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Integration of 10R principles into CIRCLE as an innovative tool for assessing circular economy

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This paper introduces the Circular Index for Resource Conservation and Loop-based Economy (CIRCLE), a novel metric designed to assess circular economy performance. Grounded in the 10R hierarchy, CIRCLE employs a structured point-based system (0–3) to evaluate practices across all R-principles, with particular emphasis on the often-overlooked dimensions of Rethink, Repurpose, and Resell. Unlike prior models, it enables a more granular and comprehensive assessment of resource efficiency, innovation, and value recovery. Adaptable across industries, systems, and scales, CIRCLE establishes clear scoring criteria, integrates theoretical foundations, and validates its applicability through three real-world case studies. These applications demonstrate the tool's capacity to distinguish levels of circular performance, identify sustainability gaps, and guide targeted interventions. CIRCLE is available as a user-friendly free tool at bit.ly/CIRCLE2026. By offering a standardized yet flexible framework, CIRCLE advances circularity assessment and provides a practical decision-support tool for sustainability science, industrial ecology, and policy development.

Sustainability spotlight

This work introduces CIRCLE as a novel 10R-based metric that provides a standardized, quantitative tool for assessing circular economy performance. By integrating the 10R principles in one framework, CIRCLE enables a holistic evaluation of resource efficiency, waste minimization, and value recovery across industries and scales. This innovative tool directly supports the UN's Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) by promoting sustainable resource management, and also contributes to SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action) by guiding targeted interventions that reduce environmental impact and foster resilient, low-carbon systems.

1. Introduction

The transition from a linear economy where resources are extracted, used, and discarded to a circular economy has become a fundamental strategy for achieving sustainable resource management.[1] A circular economy aims to minimize waste, maximize resource efficiency, and keep materials in continuous circulation for as long as possible. This approach is essential for mitigating environmental degradation, reducing dependency on newly extracted materials, and fostering long-term economic resilience.[1] Over the years, various models have been developed to advance circular economy principles, beginning with the widely known 3R model and evolving into more comprehensive frameworks intended to close material loops more effectively.[2,3]

The 3R model Reduce, Reuse, and Recycle has historically served as the foundation of sustainable waste management. It promotes minimizing resource consumption (Reduce), extending product life through repeated use (Reuse), and converting waste into new materials (Recycle). While influential, the 3R model does not fully capture the complexity of modern resource flows and waste streams.[4] Consequently, extended models such as 4R, 5R, 6R, 7R, and more recently 9R, have incorporated additional strategies to improve circularity. However, even these iterations leave critical gaps. Most remarkably, they lack explicit emphasis on innovation and economic value recovery, and they often exclude practical tools to measure circular performance quantitatively. Moreover, the absence of an integrated scoring mechanism limits their effectiveness for benchmarking and decision-making.[5] In our previous work, we introduced a set of metrics to address similar limitations in green chemistry

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assessments,[6–12] focusing on resource efficiency and waste minimization without being centered on the R principles.

To fill this gap and address these limitations, we introduce the Circular Index for Resource Conservation and Loop-based Economy (CIRCLE) as a 10R-based assessment tool designed to evaluate and quantify circular economy practices systematically. Unlike previous models, CIRCLE uniquely combines a comprehensive R-based hierarchy with a weighted scoring system, providing a single, interpretable circularity score. This score reflects the degree to which a system or process embodies circular economy principles, enabling clear comparisons, progress tracking, and performance optimization. The inclusion of 10-Rs further distinguishes CIRCLE by incorporating innovation and economic valorization two often overlooked pillars of sustainability.

A core advantage of CIRCLE is its user-friendly design. The tool is structured for accessibility by policymakers, industries, researchers, and sustainability practitioners alike, enabling rapid adoption without sacrificing analytical rigor. This work presents the conceptual development, methodology, and real-world application of the CIRCLE metric, demonstrating its utility as a standardized yet adaptable instrument for evaluating circularity across sectors. By enabling both qualitative insights and quantitative scoring, CIRCLE strengthens decision-making in sustainable design, resource management, and circular economy implementation.

2. CIRCLE – Circular Index for Resource Conservation and Loop-based Economy

In response to the limitations inherent in traditional circular economy models, the CIRCLE tool emerges as a comprehensive, metrics-based system designed to holistically evaluate circular economy practices. Grounded in the 10R hierarchy, CIRCLE introduces a more expansive view of resource management by incorporating less conventional but increasingly relevant principles such as Rethink, Repurpose, and Resell alongside the classic Rs (Fig. 1). This expanded scope enables a more robust analysis of how materials and products are managed throughout their life cycles. The metric functions as a weighted scoring tool that allows organizations, practitioners, and policymakers to quantify, compare, and enhance their sustainability strategies. By assigning scores based on the depth and effectiveness of each practice, CIRCLE advances informed decision-making in domains such as sustainable product design, resource optimization, and waste reduction, aligning closely with the core objectives of the circular economy.

Each R within the CIRCLE tool is individually assessed using a structured scoring system (typically ranging from 1–3) Table 1, reflecting the degree to which the principle is implemented. The first principle, Refuse, represents a forward-looking commitment to eliminating the use of hazardous materials during design and manufacturing stages. This preventive approach fosters innovation while prioritizing safety and environmental integrity. The scoring for Refuse is based on the extent of hazardous substance avoidance: full avoidance (3), partial avoidance (2), usage without consideration (1), and not applicable. Principles such as Rethink and Reduce emphasize the importance of innovation and resource efficiency by encouraging organizations to redesign processes and minimize material consumption. Reuse, Repair, and Refurbish focus on extending the life of products through repeated use, functional restoration, or performance upgrades. Recycle remains central, aiming to recover and reintegrate materials into the production cycle, while Rot highlights the sustainable management of biodegradable waste. Meanwhile, Repurpose supports the creative transformation of discarded materials for new applications, and Resell promotes product longevity through secondary use. Together, these strategies offer a comprehensive lens for evaluating sustainability performance across diverse systems and will be analyzed further to understand their individual roles and scoring criteria.

