials remain legally classified as waste, triggering burdensome compliance requirements under the Waste Shipment Regulation. There is also a significant implementation gap at the waste-chemicals-product interface, where rigid limit values under REACH or Persistent Organic Pollutants (POP) regulations can effectively ban the recycling of entire material streams.

A primary example of this regulatory conflict is found in the management of technical plastics from WEEE. Projects such as PLAST2bCLEANED and NONTOX have validated advanced purification and dissolution-based recycling technologies capable of removing over 99% of hazardous legacy substances, such as brominated flame retardants, from plastic streams. However, because current REACH and POP regulations often fail to distinguish between intentionally added chemicals and these trace legacy substances, rigid limit values can render the resulting high-purity resins, like ABS and HIPS, non-compliant. Consequently, entire material streams that have been technically purified to meet stringent safety standards are frequently diverted to incineration rather than being recirculated into the economy.

Administrative hurdles for by-products also prevent immediate valorisation, as the process for reclassifying industrial side-streams is often slow and inconsistent across different national authorities. I.e., chemical safety thresholds are too rigid to accommodate the trace impurities inevitable in recycled materials, even when those materials have undergone sophisticated molecular purification. Furthermore, a lack of harmonised definitions for key terms leads to policy gaps that may favour less sustainable pathways. A primary example of a key term lacking a harmonised definition is "recycled content," which currently remains too generic to prevent suboptimal environmental outcomes. This ambiguity creates a policy gap in the textile sector, where there is no regulatory distinction between high-value textile-to-textile recycling and the use of non-textile feedstocks, such as polyester garments made from plastic bottles. Finally, verification and traceability gaps persist; while Digital Product Passports are seen as a solution, their current absence makes it difficult to credibly enforce mandatory recycled content quotas or prevent greenwashing regarding the origin of feedstocks.

5.3. Common features of successful solutions

5.3.1. Good Practices and Innovative Solutions

The core technical feature is achieving performance and safety parity with virgin materials. This is accomplished through advanced molecular purification that removes over 99% of hazardous substances and the use of "double functional migration barriers" to ensure food-contact safety. Additionally, the valorisation of industrial side-streams (like brewery residues) and the integration of material data into Building Information Modelling (BIM) ensure that materials remain valuable, high-purity assets rather than being downcycled.

5.3.2. Minimum Enabling Conditions

Success depends on a baseline of non-negotiable requirements, specifically digital traceability, and regulatory certainty. Tools like Digital Product Passports and standardised Technical Data Sheets are essential for providing the verification needed by industrial off-takers. Furthermore, mandatory recycled content quotas are identified as the primary catalyst for investment, while regional material hubs are necessary to ensure the stable, high-volume supply of feedstock required for economic viability.

5.3.3. Transferable and Replicable Design Principles

Universal design strategies focus on simplifying the recovery process and enhancing user engagement. This includes mono-material simplification to improve recyclate quality and safe-by-design principles to eliminate toxins early in the product lifecycle. Strategically, successful projects utilize design for divestment" to make returning products frictionless for users and apply context-specific communication, using "silent green" messaging for B2B performance products and storytelling for consumer goods to drive demand.

6. Upscaling, Replication, Transferability

6.1. Replication Potential

The project portfolio demonstrates significant replication potential by establishing modular circular interventions that can be adapted beyond their original industrial sectors. Cross-sectoral technology transfer is a primary driver of this potential. Technologies validated in specific contexts, such as the dissolution-based recycling and near-infrared or Fourier-transform infrared sensor-based sorting proven for electronic waste plastics in the NONTOX and PLAST2bCLEANED initiatives, are directly transferable to the automotive and textile industries. These methods allow for the recovery of high-purity polymers from complex and contaminated waste streams across different value chains.

Geographic scalability is further facilitated through the regional material hubs and cadastres model tested in the construction sector under the Circ-Boost project. This decentralized approach is highly replicable across all Member States, as it enables the aggregation of fragmented waste streams, such as demolition waste or municipal bio-waste, at the local level. Such a model serves to reduce both transport costs and associated carbon emissions.

Furthermore, the development of harmonized governance frameworks, including digital product passports and standardized technical data sheets, provides a universal language for circularity. Once these digital infrastructures are established, they can be deployed across the Union to facilitate the frictionless transboundary trade of secondary materials. Finally, the success of cascading bio-refineries, as seen in the valorisation of brewery side-streams in the CHEERS project, provides a blueprint for other food and beverage sub-sectors, such as the dairy or wine industries, to implement industrial symbiosis.

