Integration of 10R Principles into CIRCLE as an Innovative Tool for Assessing Circular Economy

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The 10 R principles if the CIRCLE assessment

1.1. Refuse

Technological innovations further illustrate high-scoring applications under the Refuse criterion. One such example is solvent-free chemical synthesis using microwave (MW) irradiation, where neat reactants undergo transformation without any added solvents. As Varma describes, this method eliminates the use of flammable and toxic organic solvents major contributors to chemical waste and operational hazards thus preventing pollution at the source [1]. By avoiding solvent use entirely, this method is and example for the Refuse principle at its highest level, qualifying for a Score 3. Biocatalysis provides another noteworthy pathway toward solvent and hazard reduction. Widely adopted in pharmaceutical manufacturing, enzymatic transformations often operate under mild conditions and can significantly reduce or even eliminate solvent usage. For instance, lipase-catalyzed reactions may proceed without solvents, and the synthesis of (S)-2-indolinecarboxylic acid using phenylalanine ammonia lyase (PAL) has demonstrated a 50% reduction in solvent use. Additionally, enzymatic methods frequently avoid toxic metal catalysts; a prominent case is the enzymatic synthesis of Sitagliptin, which replaces rhodium-based systems. Depending on the degree of hazardous material elimination, such processes can justifiably earn a Score 2 or 3 under the Refuse principle [2]. An additional example of hazard avoidance is the modified Stöber process for synthesizing silica particles. While the traditional method heavily relies on organic solvents such as ethanol, recent advancements omit these solvents altogether, generating submicron silica spheres with high uniformity. Though ethanol is still produced in situ from TEOS hydrolysis, the exclusion of externally added solvents represents a significant step toward hazard minimization. This deliberate modification supports waste reduction, enhances scalability, and fully aligns with the Refuse principle, meriting a Score 3 [3]. The use of hydrogen peroxide (H_2O_2) as a green oxidant also illustrates partial adherence to the Refuse principle. As a cost-effective, environmentally benign reagent that decomposes into water, H_2O_2 avoids the toxic by-products associated with traditional oxidants like Cr(VI), Mn(VII), and nitric acid. Its industrial applications include the ARKEMA process for hydrazine hydrate, the HPPO method for epoxypropane production, and the epoxidation of chloropropene. These processes significantly reduce waste, energy consumption, and corrosion risks [4, 5]. However, since other hazardous materials may still be involved in these systems, such applications are better categorized as Score 2, reflecting partial but meaningful avoidance of harmful substances.

1.2. Rethink

Several recent studies illustrate practical applications of the Rethink principle. One notable example is the development of recyclable vitrimer-based printed circuit boards (vPCBs), as presented by Zhang et al. [6]. Unlike traditional PCBs made from irreversible thermoset epoxies, which are difficult to recycle, these vPCBs utilize transesterification-based vitrimers a type of dynamic covalent network that supports reversible crosslinking. This allows the boards to be repaired, remanufactured, and recycled multiple times without compromising material performance. The vPCBs can also self-heal with heat treatment and be separated non-destructively from reinforcing fibers, promoting closed-loop recycling. This innovative material redesign significantly reduces electronic waste and enhances product lifespan, offering a clear Score 3 example of the Rethink principle in action. In a similar vein, Li et al. [7] demonstrated a Score 3 application through the creation of carbon fiber/vitrimer composites, which rethink traditional carbon fiber reinforced epoxy composites (CFRECs). These next-generation composites integrate dynamic covalent bonds, allowing dual self-healing and dual recyclability both in the resin and the fiber interface. Their design enables efficient recovery and reuse through mild physical or chemical methods without performance loss. This fundamental re-engineering of composite materials represents a systemic shift that embodies the goals of the Rethink principle: enabling multiple product life cycles, reducing end-of-life waste, and enhancing circularity. Beyond material innovations, modular design in power electronic converters (PECs) is emerging as a transformative application of the Rethink principle. Traditional PECs are often monolithic, hindering repair, reuse, and disassembly. In contrast, modular architectures introduce physically and functionally independent units with standardized interfaces, facilitating component replacement, upgrading, and recyclability. This design approach groups failure-prone components into detachable modules while designing others (e.g., inductors or controllers) for long-term reuse. Though modular systems such as Power electronics building block (PEBBs), Multicell interleaved converter (MICs), and Modular multilevel converter (MMCs) exist, their explicit development for circularity marks a novel shift. Despite challenges such as increased cost or complexity, this paradigm redefines how electronic products are built and maintained, fulfilling the Score 3 criteria by intentionally incorporating sustainability into system architecture [8].