To calculate the final total score, the CIRCLE metric employs a two-stage scoring process to ensure both precise evaluation and intuitive visualization. The fundamental assessment of each R-principle is conducted using a discrete integer scale from 1 to 3, as detailed in Table 1, where specific criteria define the performance levels corresponding to each score. This 1–3 scale provides a clear and straightforward rubric for evaluators. These raw scores are subsequently normalized to a 1–10 scale by multiplying the raw score by a factor of 10/3. Consequently, a top score of 3 translates to a normalized 10, a score of 2 becomes approximately 6.7, and a score of 1 becomes approximately 3.3. This normalized 1–10 scale is used to generate the illustrative diagrams, allowing for a consistent and maximized visual profile where each principle contributes equally to the diagram. The final score, expressed as a percentage from 0 to 100, is then calculated by summing all normalized scores for applicable principles and dividing by the maximum possible normalized score, which is 10 multiplied by the number of applicable principles. This methodology ensures that principles deemed Not Applicable (NA) do not penalize the overall score, thereby providing an accurate and fair representation of circularity performance within the defined system boundary.

For each application of CIRCLE the analyst must declare the assessment boundary (*e.g.*, product, process, plant, site, product-family, or value chain). CIRCLE scores are only interpreted within that declared boundary. An R-principle may be assigned NA only when all three of the following conditions are met:

No relevant item, material, or process within the declared system boundary can reasonably be the subject of that principle (*e.g.*, Rot for an entirely inorganic chemical process with no biodegradable streams). The principle cannot meaningfully influence circular performance of the system as scoped (*e.g.*, Resell for a single-use reagent consumption process, where no product is produced or circulated). There is insufficient or non-existent information within the declared boundary to assess the principle even qualitatively If any of these conditions is not met the principle must be scored using the rubric. The NA option is therefore a last-resort category used to preserve CIRCLE's flexibility while preventing inappropriate omission of relevant circular strategies. Validation efforts involve independent evaluators

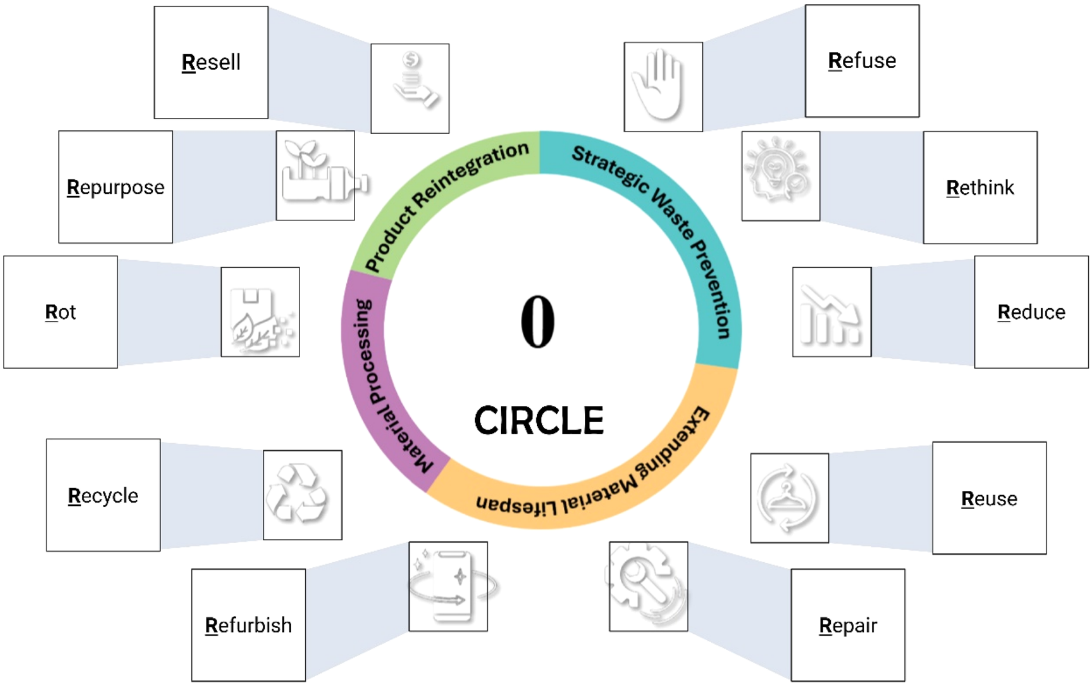

Fig. 1 CIRCLE metric with description of the 10-Rs.

applying the CIRCLE tool to the same case studies in order to assess scoring consistency and inter-user reliability. This step supports enhanced robustness and improve accuracy and precision.

The application of the CIRCLE metric is illustrated through four representative scenarios that reflect different patterns of alignment with the 10R principles. In the first case Fig. 2a, all principles are fully satisfied, resulting in a maximum CIRCLE-SCORE of 100. This all-green profile reflects an ideal circular system where hazardous substances are eliminated, resources are minimized, reuse and recycling are maximized, and economic value recovery is ensured. In contrast, the second case Fig. 2b

Table 1 The points system of the proposed CIRCLE metric

		Scoring criteria		
Principle	Core idea	3	2	1
Refuse	Avoid hazardous materials in design and production	All hazardous substances avoided	Some avoided	Used without consideration
Rethink	Innovate to minimize waste and extend product life through redesign	Novel internal solutions implemented	Adopted external innovations	Conventional approaches without innovation
Reduce	Minimize resource and material use	Measurable resource efficiency in core operations	Partial reduction	No proactive reduction
Reuse	Extend life of materials/products through repeated use	Maximum reuse, no new inputs	Partial reuse	No reuse (single-use only)
Repair	Restore functionality to extend product life	Fully repaired	Partially repaired	Not repaired
Refurbish	Upgrade products to like-new condition to extend usability	Fully refurbished (like-new)	Partially refurbished	No refurbishment
Recycle	Process materials to reduce waste and preserve resources	Full recycling, high-quality material recovery	Partial recycling	No recycling
Rot	Sustainably compost biodegradable materials	All composted	Partial composting	No composting
Repurpose	Creatively reuse discarded materials for new functions	Fully repurposed	Some repurposed	None repurposed
Resell	Extend product life through resale	Actively resold and reused	Viable but unsold	Not resellable