6.2. Limits and risks

Despite high replication potential, several ceiling effects and risks may impede upscaling efforts. A major challenge is the lock-in of linear infrastructure. Existing large-scale investments in waste-to-energy and incineration plants in certain Member States create an economic environment where the incentive to burn waste remains higher than the incentive to recover high-quality materials. Additionally, technical performance ceilings present a risk. While pilot projects demonstrate success, upscaling to 100% recycled content is often limited by material fatigue. In the textile sector, for example, fibres can only undergo mechanical recycling a finite number of times before losing the tensile strength necessary for high-quality garment production.

Supply chain vulnerabilities also exist when relying on secondary raw materials, particularly regarding feedstock consistency. Unlike virgin markets, circular markets are susceptible to fluctuations in waste quality and seasonal availability, which can disrupt industrial-scale production lines, especially for bio-based inputs. Furthermore, there is a risk of greenwashing if upscaling occurs without robust verification. Without the mandatory and immediate deployment of digital product passports, there is a danger that unverified claims regarding recycled content will undermine consumer trust and market stability.

6.3. Estimated impacts of EU-wide deployment

Based on the extrapolation of pilot results, the following matrix summarizes the estimated impacts of deploying these circular solutions at an EU-wide scale:

- **Environmental:** Potential 56% reduction in CO2 emissions for the plastics packaging sector; significant reduction in primary aggregate extraction and landfilling of CDW.
- **Economic:** Creation of a lead market for secondary raw materials; potential reduction in "green premiums" as advanced recycling technologies (chemical/ molecular) reach economies of scale.
- **Regulatory:** Elimination of the "waste" stigma for high-purity recyclates through harmonized End-of-Waste criteria, facilitating a frictionless Internal Market.
- **Technological:** Shift from low-value mechanical "downcycling" to high-value molecular-level recovery, enabling fibre-to-fibre and food-grade plastic loops.
- **Social:** Transition to a "Design for Divestment" culture where the end-of-life phase is as institutionalized as the purchase phase; increased public trust via certified safety data.

In conclusion, the fundamental takeaway for policy deployment is that upscaling must focus on qualitative infrastructure development rather than a mere increase in volume. For the upcoming Circular Economy Act to be successful, it must move beyond the support of isolated pilots and prioritize the mandate of digital and fiscal frameworks, such as digital product passports and eco-modulated extended producer responsibility, to ensure these validated solutions become the default industrial standard.

7. Regulatory insights for the Circular Economy Act

7.1. Regulatory gaps identified

The project portfolio provides clear evidence that while existing frameworks such as the Ecodesign for Sustainable Products Regulation and the Packaging and Packaging Waste Regulation establish a solid foundation, several critical regulatory blind spots remain. These gaps must be addressed to ensure the upcoming Circular Economy Act effectively transitions the Union from a waste management logic toward a high quality secondary raw material economy:

- The absence of unified, Union level end of waste criteria for complex material streams, specifically textiles, multi-layer plastics, and composites, represents the most significant gap. Currently, high purity secondary materials often remain legally classified as waste during transboundary movement, triggering burdensome compliance with the Waste Shipment Regulation. This creates a systemic bottleneck that prevents the scaling of recycling industries. Furthermore, in the absence of harmonised rules, Member States apply divergent interpretations, leading to a fragmented internal market where a material may be considered a product in one jurisdiction but waste in another (**DigInTraCE**, **PRIMUS**, **PLAST2bCLEANED**, **FiberEUse**, **MERLIN**, **Circular Biocarbon**, **SYMBIO**, **CHEERS**).
- The current regulatory framework creates a vacuum for the intermediate "pre-processing" phase in the textile sector, as it fails to provide formal definitions or standards for the sorting, cleaning, and preparation stages required for fibre-to-fibre recovery. This ambiguity places sorted textile waste in a legal "grey zone," where it lacks a clear status as either a waste fraction or a manufacturing-ready feedstock, thereby stalling the large-scale industrial investment needed for sorting infrastructure. To rectify this, the Circular Economy Act must establish material-specific Union regulations and harmonised technical standards that clearly define when these pre-processed fractions cease to be waste, providing the legal certainty necessary for frictionless trade and infrastructure scaling (**T-REX**, **SCIRT**).