While Score 3 innovations introduce original, transformative solutions, the Rethink principle also values the meaningful adoption of existing innovations, meriting a Score 2 when applied effectively. A leading example is the PRESERVE initiative, which scales up established upcycling technologies to convert agricultural bio-waste into high-barrier, bio-based food packaging. While the technologies themselves are not new, their deployment at an industrial scale represents a strategic rethinking of packaging shifting from fossil-derived plastics to renewable sources while improving recyclability and functionality. With the goal of replacing 60% of conventional packaging by 2030, this initiative illustrates how scaling proven solutions can meaningfully reduce plastic waste and promote a circular bioeconomy [9]. Similarly, the growing adoption of modified starch-based films in food packaging provides another Score 2 example. Although starch as a material is well known, recent innovations have focused on enhancing its functional properties through physical, chemical, and enzymatic modifications, as well as the integration of additives like essential oils or nanomaterials. These improved films offer increased mechanical strength, antimicrobial activity, and moisture resistance, significantly extending the shelf life of produce such as spinach, grapes, peaches, and mangoes. By substituting petrochemical-based packaging with renewable, biodegradable alternatives, and applying these improvements at scale, this strategy rethinks how perishable goods are protected aligning closely with the Rethink principle's emphasis on reducing food waste and improving resource efficiency [10].

1.3. Reduce

Among the most promising technologies aligning with a Score 3 under the Reduce criterion is the recently introduced chlor-iron electrochemical process for producing iron. This method eliminates the need for traditional blast furnaces by using an electrochemical cell powered by iron oxide and sodium chloride inputs that are not only abundant but potentially derived from seawater. The process also generates valuable co-products such as sodium hydroxide (NaOH) and chlorine, thereby maximizing material utility and significantly reducing waste. High-purity iron (≥95 wt%) is produced in freestanding film form, minimizing the need for post-processing and resource-intensive purification. These innovations collectively represent a paradigm shift in how material input reduction can be achieved at scale [11].

Similarly, the use of topology optimization (TO) in conjunction with additive manufacturing (AM) presents a clear exemplar of Score 3 performance. By leveraging computational design to optimize material layout and structural performance, researchers have achieved material savings of 22–35% in steel components and a 28% reduction in total steel tonnage for bridge prototypes. These advances are achieved without compromising safety or load-bearing capacity. Wire Arc Additive Manufacturing (WAAM), in particular, allows for precise, waste-minimizing layer-by-layer fabrication, eliminating inefficiencies inherent in subtractive manufacturing. Together, TO and AM not only enable complex geometries but also significantly enhance resource efficiency highlighting the power of integrated design and manufacturing innovation in meeting the CIRCLE standards for significant material reduction [12].

In contrast, hydrogen injection in conventional blast furnaces constitutes a more moderate, Score 2 approach under the Reduce principle. While the substitution of hydrogen for a portion of carbon-based reducing agents yields important environmental benefits, the metallurgical limitations of blast furnaces still necessitate the use of coke to maintain process integrity. European steelmakers have reported 12–15% reductions in iron ore use and modest decreases in coking coal consumption. However, life cycle assessments reveal that total raw material input remains high 2.8 to 3.2 tons per ton of steel with overall material footprint reductions limited to 9–11% [13–15]. These figures fall short of the systemic optimization targeted by Score 3 but nonetheless represent valuable progress in adapting existing infrastructure toward more sustainable outcomes.