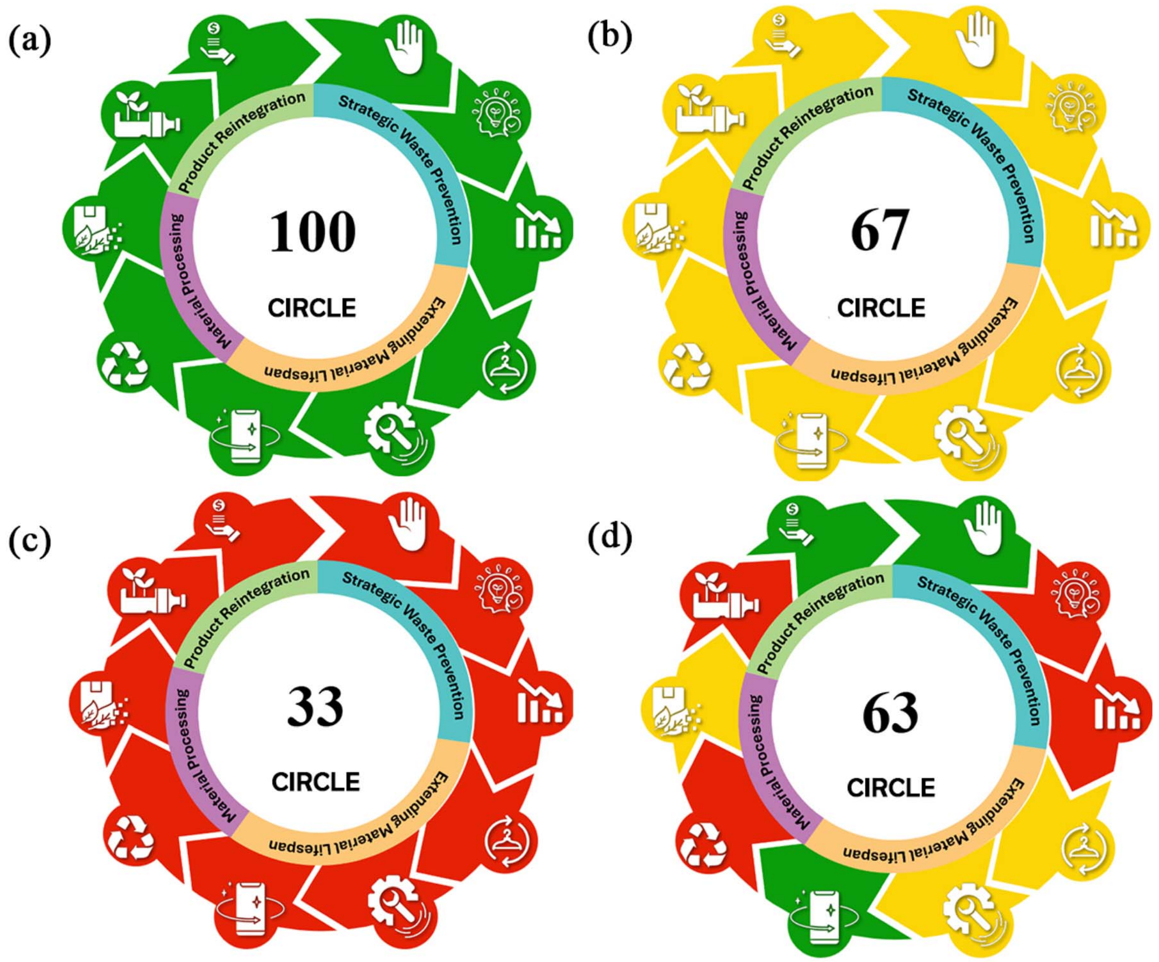

Fig. 2 Illustrative application of the CIRCLE metric (CIRCLE-SCORE) across four scenarios. (a) Full compliance with all 10-R principles, achieving a maximum score of 100 (ideal all-green profile). (b) Uniform partial compliance, reflected in a yellow profile and an intermediate score of 67. (c) Minimal adoption of circular strategies, resulting in an all-red profile and a low score of 33. (d) Mixed adoption, with strengths in some principles and weaknesses in others, yielding a score of 63.

represents a system where all principles are moderately addressed, yielding a uniform yellow profile and a score of 67. Here, partial adoption across the 10-Rs achieves measurable but suboptimal circularity, highlighting the common situation of incremental progress without systemic redesign. The third case Fig. 2c shows a fully red profile with a score of 33, signifying minimal integration of the 10-Rs. Such systems remain strongly aligned with linear economy models, characterized by single-use practices, low recovery, and high environmental burden. The mixed case Fig. 2d produces a CIRCLE-SCORE of 63, reflecting uneven adoption across principles. Some dimensions, such as the avoidance of hazardous materials and product reintegration, are well implemented (green), while others remain weak (red) or intermediate (yellow). This heterogeneous pattern demonstrates how circularity performance is often fragmented in practice, with strengths in certain areas offset by deficiencies in others. Together, these cases underscore the diagnostic capacity of the CIRCLE tool to distinguish between ideal, partial, poor, and mixed circular strategies, while providing a clear roadmap for targeted improvement.

2.1. Refuse

Within the CIRCLE metric, the principle of Refuse represents a proactive commitment to avoiding the use of hazardous materials in industrial and chemical processes. This criterion supports safety, environmental responsibility, and sustainable innovation by encouraging the design of systems that minimize harm at the source. Closely aligned with circular economy goals, Refuse discourages the introduction of harmful substances into the production cycle, thereby reducing long-term risks to human and environmental health. The scoring within CIRCLE reflects varying levels of commitment to this principle: a score of 3 is awarded when hazardous substances are entirely avoided; 2 points are granted when some harmful materials are avoided but others remain; 1 point applies when hazardous materials are used without active consideration; and NA indicates that the criterion is not applicable.

2.2. Rethink

The Rethink principle in the CIRCLE metric advocates for the implementation of innovative strategies to minimize waste and extend product life. At its core, this principle challenges organizations to critically reassess and redesign their products and processes, fostering sustainability through systemic innovation and enhanced resource efficiency. It aligns closely with circular economy ideals by encouraging forward-thinking design that addresses waste prevention from the outset.

Scoring under the Rethink criterion reflects the level of innovation and integration. A score of 3 is awarded when novel solutions are created and implemented to maximize reuse, extend product durability, and minimize waste generation. A score of 2 recognizes the adoption of externally developed innovations that contribute meaningfully to sustainability, while a score of 1 applies when conventional approaches are followed without incorporating new environmentally driven improvements.