- Another major blind spot is the insufficient alignment at the waste, chemicals, and product interface. There is a lack of coherence between REACH or Persistent Organic Pollutants regulations and circularity targets. Current legislation often fails to distinguish between intentional chemicals and legacy substances found in recycled streams. Rigid limit values can effectively ban the recycling of entire batches of electronic waste plastics or construction materials, even when the risk in a second life application is proven to be low (**DigInTraCE, PRecycling**).
- In the electronics value chain, technical plastics from e-waste often contain brominated flame retardants; although projects like **PLAST2bCLEANED** and **NONTOX** have validated that purification can remove over 99% of these contaminants, rigid REACH and POP regulations fail to distinguish between intentional additives and trace legacy substances, legally mandating incineration. Similarly, the construction sector faces barriers where recycled aggregates, proven by the **Circ-Boost** project to meet the structural parity of virgin concrete, are "effectively banned" or diverted to landfills due to diverging national End-of-Waste criteria and substance rules that ignore the proven structural parity with virgin content. Beyond end-of-waste criteria, the project identifies CPR, REACH, and POP as critical barriers that impose rigid safety and performance standards, often forcing the landfilling of structurally sound recycled aggregates due to uncoordinated rules on chemical legacy substances and CE marking requirements.
- The scope of recycled content definitions is also considered too generic, which may unintentionally favour suboptimal environmental outcomes. There is an insufficient regulatory distinction between textile-to-textile recycling and the use of non-textile feedstocks, such as polyester garments made from plastic bottles. This allows the textile industry to draw high quality recycled plastics away from the packaging sector's closed loop systems. For the bioeconomy, the lack of mandatory reporting and standardised verification for bio-based content leads to market confusion and potential greenwashing (**T-REX, SCIRT, WOOD2WOOD, PRIMUS, SYMBIO, SYMBA, SUSTRACK, CIRCULAR BIOCARBON**).
- Current consumer facing legislation focuses on the purchase and use phases while neglecting the divestment phase of the customer journey. There are no specific regulatory requirements for design for divestment, meaning products are not yet mandated to be designed to facilitate the collection and sorting limitations of end-of-life infrastructure. Finally, the framework lacks sufficient pull mechanisms to address the 20-30% green premium of recycled materials. The absence of a Union wide fossil carbon tax or an aggressive eco-modulation framework for producer responsibility fees leaves recycled content at a structural economic disadvantage (**SYMBIO, SYMBA, LEX4BIO; CHEERS, HEFT, SUSTRACK, INCREASE, CIRCULAR BIOCARBON**).

7.2. Legislative and administrative burdens

7.2.1. Barriers Identified through Project Implementation

The practical implementation of these projects reveals a disconnect between circularity ambitions and granular administrative realities. The legal classification of materials as waste rather than products remains a pervasive burden. Under the Waste Framework Directive, purified flakes or pre-processed fractions often trigger the Waste Shipment Regulation, imposing exhaustive notification procedures, financial guarantees, and administrative delays that hinder the movement of feedstocks.

Under the Waste Framework Directive, purified materials like plastic flakes or shredded textiles often remain legally classified as "waste" rather than "products," triggering the stringent Waste Shipment Regulation (WSR) for cross-border movement. This classification forces circular businesses to navigate exhaustive Prior Informed Consent (PIC) procedures and provide costly financial guarantees for every shipment, creating administrative delays that do not apply to virgin raw materials. Without harmonized EU-level End-of-Waste (EoW) criteria, these secondary feedstocks remain trapped in a legal "grey zone" where they are treated as a liability in one jurisdiction and a resource in another, ultimately hindering the development of a frictionless, industrial-scale circular economy.

The paradox between REACH and waste legislation has also been identified as a critical conflict, particularly for technical plastics. Rigid limit values for legacy substances, such as brominated flame retardants (BFRs) found in ABS and HIPS resins, often lack de minimis thresholds for recycled content, effectively prohibiting the recycling of large material volumes even when sophisticated molecular purification is utilised. Additionally, the process to reclassify industrial side-streams as by-products is fragmented across Member States, creating prohibitive administrative overhead for small and medium sized enterprises. Approval delays for sensitive applications, such as the length of authorization processes for food grade plastics, further create high barriers for innovators trying to prove the safety of migration barriers.