At the opposite end of the spectrum, certain practices remain fundamentally misaligned with the Reduce principle. A clear example is the continued use of static polyethylene films in fast-moving consumer goods (FMCG) packaging. Despite the availability of advanced multi-layer barrier films and topology-optimized alternatives capable of reducing material use by 35–40%, many manufacturers persist in using 85–90 μm single-material polyethylene films. This unwillingness to transition to more efficient materials has resulted in an estimated global overshoot of over 12 million metric tons of plastic annually. Such inertia exemplifies a Score 1 scenario: while technically functional, the packaging strategies show no engagement with established material optimization practices and represent a missed opportunity for significant waste reduction [16, 17].

These varied examples highlight the essential role of the Reduce principle within the CIRCLE metric in guiding industries toward more sustainable, resource-conscious practices. From transformative innovations like chlor-iron processing and topology-optimized structures to more incremental changes like hydrogen injection and even regressive practices in the packaging sector CIRCLE offers a structured lens for evaluating and incentivizing material efficiency. The effective implementation of the Reduce principle not only supports environmental stewardship but also enhances competitiveness and resilience in an increasingly resource-constrained world.

1.4. Reuse

An exemplary application of the Reuse principle at the Score 3 level is the closed-loop recycling of poly(imine-carbonate) materials synthesized from plastic waste and bio-based feedstocks. This process involves the depolymerization of waste bisphenol A polycarbonate (BPA-PC) using vanillin-based derivatives, yielding high-purity monomers specifically, BPA and di-vanillin ethoxy carbonate (DVEC) which are subsequently reused to produce new polymers. Remarkably, these poly(imine-carbonate)s are designed for full chemical recyclability, enabling their breakdown and regeneration under mild conditions, with monomer recovery yields exceeding 90%. This high-fidelity monomer recovery and direct reuse, without degradation in quality, exemplify the concept of material circularity. Unlike systems that downcycle or partially reuse degraded materials, this approach reinstates original building blocks, facilitating the creation of new materials with performance characteristics identical to those of raw counterparts thereby eliminating the need for new material inputs and aligning fully with CIRCLE's highest reuse benchmark [18].

Similarly, Saito et al. demonstrate a pioneering closed-loop strategy for crosslinked thermosets, long considered irrecyclable due to their rigid, permanent structures. Their system integrates dual-cleavable bonds (imine and acetal linkages) that enable controlled depolymerization into chemically intact monomers such as vanillin, diethylene glycol (DEG), acetaldehyde, and tris(2-aminoethyl)amine (TREN). These components can be recovered with high yields (up to 97% for vanillin) and reused to reconstruct polymer networks with mechanical and thermal properties indistinguishable from those of the original materials. Characterization techniques, including FTIR, DSC, DMA, and tensile testing, confirm the stability of these regenerated networks over multiple cycles, validating their reuse potential without functional compromise. Crucially, this system offers recovery from mixed plastic waste streams, enhancing its real-world applicability and highlighting its robustness as a Score 3 reuse strategy. It advances beyond traditional recycling by maintaining the integrity and utility of the recovered components through repeated use cycles [19].

The work of Catholico et al. provides another compelling Score 3 example through the reuse of waste soda-lime glass as a catalyst support. In this study, post-consumer glass waste is doped with copper nanoparticles (Cu(0)NPs) to create a durable, high-performance catalyst tablet. This innovation not only repurposes an abundant, non-biodegradable waste stream but also enhances the practicality of catalyst reuse by enabling easy mechanical recovery between reaction cycles an advancement over traditional nanoparticle systems that often require complex separations. The catalyst demonstrated high reusability in solvent-free A^3 coupling reactions and in 4-nitrophenol reduction, maintaining over 96% activity after multiple uses. Despite minor morphological changes and surface oxidation, the catalytic efficiency remained stable, illustrating both the durability of the material and its suitability for repeated use. By eliminating the need for new catalyst substrates and reducing process waste, this strategy exemplifies the principles of green chemistry and operationalizes the CIRCLE definition of comprehensive reuse [20].