2.3. Reduce

Within the CIRCLE tool, the principle of Reduce centers on minimizing material and resource consumption as a foundational strategy for achieving sustainability and advancing circularity. This principle urges organizations to rethink their design and production processes, with the goal of optimizing resource use, reducing waste generation, and mitigating environmental impacts. The scoring system reflects the degree of effort made to reduce material inputs: a full score of 3 points is awarded when resource efficiency is embedded into core operations through measurable reductions in material use; 2 points are given when partial efforts are evident but excessive consumption persists; 1 point is assigned when no proactive reduction is pursued; and NA points are reserved for instances where the criterion does not apply.

2.4. Reuse

Within the CIRCLE metric, the Reuse principle emphasizes the repeated use of products, components, or materials to extend their functional life and decrease reliance on raw resources. This approach aligns closely with the broader goals of the circular economy by minimizing waste, conserving energy, and mitigating environmental impact. Scoring under the CIRCLE metric is structured to reflect the degree of reuse achieved: a score of 3 is assigned when reuse is maximized to the extent that the need for new material inputs is effectively eliminated; a score of 2 indicates partial reuse accompanied by continued reliance on new resources; a score of 1 reflects single-use practices with no evident reuse efforts; and NA applies when the criterion is not applicable to the process under evaluation.

By encouraging organizations to adopt strategies that prioritize the continued utility of materials, the CIRCLE metric fosters practices that reduce environmental burden while promoting resource efficiency and resilience in production systems.

2.5. Repair

The Repair principle, as articulated within the CIRCLE tool, emphasizes the restoration of product functionality to extend service life, thereby conserving resources, minimizing waste, and reducing reliance on new material inputs. It plays a central role in advancing circular economy goals by enabling the continued use of products and infrastructure rather than their premature disposal. Scoring in CIRCLE reflects the degree of functional recovery achieved: a score of 3 indicates that all defects caused by use have been completely repaired, restoring full functionality; a score of 2 denotes partial repair with incomplete restoration; a score of 1 applies when no repair has occurred and the product remains non-functional; and NA is assigned when the repair criterion is not relevant to the evaluated process.

By quantifying the extent of repairability, CIRCLE encourages organizations to adopt maintenance-oriented strategies that prolong product lifespans, mitigate environmental burdens, and foster more sustainable consumption and production systems.

2.6. Refurbish

Within the CIRCLE sustainability metric, the concept of *Refurbish* is central to promoting the renewal and functional upgrade of products, thereby extending their usable lifespan and minimizing environmental burdens. This principle aligns closely with the objectives of the circular economy, which advocates for reducing the consumption of new materials by keeping products in use for as long as possible. In this context, refurbishment is defined not merely as repair, but as a transformative process that restores an item to a "like-new" condition, both in appearance and performance.

The CIRCLE evaluation rubric distinguishes the degree of refurbishment by assigning scores based on outcome: a score of 3 is awarded when a product is fully refurbished to resemble and perform like new; a score of 2 reflects partial refurbishment with some outdated or degraded components; a score of 1 is given when no refurbishment is undertaken; and NA is reserved for cases where refurbishment is irrelevant to the process. This structured approach incentivizes comprehensive renewal strategies that restore value, reduce waste, and promote sustainable consumption patterns.

2.7. Recycle

Within the CIRCLE tool, the principle of Recycle underscores the implementation of thorough and effective material recycling strategies aimed at minimizing waste generation and conserving finite resources. This principle is deeply rooted in the circular economy ethos, which emphasizes the continuous circulation of materials through productive use cycles. By ensuring that recyclable materials are correctly separated and reprocessed, the Recycle criterion reduces dependency on raw resources and mitigates the environmental impacts associated with raw material extraction and disposal.

The scoring methodology within CIRCLE evaluates recycling efforts based on their comprehensiveness and effectiveness. A full score of 3 points is awarded when all recyclable materials are meticulously separated and properly processed, enabling their re-entry into production chains at a quality comparable to that of raw inputs. A score of 2 reflects partial recycling, where some materials are recovered while others are discarded. A minimum score of 1 is given when no recycling occurs, and recyclable materials are entirely wasted.

2.8. Rot

The Rot principle in the CIRCLE sustainability assessment metric emphasizes the responsible management of biodegradable materials through composting or other sustainable biological decomposition methods. This principle directly supports circular economy goals by reintegrating organic matter into the ecosystem, thereby reducing the burden on landfills and curbing greenhouse gas (GHG) emissions. By encouraging the return of nutrients to the soil and minimizing environmental degradation, the Rot criterion promotes a regenerative approach to waste management.

In CIRCLE, the Rot metric is assessed based on the effectiveness and completeness of composting practices. A score of 3 points is assigned when all biodegradable materials are sustainably composted or biologically decomposed. A score of 2 applies when only part of the biodegradable waste is treated, with a significant portion discarded unsustainably. A score of 1 reflects no composting at all, with biodegradable waste mixed with general refuse, and NA are reserved for processes where the Rot criterion is not applicable.

Evaluating adherence to the Rot principle encourages institutions and industries to adopt comprehensive composting systems that divert organic waste from landfills, enrich soil health, and contribute to climate mitigation. When fully implemented, composting can serve as both a waste diversion strategy and a restorative environmental practice, making it integral to a sustainable circular economy.

2.9. Repurpose

Within the CIRCLE sustainability assessment tool, the Repurpose principle underscores the innovative transformation of materials that would otherwise be discarded, assigning them new functions to extend their life cycle and reduce overall waste. This approach directly contributes to the goals of the circular economy by maximizing the utility of resources, minimizing environmental impact, and stimulating creative problem-solving in material reuse.

The CIRCLE evaluation of Repurpose is structured around the degree to which materials are creatively re-employed for new purposes. A score of 3 points is awarded when materials are fully repurposed into functional and valuable products. A score of 2 points applies when some materials are repurposed, but a significant portion is still discarded. A score of 1 is given when no repurposing occurs, and all materials are treated as waste. Finally, NA is reserved for cases where repurposing is not relevant to the process being assessed.

By assessing adherence to the Repurpose principle, CIRCLE encourages organizations, industries, and communities to implement imaginative and functional reuse strategies. Such initiatives reduce waste generation, conserve finite resources, and promote a more circular and resilient system of production and consumption. Moreover, effective repurposing not only diverts waste from landfills but also fosters economic value by converting discarded materials into productive assets.

2.10. Resell

The Resell principle in the CIRCLE sustainability metric emphasizes extending a product's lifecycle through its resale, thereby avoiding premature disposal and reducing environmental impacts. This strategy aligns with the circular economy's core objective of keeping products in use for as long as possible, thereby maximizing resource efficiency and minimizing waste. Resale not only prolongs the functional life of products but also creates opportunities for economic and environmental value recovery.