7.2.2. How Regulatory Sandboxes Could Help

The project portfolio suggests that regulatory sandboxes could be a decisive tool for the Circular Economy Act to overcome these burdens by allowing innovations to be tested under supervision. Drawing on insights from PLAST2bCLEANED and NONTOX, these sandboxes could allow recyclers to operate under a temporary product status while validating new purification technologies, enabling the movement of materials without the full burden of the Waste Shipment Regulation, provided quality and safety benchmarks are monitored in real time.

A sandbox approach could also help define technical standards for the pre-processing stage in the textile value chain, bridging the gap between collection and fibre-to-fibre recovery. Regarding the chemicals and product interface, sandboxes could establish safe use pathways for materials containing legacy substances by testing specific applications where exposure risk is negligible. This would help calibrate more nuanced limit values for recycled streams. Finally, regulatory sandboxes provide an ideal environment to test the interoperability of digital product passports across different value chains, identifying minimum data requirements and administrative hurdles for enterprises before a full Union wide mandate is implemented.

8. Policy recommendations

8.1. Prioritisation logic

The following recommendations are structured according to a strategic prioritisation logic designed to maximise the efficacy of the upcoming EU Circular Economy Act. This logic ensures that policy interventions are not only ambitious but also technically grounded and administratively viable.

8.1.1. Impact Potential

Policy interventions are prioritised based on their capacity to decouple economic growth from resource consumption and carbon emissions across high-impact sectors. A primary consideration is the decarbonisation dividend; priority is given to materials where the shift from

virgin to secondary raw materials yields the highest carbon savings. The scale of material flows also dictates priority, with actions targeting construction and demolition waste as well as textiles being high-priority due to the massive, underutilised waste volumes. Finally, substitution capacity is assessed by the ability of secondary materials to achieve performance equivalence, ensuring they can replace virgin inputs in structural or food-contact applications without compromising safety.

8.1.2. Feasibility

The feasibility of these recommendations is anchored in the technology readiness levels and business models already validated by the project portfolio. Recommendations focus on market-ready solutions, such as dissolution-based recycling for technical plastics and pre-demolition audits for construction, which have moved beyond laboratory scales to industrial demonstration. Data-driven implementation is central to this feasibility, as the enforcement of mandatory quotas is directly linked to the deployment of digital product passports. These digital tools provide the necessary verification infrastructure to make enforcement administratively possible for both regulators and enterprises. Furthermore, economic bridging is achieved using eco-modulated producer responsibility fees to address the 20-30% green premium, ensuring circular solutions are economically competitive.

8.1.3. Urgency

The urgency dimension identifies critical bottlenecks requiring immediate legislative correction to prevent market stagnation. There is an urgent need to establish harmonised Union-level end-of-waste criteria to prevent secondary materials from being legally trapped as waste, which currently hinders transboundary trade. Similarly, immediate action is required to resolve the conflict between chemical regulations and circularity objectives.

Delaying the establishment of safe-use thresholds for legacy substances continues to lead to the incineration of material streams that could otherwise be purified. Finally, establishing mandatory recycled content quotas is essential to provide the regulatory signal needed to unlock private capital investment for high-capacity infrastructure.

8.1.4. Circular Economy Act Alignment

The recommendations are specifically aligned with the strategic pillars of the upcoming EU Circular Economy Act, intended to move beyond the existing ecodesign framework. This includes strengthening the internal market for secondary raw materials by creating a frictionless market for non-virgin inputs through harmonised criteria and reduced administrative burdens.

Alignment is also achieved by shifting the focus toward sustainable resource management and quality-based recovery, ensuring the Act supports closed-loop cycles rather than downcycling. Lastly, the recommendations support the Act's goal of global leadership by setting benchmarks for circularity through standardized technical data sheets and mandatory digital passports.

8.2. Prioritised recommendations

Drawing from the evidence provided by the project portfolio, the following recommendations provide direct, actionable inputs for the upcoming EU Circular Economy Act.

i. Harmonisation of End-of-Waste (EoW) Criteria for High-Value Fractions

The policy objective is to eliminate legal fragmentation and administrative burdens that treat secondary raw materials as waste during transboundary movement. This is highly relevant to the internal market and the waste-chemicals interface, specifically concerning textiles, plastics, composites, and WEEE. Evidence from projects such as T-REX and NONTOX identifies the

lack of Union-wide criteria as a systemic bottleneck that increases costs and delays investment. Actionable steps include:

- Develop material-specific Union regulations defining when pre-processed textile fractions and purified technical plastics cease to be waste.
- Like the Construction Products Regulation (CPR), the proposed Circular Economy Act could utilise harmonised technical standards to define "End-of-Waste" (EoW) criteria. This approach provides the legal certainty required for industrial off-takers to treat secondary materials as products rather than liabilities.
- Establish mandatory, harmonised technical standards for recycling-ready feedstocks to facilitate frictionless trade across Member States.

ii. Implementation of Progressive Mandatory Recycled Content Quotas

This recommendation aims to create guaranteed market demand and provide the long-term investment signals necessary to scale advanced infrastructure. It is relevant to ecodesign implementation and market-pull mechanisms for the textile, plastic, and construction sectors. Evidence from Circular FoodPack and Circ-Boost demonstrates that while technical equivalence is possible, a mandate is required to drive uptake. Actionable steps include:

- Introduce binding, sector-specific targets starting with 10-20% recycled content by 2030.
- Distinguish between closed-loop and open-loop inputs to ensure high-value materials are not diverted to lower-quality applications.

iii. Deployment of Digital Product Passports (DPP) for Material Traceability

The objective is to provide a verified, data-driven backbone for enforcing recycled content claims and ensuring chemical safety. This is a horizontal requirement for transparency and consumer empowerment across all sectors. Projects like SCIRT and PLAST2bCLEANED identify passports as the only credible tool to verify feedstock origin and ensure REACH compliance. Actionable steps include:

- Standardise the data architecture for passports, requiring mandatory disclosure of material origin and legacy substances.
- Integrate passport data with building information modelling in the construction sector to track structural material assets.

iv. Eco-Modulation of EPR Fees to Bridge the Green Premium

This involves using fiscal instruments to internalize the environmental costs of virgin materials, specifically for textiles and packaging. Research from SCIRT and T-REX reports a persistent price gap that voluntary action cannot overcome. Eco-modulated fees provide a mechanism to subsidize high-quality recycling through penalties on non-circular designs. Actionable steps include:

- Mandate Member States to implement fee structures that reward design for recycling and verified post-consumer content.
- Utilize fee revenues to fund the development of national and regional sorting and purification hubs.

v. Alignment of the Waste-Chemicals-Product Interface (Safe-by-Design)

The policy objective is to resolve contradictions between chemical safety and circularity to prevent the incineration of valuable materials. This is particularly relevant for electronic waste plastics and construction waste. Evidence shows that advanced purification can remove over 99% of contaminants, but rigid limits block market entry. Actionable steps include:

- Establish safe-use thresholds and challenge-test protocols that allow for de minimis concentrations of legacy substances in controlled applications.
- Adopt design for detoxification standards to phase out hazardous additives at the production stage.

vi. Institutionalisation of Design for Divestment

This recommendation shifts focus to the end-of-life phase by making product return an effortless consumer experience. This is relevant to social drivers and resource management in electronics, textiles, and packaging. Evidence suggests that circularity often fails at the divestment stage, requiring a paradigm shift in the customer journey. Actionable steps include:

- Mandate that manufacturers include clear end-of-life instructions and return pathways within the digital product passport.
- Provide incentives for product-as-a-service and take-back schemes that maintain producer ownership over the material loop.

vii. Fund development of national and regional sorting and purification hubs

To secure the supply of high-quality feedstocks for the 2030 targets, the EU must fund the development of Regional Circular Material Hubs to overcome the current fragmentation of waste streams. By centralizing advanced sorting and purification, these hubs aggregate sufficient volumes of secondary materials to achieve the economies of scale required for industrial-grade output. This infrastructure is essential to bridge the geographic gap between decentralized waste collection and the high-volume requirements of manufacturers.

- Aggregate regional feedstock to ensure a stable, high-volume supply of purified resins (ABS, HIPS) and textile fractions.
- Provide SMEs with shared access to molecular purification and detoxification infrastructure that is otherwise cost-prohibitive.
- Reduce the administrative burden of the Waste Shipment Regulation by processing materials closer to the source of generation.

9. Conclusions

The findings from the project portfolio confirm that the technical and industrial foundations for a high-performance circular economy are largely established. However, the transition from successful pilots to a systemic EU-wide reality depends on addressing the remaining regulatory and economic misalignments.