Together, these case studies underscore how innovative material design and process integration can achieve high-performance reuse systems, contributing significantly to the realization of circular economy objectives. They demonstrate that reuse, when implemented with strategic foresight and supported by enabling technologies, can match or even surpass traditional linear production systems in terms of efficiency, sustainability, and economic viability. The CIRCLE metric not only captures the maturity of such efforts but also provides a structured lens for evaluating and promoting best practices in material lifecycle extension.

1.5. Repair

A compelling example of a Score 3 application comes from the study by Tonkin et al., which explores self-healing sulfur-based polymers synthesized through inverse vulcanization. These materials incorporate dynamic polysulfide (S–S) bonds into their structure, allowing for intrinsic chemical repairability. Unlike traditional thermoset polymers that often require high heat or solvents to mend damage, this system enables room-temperature self-healing via nucleophile-catalyzed S–S bond exchange. Catalysts such as pyridine, triethylamine, and tributylphosphine were applied to damaged surfaces, initiating S–S metathesis reactions that rejoined fractured interfaces. Notably, triethylamine facilitated full mechanical restoration, achieving 100% recovery in tensile strength, with failure occurring outside the repaired region an indication that the bond between the repaired surfaces was as strong as the original material. This performance clearly satisfies the CIRCLE criteria for full repair. Additionally, the use of readily available, reusable catalysts makes this process not only efficient but also sustainable, aligning with Green Chemistry principles such as reduced energy consumption, safer chemicals, and waste minimization. In a broader context, this repair technology is applicable to real-world products such as tires and structural adhesives, where mechanical resilience and reparability are key [21].

Another study by D'Elia et al. highlights a self-healing coating system based on poly(phenylene methylene) (PPM) copolymers, tailored for corrosion protection. These materials, modified with alkoxy side chains, offer increased flexibility and resistance to cracking key limitations in traditional PPM coatings. Using accelerated electrochemical degradation and impedance spectroscopy, the researchers showed that PPM copolymer films not only withstood harsh testing conditions but also repaired themselves, restoring barrier functionality after damage. Artificial scratches induced in the coatings were shown to close over time, and impedance values increased dramatically indicative of restored protective performance. This autonomous healing behavior, likely driven by the material's thermoplastic, amorphous nature, allowed localized flow and sealing of defects during electrochemical cycling, without the need for external intervention. The system thus meets CIRCLE's Score 3 definition by restoring its protective role and mechanical integrity after damage. Its potential application in corrosion-prone environments such as marine coatings or infrastructure indicating the relevance of repairable materials in enhancing durability and reducing maintenance frequency [22].

In contrast, the repair of reinforced concrete (RC) bridge columns subjected to seismic damage offers a nuanced example of partial restoration, corresponding to a Score of 2 under CIRCLE. In this case, fractured longitudinal steel bars were replaced, concrete was recast, and the columns were wrapped in carbon fiber reinforced polymer (CFRP) jackets. This intervention successfully restored load-bearing and torsional strength, ensuring structural safety. However, key performance metrics such as lateral and torsional stiffness remained significantly below original values, at just 64% and 48%, respectively. Moreover, the system's energy dissipation capacity was reduced, limiting its effectiveness under repeated dynamic loading. While the structural integrity of the columns was sufficiently recovered for continued use, the repair did not achieve full functional equivalence with the undamaged state. This example illustrates the importance of qualitative distinctions within repair assessments: restoring functionality is essential, but without recovering original resilience or adaptability, the repair remains incomplete. For civil infrastructure, such distinctions are especially critical, as structural systems must retain performance over extended timeframes and under variable loads [23].

Together, these case studies demonstrate the diverse manifestations of repair across materials and structures, while emphasizing the critical role of functional recovery in sustainable design. Whether through chemical self-healing, thermoplastic reformation, or structural reinforcement, the ability to restore functionality without total replacement is essential for closing resource loops and achieving circularity. The CIRCLE tool provides a valuable lens to recognize and reward such efforts, driving innovation in repairable systems across scientific and industrial domains.