The CIRCLE metric evaluates the effectiveness of resale strategies based on the extent to which products are successfully reintroduced into circulation. A score of 3 points is assigned when a product is actively resold and continues to function in a new context. A score of 2 points applies when the product is in demand and viable for resale, but the transaction has not yet occurred. A score of 1 reflects situations where the product is unsuitable for resale due to poor condition or lack of market demand. NA is reserved when resale is not relevant to the assessed system.

By encouraging adherence to this principle, CIRCLE incentivizes both organizations and consumers to embrace resale practices. Such strategies conserve resources, reduce pressure on raw material extraction, and promote sustainable consumption patterns. As part of a broader circular economy strategy, resale contributes significantly to minimizing environmental impact while also supporting secondary markets.

3. Comparison with other metrics of circular economy

The landscape of circularity metrics is supported by specialized tools, each designed to tackle a specific aspect of the challenge. The journey often begins with the Material Circularity Indicator (MCI),[13,14] a foundational framework for assessing product-level circularity through material flows. Building on this, the MCI' metric enhances the original by addressing a key criticism, replacing its reliance on mass with a more nuanced economic value-based unit and introducing a residual value calculator to provide a realistic assessment of a product's retained worth at end-of-life. For earlier in the product lifecycle, the CN_Con metric enters the stage, uniquely crafted for the conceptual design phase where it jointly assesses the novelty and circularity of proposals, helping designers prioritize innovative and sustainable ideas with limited data.[14] Taking a more macro-level perspective, the PwRD metric introduces a critical absolute sustainability approach, evaluating whether a product's resource use is justified by its function when measured against the finite backdrop of global mineral reserves.[15] Linder *et al.*[16] made a robust case for using economic value as a universal aggregator, arguing that prices best reflect the relative scarcity and utility of materials and components. While R-based models like the 3-Rs and their successors provide a valuable conceptual hierarchy of circular strategies, their primary shortcomings include a lack of standardized, quantitative assessment methods and often overlook critical strategies like innovation-driven redesign and economic value recovery.[17–19]

In this ecosystem of specialized metrics, the CIRCLE framework emerges not as a replacement but as a complementary and holistic diagnostic tool. Its unique strength lies in its comprehensive scope across the entire 10R hierarchy, capturing strategic and innovative principles like Rethink, Repurpose, and Resell that are often outside the horizon of other models. While metrics like MCI' and PwRD provide deep, quantitative answers to specific questions of material flow or resource sustainability, CIRCLE offers a broader map of circularity performance. It acts as a strategic guide that can identify strengths and gaps across all circular strategies; for instance, a poor PwRD score might indicate a problem, and CIRCLE can diagnose it by revealing low scores on Recycle or a lack of Rethink. Thus, where other tools are precision instruments measuring specific outcomes, CIRCLE serves as a versatile and practical framework for guiding comprehensive circular economy strategy from design through to implementation.

4. Case studies

To demonstrate the applicability and comparative value of the CIRCLE assessment tool, three diverse case studies from recent literature were selected and analyzed. Each represents a distinct domain of circular innovation, illustrating how the framework can capture the multifaceted nature of circularity across technological scales and material systems. The first case explores a full-scale membrane treatment technology for livestock manure management, exemplifying nutrient and water recovery within the agricultural sector. The second case examines a circular chemical synthesis that upcycles post-consumer aluminium into functional electrodes, highlighting waste-to-resource transformation in advanced materials processing. The third case investigates a closed-loop recycling system for multi-use plastic plates, representing circularity in consumer product design and reuse. Traditional circularity metrics remain oriented to quantitative mass and energy efficiencies, overlooking qualitative dimensions such as innovation, system redesign, and value regeneration. In contrast, the CIRCLE framework applied in this research offers a more holistic and discriminating assessment one that integrates technical performance with functional, economic, and systemic dimensions of circularity. This demonstrates that the proposed tool can better capture the multifaceted nature of circular transformation than other mass-based evaluations.

4.1. Case study 1

A recent study showcases an innovative full-scale membrane treatment technology applied to livestock manure, demonstrating strong alignment with several key principles of the CIRCLE circularity framework.[20] By recovering valuable nutrients and water from agricultural waste, the system not only reduces environmental burdens but also enables the substitution of conventional inputs, thereby advancing circular economy objectives (Fig. 3a).

The Refuse principle is partially fulfilled through the process's ability to displace synthetic fertilizers. Herrera *et al.* report that the membrane-generated concentrate meets RENURE (Recovered Nitrogen from Livestock Manure) criteria, enabling the substitution of nitrogen fertilizers with nutrients derived from animal waste. This substitution reflects a deliberate refusal to depend on non-renewable nitrogen and phosphorus inputs, justifying a score of 2 out of 3.

Simultaneously, the system exemplifies a complete Rethink of livestock waste management. The deployment of full-scale membrane technology to decentralize and treat manure is presented as a novel approach, replacing traditional slurry disposal methods with a nutrient recovery model that integrates LCA to quantify environmental performance. This systemic shift demonstrates a fundamental reconfiguration of waste handling practices and earns the maximum score of 3.

Substantial environmental and material efficiency gains also satisfy the Reduce criterion. The treatment significantly lowers the total volume of slurry through water extraction. In addition, the LCA shows that the environmental impacts of the recovered fertilizers are markedly lower than those of synthetic alternatives, particularly in terms of greenhouse gas emissions. These clear reductions support a top score of 3.

The process also strongly supports the Reuse principle. Water and nutrients recovered from the slurry are reused in the agricultural system. The plant extracts water suitable for reuse and generates recycled derived fertilizers, effectively reincorporating both components into productive use. This closed-loop recovery and reuse of materials justifies a score of 3.

Conversely, no evidence is presented to support the Repair principle. The study does not address the maintenance, repair, or extension of equipment lifespan. Its focus is limited to process outputs and environmental performance, So, NA was assigned. Similarly, the Refurbish principle is not applicable, as the case involves waste processing rather than the restoration or upgrading of used products. No mention is made of repurposing physical items, and thus this criterion also considered NA.