9.1. Key Messages for the Circular Economy Act

The upcoming Circular Economy Act represents a vital opportunity to move beyond product design and address the systemic infrastructure of the secondary raw material market. The evidence points to three essential priorities:

- Standardisation as a Market Enabler:** The lack of harmonised End-of-Waste criteria and technical data standards remains the primary obstacle to the free movement of secondary materials. The Act must provide a single European "legal identity" for high purity recyclates to eliminate the administrative burden of waste legislation for compliant materials.
- Mandating Demand through Quotas:** Technical parity with virgin materials has been proven in sensitive sectors, including food-contact packaging and structural construction. The Act must now transition from voluntary targets to mandatory recycled

- content quotas to provide the investment certainty required to scale purification and sorting infrastructure.
- iii. **Operationalising the Digital Product Passport:** The passport must be positioned not as a secondary reporting burden, but as the central verification tool for the internal market. It is the only viable mechanism for enforcing recycled content mandates and managing the chemicals-waste-product interface at scale. To effectively manage the chemicals-waste-product interface, the DPP must function as a tiered information system, providing tailored data to three primary stakeholder groups:
- **Manufacturers and Off-takers:** Require high-detail technical data, including chemical composition and precise recycled content percentages (pre- vs. post-consumer). Crucially, this includes verification of detoxification, confirming the removal of >99% of legacy substances like BFRs to ensure REACH compliance and the statistical confidence needed to replace virgin feedstock.
 - **Market Surveillance Authorities:** Require full "cradle-to-gate" traceability, including material origin tracking and compliance certifications. This access is essential for automating the enforcement of mandatory recycled content quotas and preventing "greenwashing" through verifiable, audit-ready data.
 - **Consumers and End-users:** Require simplified, scorable metrics accessible via QR codes or NFC. Data should focus on durability, repairability, and "Design for Divestment" instructions to make the return and recycling process frictionless, using storytelling to drive premium demand for circular goods.

Strategic Implications for EU Circular Economy Policy

The results of the portfolio suggest a fundamental shift in how the Union should approach circularity at a strategic level:

- i. **From Volume to Quality:** Strategic success should no longer be measured by bulk recycling rates but by the quality and "circularity potential" of the output. Policy must explicitly favour closed-loop systems (such as fibre-to-fibre and food-grade plastics) over traditional downcycling to preserve the economic and technical value of materials.
- ii. **Harmonising Safety and Circularity:** There is a critical need for a more nuanced approach to legacy substances. The "Safe-by-Design" principle must be balanced with pragmatic, risk-based thresholds for recycled materials in non-sensitive applications to prevent the unnecessary incineration of purified material streams.
- iii. **Internalising Environmental Costs:** As long as a 20-30% "green premium" exists, circularity will remain a niche market. EU policy must increasingly lean on fiscal drivers, such as eco-modulated EPR fees and the eventual integration of resource-based carbon accounting, to ensure that the "Polluter Pays" principle is fully reflected in material pricing.

The transition to a circular economy is now less a challenge of invention and more one of integration. By providing the digital, legal, and fiscal glue identified in these projects, the EU can ensure that its circular leadership translates into long-term industrial competitiveness and resource resilience.

10. Annexes

10.1. Annex I: Project Portfolio Matrix

#	Project Number	Project Name	Sector
1	101058670	PRecycling	Advanced Materials
2	101057067	PRIMUS	
3	101058487	INCREASE	
4	101091801	DigInTraCE	Energy-Intensive Industries
5	101138789	WOOD2WOOD	
6	101096306	HEFT	Transport CRMs
7	101060814	CHEERS	Bio-Based
8	101081823	SUSTRACK	
9	101135562	SYMBA	
10	101135166	SYMBIO	
11	818309	LEX4BIO	CBE JU
12	101023280	CIRCULAR BIOCARBON	
13	730323	FiberEUse	Composites (REA)
14	101003883	MERLIN	Plastics
15	820895	NONTOX	
16	821087	PLAST2BCLEANED	
17	101082068	CIRC-BOOST	Construction
18	101003806	CIRCULAR FOODPACK	Plastics
19	101060343	T-REX	Textiles
20	101003906	SCIRT	

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This report presents key findings from a project portfolio analysis conducted to generate evidence-based recommendations for the Circular Economy Act (CEA), with a specific focus on recycled and bio-based content and End-of-Waste criteria.

Evidence from EU-funded Research and Innovation projects demonstrates how the Circular Economy Act should harmonise End-of-Waste criteria, create strong market pull through recycled content quotas, deploy Digital Product Passports, and incentivise circular design. The report points to a broader shift in EU circular economy policy: from volume to quality, from voluntary action to mandated demand, and from fragmented regulation to system-wide integration.

Studies and reports