1.6. Refurbish

A compelling demonstration of full refurbishment under this criterion is found in the study by Gong et al., which targets the structural degradation of nickel-rich NCM811 cathodes in high-energy lithium-ion batteries a common failure mode responsible for significant performance decline. Through a magneto-electrochemical synergistic activation (MEA) process, the researchers successfully reversed Ni/Li antisite disorder, thereby restoring the crystallographic order and electrochemical performance of aged electrodes. This was achieved by applying a magnetic field alongside electrochemical activation, which induced a spin state transition in Ni^{3+} ions, promoting cationic reordering. The process reduced the antisite disorder from 4.90% to 1.85% and improved critical metrics including internal resistance and lithium diffusion. Importantly, the post-treatment batteries regained 10% of their capacity (from 6.49 Ah to 7.14 Ah), and structural analyses confirmed the absence of typical degradation features such as surface cracking. The rejuvenated electrodes not only performed comparably to new ones but also exhibited improved cycle stability, meeting the CIRCLE standard for a complete refurbishment (score 3) [24].

Further exploration of refurbishment strategies in lithium-ion batteries highlights the varied depth of achievable recovery. For instance, pulse charging techniques employed to restore degraded capacity by applying current pulses at optimized frequencies can offer measurable improvements. In tests on 25 Ah lithium cells from a VW eGOLF, a pulse frequency of 400 Hz yielded a modest 7.5% capacity increase, coinciding with the impedance minimum. However, this strategy did not fully restore the battery's original capacity, indicating a partial refurbishment consistent with a score of 2 under CIRCLE [25].

In contrast, Yang et al. demonstrated a more effective approach by applying a brief, high-voltage electrical pulse to silicon anodes, resulting in a 92% restoration of original capacity. This method targeted the structural redistribution of lithium silicide phases, directly addressing the root causes of capacity fading. Additionally, it achieved significant energy savings (~70%) compared to traditional regeneration techniques. This high-efficiency and deep-level rejuvenation restored the anode's functionality to near-original performance, justifying a score of 3 under the Refurbish principle [26]. Together, these cases Indicate the importance of evaluating not just the presence but the *depth* of refurbishment in circular economy frameworks.

The principles of refurbishment also extend beyond energy storage systems. Suh et al. provide a noteworthy example within the domain of water treatment, developing a photoregenerable adsorbent composite (Δ-Au/TiO_2/LDH) designed for sustainable pollutant capture and solar-driven regeneration. The composite leverages photocatalytic TiO_2 and plasmonic Au nanoparticles embedded in a layered double hydroxide (LDH), enabling solar-powered oxidative degradation of adsorbed contaminants. Notably, the composite maintained over 97% of its original adsorption capacity across five regeneration cycles, without exhibiting morphological degradation. These features affirm its readiness for long-term use and meet the CIRCLE definition of full refurbishment. The technology's low energy input, consistent performance recovery, and material durability exemplify circular economy principles in action designing for sustainability from the outset rather than relying on after-the-fact interventions [27].

Liu et al. offer a sophisticated example of refurbishment in the area of fuel cell technology. Their work focuses on restoring platinum (Pt) electrocatalysts in proton exchange membrane (PEM) fuel cells, which suffer from performance loss due to sulfur dioxide (SO_2) poisoning. Rather than relying on energy-intensive and often incomplete regeneration protocols, Liu et al. developed a square wave potential technique that facilitates the transformation of adsorbed SO_2 into more reactive forms, which are then electrochemically removed. This strategy enabled the catalyst to recover 94% of its Electrochemical Surface Area (ECSA) and 99% of its original Oxygen Reduction Reaction (ORR) activity well within the threshold for a 3-point refurbishment score. The process is notably efficient, requiring only three regeneration cycles and avoiding thermal or chemical treatments. It serves as a prime example of how intelligent electrochemical design can deliver high-fidelity refurbishment, extending the operational lifespan of critical materials while aligning with sustainability goals [28].

These studies demonstrate the versatility and impact of refurbishment across domains from batteries and catalysts to filtration media. The CIRCLE metric provides a robust lens for assessing the quality and sustainability of these interventions, highlighting the importance of performance restoration, structural integrity, and material conservation. As these examples illustrate, successful refurbishment not only revives individual products but also supports broader transitions toward circular, low-waste production systems.