In contrast, Recycle is a central function of the system. The membrane process concentrates and recovers nutrients, capturing 46% of total nitrogen and 43% of total phosphorus in forms suitable for reuse as fertilizer. These materials are returned to the production cycle, displacing the need for raw nutrient sources. The environmental superiority of this recycling approach over conventional fertilizer production is clearly demonstrated by LCA results, warranting a score of 3.

The process does not involve composting or biological degradation of waste, and thus does not engage with the Rot principle. The technology relies solely on physical membrane filtration, excluding microbial or thermochemical breakdown, So, NA is assigned.

The case study also clearly fulfills the Repurpose criterion. Manure slurry, previously regarded as a problematic waste stream, is transformed into a nutrient-rich concentrate suitable for use as fertilizer. This redefinition of waste into a valuable agricultural

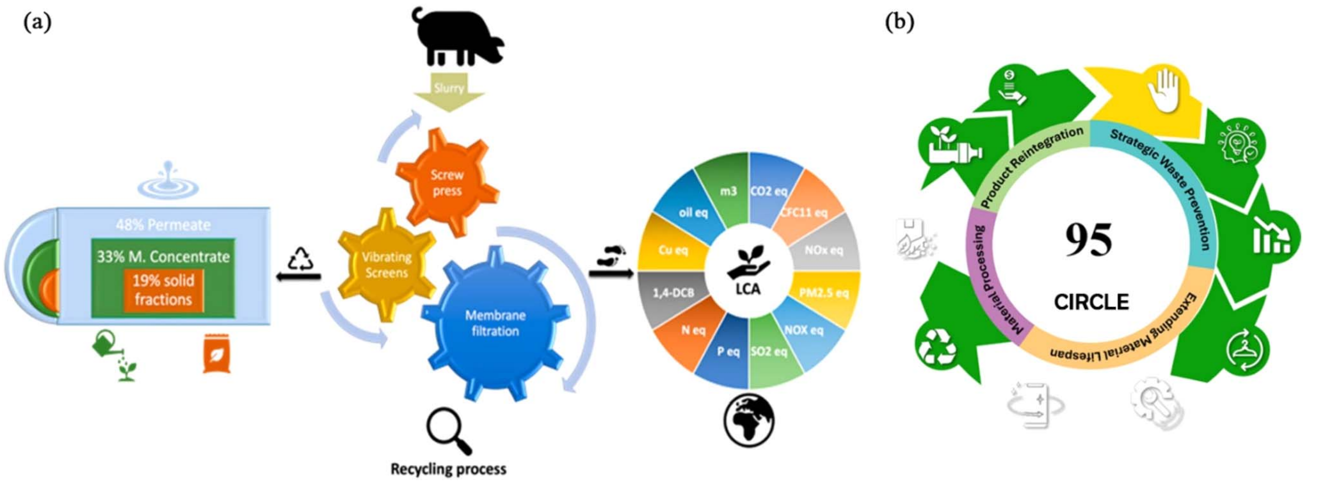

Fig. 3 (a): Concise process flow diagram (inputs → membrane unit → outputs) showing mass/volume arrows and the recovered products (b) CRICLE metric evaluation for case study 1.

input illustrates effective repurposing within the circular economy context, earning a score of 3.

Finally, the economic value of the recovered products affirms compliance with the Resell principle. The study notes that high-quality ammonium sulfate produced through the process has an expected market value of 50–120 € per ton, significantly higher than that of untreated slurry. The researchers emphasize the importance of this as a revenue stream, reinforcing the notion that the output is not only reusable but also commercially viable. The explicit mention of product pricing and market integration supports the full score of 3.

Capital equipment and plant infrastructure (*e.g.*, membranes, pumps, piping) were excluded from the boundary because the assessment aimed to evaluate the circularity of material outputs and resource recovery, rather than the facility's asset-management practices. Applying the three-rule NA test (Absence, Irrelevance, Measurement) leads to NA assignment for Repair and Refurbish: while equipment repair/refurbishment is technically feasible, it falls outside the declared boundary (Irrelevance) and relevant data on plant-level asset management were not available in the source study (Measurement).

The system scores highly across the CIRCLE metric: Refuse – 2; Rethink – 3; Reduce – 3; Reuse – 3; Repair – NA; Refurbish – NA; Recycle – 3; Rot – NA; Repurpose – 3; Resell – 3. These scores are substantiated by clear evidence within the study Fig. 3b, particularly regarding nutrient recovery, waste volume reduction, economic viability, and systemic innovation. The lack of attention to equipment maintenance, product refurbishment, and composting explains the lower scores in those respective categories. Collectively, the case exemplifies a high-value circular solution that not only enhances resource efficiency and environmental performance but also generates economic returns through the strategic recovery and commercialization of waste-derived products.

4.2. Case study 2

The study by Trastulli *et al.*[21] represents another case study of a circular chemical process, evaluated using the CIRCLE tool. Central to this work is the innovative use of recycled aluminum scrap as electrodes in an electrochemical synthesis protocol (Fig. 4a). Although the study does not explicitly frame its approach around the principle of refusal, the selection of secondary aluminum inherently avoids the need for raw metal inputs, thus implicitly refusing the environmental burdens associated with new aluminum mining and processing. While this aspect is not the main focus of the study, it still reflects a meaningful shift away from primary resource consumption, meriting partial alignment with the Refuse principle.

More notably, the researchers fundamentally rethink the traditional electrochemical setup by redefining both the materials and processes used. They develop a synthetic route based on recycled materials, and further optimize the method to operate without oxidants. This redesign, which embeds sustainability considerations such as carbon footprint analysis from the outset, represents a significant departure from conventional practices and aligns strongly with the Rethink criterion.

The process is also explicitly designed to minimize waste and environmental impact, fully satisfying the Reduce principle. Trastulli *et al.*[21] offer quantitative comparisons of waste distribution and carbon emissions. The use of recoverable solvents and repurposed aluminum electrodes plays a central role in this reduction, showcasing the thoughtful integration of circularity into chemical design.

A strong emphasis on material reuse further reinforces the circular intent of the work. Aluminium scrap, a post-consumer waste material, is directly converted into functional electrodes. This not only extends the life of a discarded material but also demonstrates a practical application of reuse within an advanced chemical system.

While the study excels in rethinking, reducing, and reusing, it does not address repair or refurbishment. Instead, the electrodes are freshly fabricated from recycled scrap, bypassing any intervention in the lifecycle of an existing item. As such, the Repair and Refurbish principles are not applicable in this context and receive NA.