1.7. Recycle

By promoting high-fidelity recycling practices, this metric encourages industries to embrace closed-loop systems, which play a vital role in reducing waste generation and fostering more sustainable consumption patterns. This is particularly crucial for complex product systems, such as lithium-ion batteries (LIBs), which house a diverse range of valuable and often interdependent components. A recent review indicated the value of direct recycling in this context, positioning it as a high-efficiency alternative to traditional methods like pyrometallurgy and hydrometallurgy. Unlike these conventional approaches, which often focus solely on extracting high-value metals (e.g., cobalt, nickel) while sacrificing the integrity of other components, direct recycling aims to preserve and regenerate entire battery architectures including electrodes and electrolytes. This strategy not only retains the functionality of cathode active materials (CAM) and graphitic anodes but also drastically reduces the energy, emissions, and material losses typical of end-of-life battery treatment. Moreover, its adaptability across different LIB chemistries, including cobalt-free designs, reinforces its potential for wide industrial implementation thus directly satisfying the CIRCLE benchmark for full material recovery [29].

An exemplary technological advance In this domain Is presented by Mecking et al., who Id an enzymatic depolymerization approach for polyesters such as poly(caprolactone) (PCL) and poly (lactic acid) (PLA). By embedding nano-dispersed enzymes within these polymers, their method enables processive and nearly complete depolymerization, achieving conversion rates of up to 98% into repolymerizable small molecules. These molecules can be directly reused in the synthesis of new polymers, thereby closing the material loop. This system also addresses critical challenges such as microplastic accumulation and high energy inputs, as it operates under mild conditions (37–50°C) and enables efficient degradation in everyday environments like tap water or compost. The integration of enzyme-protectant-polymer complexes ensures scalable and uniform breakdown, making the system industrially viable. This near-total recovery of high-purity materials exemplifies the rigorous standards necessary for a 3-point CIRCLE rating, highlighting how biochemical innovation can advance circularity in polymer lifecycle management [30].

In contrast, Dong et al. introduced a catalyst-free, electrified thermal process for plastic depolymerization, targeting polymers such as polypropylene (PP) and polyethylene terephthalate

(PET). This method significantly improves upon conventional pyrolysis, achieving monomer yields of 36% and 43% for PP and PET, respectively. However, despite these improvements, the process does not reach the near-complete recovery levels required for the maximum CIRCLE score. The residual unrecovered material and limited selectivity for specific polymers constrain its utility and necessitate further treatment or disposal of waste by-products. As such, this system aligns more closely with a score of 2 under the CIRCLE rubric representing partial recycling with notable material loss [31].

Further nuance in evaluating recycling efforts is illustrated by the study on regenerable carbon nanotube sponge (CNT) cathodes for lithium oxygen batteries. The proposed water-based regeneration method effectively removes performance-limiting residues such as Li_2O_2 and Li_2CO_3, enabling reuse of the cathode for hundreds of additional cycles. This process supports material conservation and enhances battery longevity, resonating strongly with circular economy goals. However, while the regeneration efficiently restores the electrode's functional structure, the fate of the dissolved by-products (e.g., lithium or carbonate ions) remains ambiguous. The absence of explicit recovery mechanisms for these substances indicates that not all recyclable materials are retained within the system, thereby precluding classification as full material recovery. Consequently, this approach falls within the "Partial Recycling with Residual Waste" category, meriting a score of 2 on the CIRCLE scale [32].

Taken together, these examples illustrate the diverse spectrum of recycling technologies and their varying degrees of alignment with CIRCLE standards. They indicate the importance of not only functional restoration but also the completeness of material recovery in evaluating recycling efficacy. Innovations like direct battery recycling and enzyme-assisted polymer depolymerization demonstrate how targeted, high-efficiency solutions can fulfill the highest sustainability benchmarks while intermediate approaches, though valuable, highlight the continued need for technological refinement in closing material loops.

1.8. Rot

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.