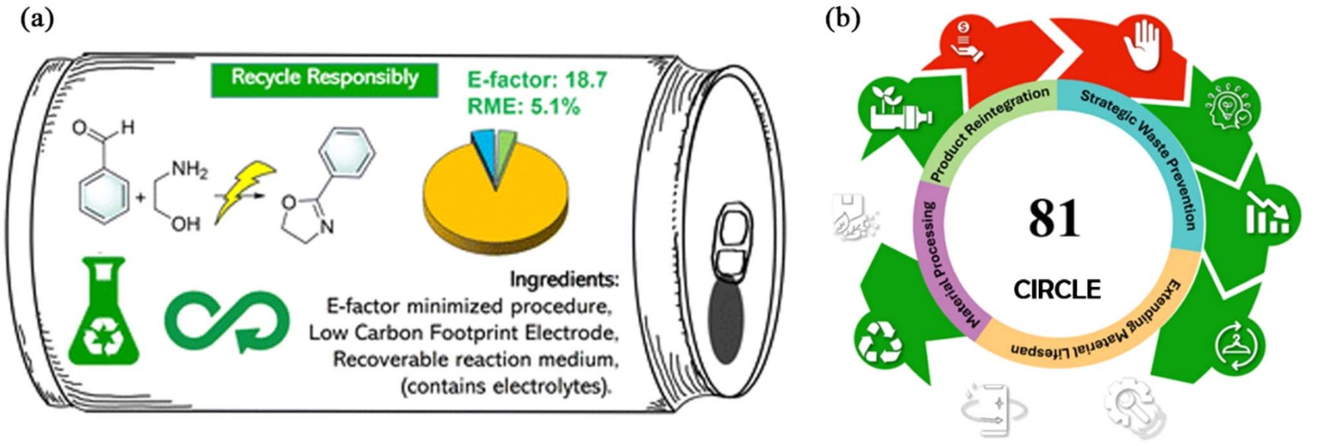

Fig. 4 (a) Material lifecycle schematic emphasizing source (scrap Al) → electrode fabrication – reaction – outputs; mark "no biodegradable streams" (b) CRICLE metric evaluation for case study 2.

The concept of recycling is, however, at the core of this research. The authors clearly demonstrate the chemical recycling of waste aluminum by converting it back into high-purity, functional electrode material.

Certain criteria within the CIRCLE tool are inherently irrelevant to this type of process. The Rot principle, which pertains to biological decay or composting, is not applicable in an inorganic electrochemical system where no biodegradable materials are present. Similarly, the Resell criterion is not addressed; the focus of the study is on internal material recovery and reuse rather than the commercialization of recovered products or intermediates.

However, the study offers a strong example of repurposing. Aluminum, originally used in entirely different applications, is creatively redirected toward a new function as an electrochemical electrode. This transformation of a waste material into a valuable input for chemical synthesis clearly aligns with the Repurpose principle and illustrates the broader potential of waste-to-resource thinking within laboratory-scale innovation.

The study demonstrates a high degree of circularity across key dimensions of the CIRCLE metric. It scores strongly in Rethink, Reduce, Reuse, Recycle, and Repurpose due to its innovative use of recycled aluminum, efficient waste management, and process redesign Fig. 4b. While Refuse is modestly addressed through the avoidance of raw aluminum, the absence of focus on repair, refurbishment, composting, or resale reflects the specific scope and goals of the work. Nonetheless, the research offers a model for integrating circular economy principles into electrochemical synthesis through material recovery and sustainable design.

4.3. Case study 3

Svensson Myrin *et al.*[22] present a comprehensive evaluation of a novel closed-loop recycling system designed for multi-use plastic dining plates, offering a significant advancement in sustainable material management. The study assesses both the material durability of the plates across repeated reuse cycles and the environmental impacts associated with the system, comparing its performance to traditional single-use or disposal-based alternatives. Through a detailed life-cycle assessment, the authors demonstrate that the plates can be reprocessed up to six times with only minimal deterioration in quality. This prolonged utility not only maintains functionality over time but also substantially reduces the environmental footprint. Specifically, the closed-loop system is shown to lower GHG emissions and energy use to approximately 20–60% of those generated by more conventional systems (Fig. 5a).

While the study does not position itself explicitly under the "Refuse" principle, it does contribute meaningfully to waste avoidance. The system circumvents the need for incineration or landfilling by diverting used plates into a controlled recycling loop. The authors emphasize that scenarios involving incineration exhibit significantly higher energy demands, indicating a deliberate departure from waste-intensive end-of-life treatments. This substitution reflects a moderate engagement with the Refuse principle by opting out of environmentally costly disposal routes.

A more direct and notable alignment is found with the Rethink principle. The authors reconceptualize plastic usage by replacing single-use dining ware with durable, multi-use plastic plates embedded within a closed-loop recycling framework. This approach challenges conventional throwaway models and exemplifies a forward-thinking design paradigm that redefines the life cycle of consumer plastics. The integration of reuse and in-house recycling reflects a systemic innovation in both product design and waste strategy.

The study also strongly supports the Reduce principle. Life-cycle modeling shows that this system significantly decreases both primary energy inputs and emissions, achieving reductions of up to 80% in GHG emissions compared to single-use or incineration-based alternatives. Likewise, primary energy demand is reduced by approximately 40–50%, highlighting the efficiency gains enabled by this closed-loop strategy. These quantifiable reductions provide robust evidence of minimized material throughput and environmental impact.

The plates' extended usability directly satisfies the Reuse criterion. Even after six complete reprocessing cycles, the study

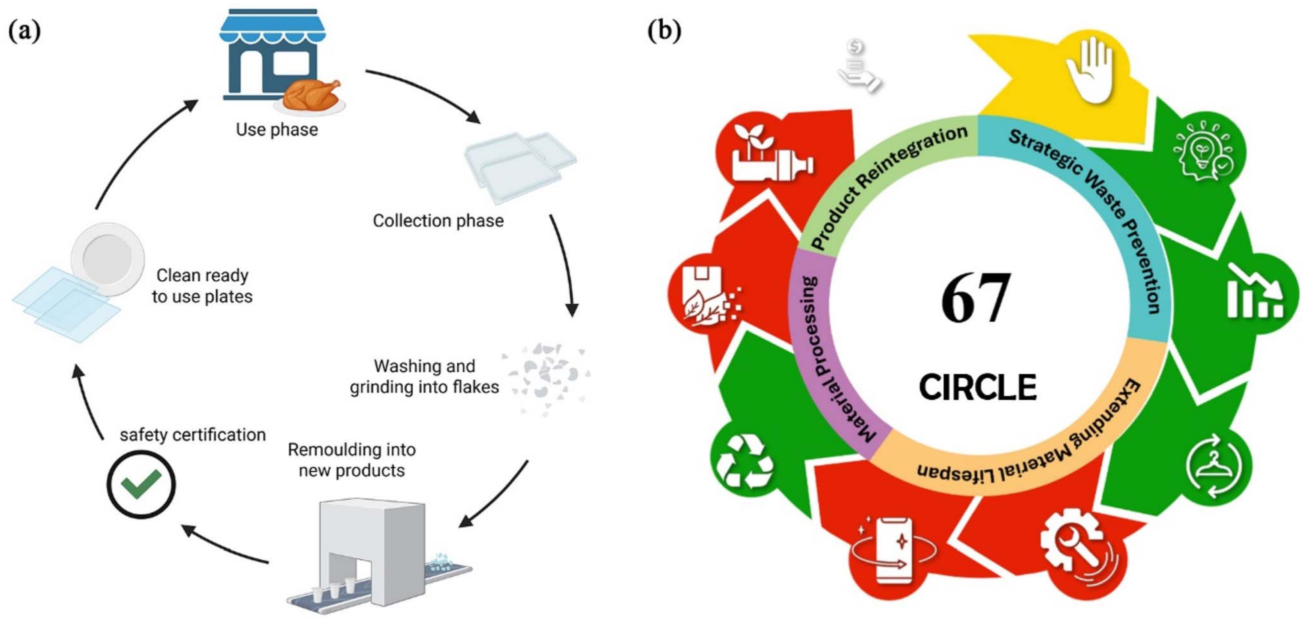

Fig. 5 (a) Lifecycle loop diagram (manufacture – use cycles – collection – closed-loop recycling) with arrows annotated by number of reuse cycles, recovery yield, or key metrics from the study. (b) CRICLE metric evaluation for case study 3.

reports that the products retain their core functionality. This capacity for repeated use over multiple lifetimes ensures that materials are conserved in their original form rather than being rapidly degraded into waste, indicating the system's emphasis on durability and functional longevity.

However, the study pays limited attention to Repair or Refurbish principles. There is no indication that damaged plates are mended or restored in their original form; instead, worn plates are remelted and remolded, a process focused more on recycling than direct maintenance. Similarly, refurbishment defined as upgrading or rejuvenating existing products is not part of the operational model. The plates are returned to their initial form without enhancement or modification, suggesting a functional rather than transformative reuse strategy.

Material recovery, particularly through full-loop recycling, lies at the heart of this case study. Used plates are systematically collected, melted down, and reprocessed into new plates within the same system. This process exemplifies a complete material loop and reflects a best-case scenario for plastic recycling under the Recycle principle. The reuse of material in identical applications not only conserves raw resources but also prevents leakage of plastic waste into the environment.

Other circular principles are less applicable in this context. The Rot principle, typically associated with biodegradable or compostable materials, is not relevant here, as the plates are made from synthetic copolyester and do not undergo biological degradation. Likewise, Repurpose is only marginally demonstrated; while materials are reprocessed, they are not redirected into new or creative applications beyond their original use. The plates remain within their original functional category dishware without being adapted for other purposes. Resell is also not addressed; the system is focused on internal reuse within the same institutional or commercial context, and no resale market or second-hand redistribution is explored.

The closed-loop plate recycling system achieves high scores in Rethink, Reduce, Reuse, and Recycle, reflecting its strong alignment with core circular economy principles Fig. 5b. The approach fundamentally reimagines plastic utility, demonstrates measurable environmental benefits, and maintains product functionality across multiple use cycles. While other dimensions such as Repair, Refurbish, Repurpose, and Resell are less central to the study's scope, the core innovations provide a compelling model for circular plastic systems in institutional or commercial food service contexts.

5. Conclusion

The CIRCLE metric offers a novel and comprehensive approach for assessing circular economy performance through a structured 10R-based metric. By expanding beyond traditional models and incorporating principles such as Rethink, Repurpose, and Resell, the tool addresses critical gaps in previous sustainability assessment tools, ensuring a more holistic representation of material and product lifecycle strategies. Through its nuanced scoring system, CIRCLE not only captures the degree of circularity but also encourages innovation, systemic redesign, and value recovery across sectors. The application of the tool to three distinct case studies ranging from nutrient recovery in agriculture to advanced electrochemical synthesis and durable plastic reuse demonstrates its versatility and robustness in real-world contexts. These cases reveal that high CIRCLE performance is driven by integrated strategies that couple technical feasibility with economic and environmental value, indicating the potential of the metric as both an evaluative and prescriptive tool. Importantly, the metric identifies not only successful practices but also areas where circular interventions remain underutilized, thereby supporting continuous improvement and informed decision-making. As industries and governments increasingly seek measurable, science-based indicators to track circular progress, CIRCLE stands as a timely and scalable solution. Future work should focus on refining sector-specific weightings and exploring digital integration for real-time assessment. Ultimately, CIRCLE lays a strong foundation for operationalizing circular economy principles in ways that are quantifiable, actionable, and aligned with global sustainability objectives.

The CIRCLE metric is intentionally designed for broad applicability: its 10R framework and flexible scoring can be used to evaluate circularity at the product, process, plant, organizational, and value-chain levels across diverse sectors from packaging and Fast-moving consumer goods (FMCG), to electronics and battery reuse, to construction materials, agro-industry, and municipal waste systems. Beyond academic assessment, CIRCLE can support corporate sustainability reporting, procurement decisions, policy benchmarking, and targeted investment in circular innovations. Future developments will prioritize tighter integration with life-cycle assessment and life-cycle costing, automated data feeds, sector-specific rubrics, and a public web tool for large-scale benchmarking and sensitivity testing. By combining diagnostic clarity with practical flexibility, CIRCLE aims to accelerate adoption of actionable circular strategies across research, industry, and policy domains.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

Data will be made available upon reasonable request.

The data supporting this article including (CIRCLE user guide and more description of the 10R principles) have been included as part of the supplementary information (SI). See DOI: **https://doi.org/10.1039/d5su00806a**.

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