An exemplary system earning the maximum score under the Rot criterion involves the composting of (3-hydroxybutyrate-co-3-hydroxyvalerate) PHBV-based biocomposites reinforced with purified cellulose (TC). Under thermophilic composting conditions, this composite achieved complete disintegration within 45 days and 99% mineralization to CO_2 and water within 60 days exceeding internationally recognized compostability standards such as ISO 17088 and EN 13432, which set thresholds of 90% disintegration within three months and 90% biodegradation within six months. These results indicate that the PHBV/TC composite not only fully breaks down but also reintegrates its organic content into the ecosystem without leaving harmful residues. As such, this material management approach satisfies the strict requirements for a Score 3, representing a model for sustainable biodegradation and organic waste recovery [33].

Another strong example of optimal composting practice comes from a life cycle assessment (LCA) conducted by Nordahl et al., which compared different treatment methods for organic municipal solid waste including landfill, composting, and anaerobic digestion. The study found that composting raw organic waste resulted in net negative GHG emissions (−41 kg CO_2e per tonne) due to soil carbon sequestration and the displacement of synthetic fertilizers. In contrast, landfilling the same waste produced nearly 400 kg CO_2e per tonne, largely because of fugitive methane emissions from decomposing food waste. The favorable environmental impact of composting particularly in terms of climate change mitigation supports its classification as a best-practice method under the Rot criterion. This comprehensive and circular treatment of biodegradable materials clearly meets the expectations for a Score 3, as it aligns with both ecological and performance-based sustainability standards [34].

A further illustration of high-scoring compostable systems can be found in the development of poly (PHBV) derived from agricultural residues such as wheat straw and sugarcane bagasse. These underutilized biomass sources are repurposed into biodegradable polymers that can decompose efficiently at end-of-life. Composting trials under ASTM D5338 conditions demonstrated a 98% mass loss of PHBV films within 50 days, indicating rapid and effective biodegradation. This approach not only valorizes agricultural waste into valuable materials but also ensures that these materials return to the soil through composting, completing a closed-loop cycle. Such integration of sustainable feedstocks with compostable outputs represents an ideal fulfillment of the Rot principle, meriting the full 3-point rating under CIRCLE [35].

In contrast, systems that lack composting practices and dispose of biodegradable materials alongside general refuse are assigned a Score of 1, reflecting a failure to manage organic waste sustainably. A representative scenario is the landfilling of untreated food and organic waste, which not only prevents nutrient recovery but also contributes significantly to climate change. A study by Nordahl et al. estimated that landfilling such waste results in GHG emissions of approximately 400 kg CO_2e per tonne, primarily due to methane generated through anaerobic decomposition in landfills. Crucially, a substantial portion of this methane is released before gas capture systems become operational. This unmanaged and unsorted disposal of biodegradable material exemplifies the lowest applicable tier under the Rot criterion. It highlights the environmental hazards of failing to implement composting, and underscores the importance of diverting organic waste from landfills in favor of sustainable alternatives [34].

The CIRCLE Rot criterion serves as a critical measure of how effectively systems handle biodegradable materials. It distinguishes between practices that truly close the loop returning organic matter to nature in a beneficial and regenerative way and those that perpetuate linear, extractive waste flows. Through rigorous assessment of composting efficacy, CIRCLE fosters accountability and innovation in organic waste management, driving progress toward a more circular and climate-resilient future.

1.9. Repurpose

A compelling example of repurposing at ’he highest level is Illustrated in a study that explores the use of biochar derived from low-value agricultural residues as a catalyst for converting waste glycerol and CO_2 into high-value chemicals, such as glycerol carbonate and acetins. This approach repurposes three distinct waste streams: biomass residues (e.g., wheat straw, miscanthus), crude glycerol from biodiesel production, and captured CO_2 emissions. The biochar, functioning as a catalytic support, facilitates chemical transformations that yield products widely used in polymer synthesis, solvents, and fuel additives. Notably, the spent biochar catalyst is not discarded after its initial use; instead, it can be further repurposed as a soil amendment, contributing to carbon sequestration and improved soil fertility. This multi-tiered repurposing model where both materials and outputs are reintegrated into productive use epitomizes a closed-loop system and strongly aligns with the vision of material circularity promoted by the Repurpose criterion. Given its comprehensive and multifunctional strategy, this process merits a Score of 3 under the CIRCLE metric [32].

Expanding on this concept, the study on biochar-assisted glycerol carboxylation with CO_2 demonstrates how agricultural residues traditionally regarded as low-value waste can be elevated into catalytically active materials. The conversion of wheat straw and miscanthus into functional biochar represents a meaningful upgrade in material functionality. When these biochars are utilized to catalyze the reaction between waste glycerol and CO_2 two challenging and abundant industrial by-products the process yields glycerol carbonate and triacetin, which have diverse commercial applications. These include uses as plasticisers, fuel additives, and solvents, providing a strong economic incentive for waste valorization. This strategy not only resolves multiple waste management challenges simultaneously but also delivers value-added outputs, creating a synergy between environmental remediation and industrial productivity.

Importantly, the study’s approach to repurposing demonstrates how systems thinking and cross-sector innovation can redefine waste as a resource. By transforming agricultural and industrial residues into new, functional materials with commercial applications, the process exemplifies the highest standard of repurposing assigning new life and purpose to materials that might otherwise contribute to environmental burdens. Such efforts validate a top-tier score of 3 within the Repurpose category of CIRCLE, showcasing how integrated material reuse can advance both sustainability and economic viability [36].

1.10. Resell

A compelling example of the Resell principle in action is provided by Wang and Hellweg, who investigated the second-life application of retired electric vehicle (EV) batteries. Batteries from Evs such as the Tesla Model S and Nissan Leaf, though no longer optimal for automotive use, retain 70–80% of their original capacity. Rather than discarding these batteries, they are resold and repurposed for residential energy storage systems, particularly in solar energy applications. This secondary use not only extends the batteries' service life by an additional 7–10 years, but also delivers economic benefits, including reduced system costs, and environmental advantages, such as decreased demand for new battery production. This process clearly meets the highest benchmark of the Resell criterion, as the products remain in active use, maintain significant functionality, and deliver measurable sustainability outcomes [37].

Another notable example is presented in the work of Shim, who demonstrated an innovative resale strategy involving the hydrometallurgical relithiation of spent $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC) cathodes. In this process, spent cathode materials are regenerated and then resold directly to EV manufacturers, where they are reintegrated into new battery cells. Remarkably, the recycled cathodes achieved 98% capacity restoration and sustained performance over 4,000 cycles, matching the quality of raw materials. The economic benefits are equally significant, with costs 30% lower than new production, and environmental savings estimated at 15 kg CO_2e avoided per kWh of battery capacity. This example illustrates a closed-loop resale model, in which high-performance materials are not only recirculated but also retain full functional equivalency, qualifying for a score of 3 under the CIRCLE metric [38].

A further illustration of the Resell principle applied at the molecular level is provided by Somoza-Tornos et al., who investigated the chemical recycling of end-of-life polyethylene (PE) through pyrolysis. This process converts waste PE into feedstock-grade monomers, notably ethylene, which are then reintegrated into plastic manufacturing chains. While the product is not resold in its original form, its core chemical components are recovered and functionally equivalent to ethylene, thereby fulfilling the CIRCLE definition of a successful resale. In addition to being economically viable with production costs at 0.386 €/kg compared to 0.835 €/kg for ethylene the process offers substantial environmental benefits, including reductions of 87% in human health impacts, 89% in ecosystem damage, and 164% in resource scarcity relative to conventional production methods. This chemical resale pathway exemplifies how circular principles can be extended to complex material flows and industrial processes [39].

These cases indicate the transformative potential of the Resell principle when effectively implemented. Whether applied to entire products, high-value components, or chemical building blocks, resale strategies preserve value, reduce environmental burdens, and advance the goals of a circular economy. The CIRCLE metric provides a structured approach to assess and reward such initiatives, encouraging broader adoption of resale as a pillar of sustainable development.

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