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# Industrial Waste Management for a Circular Economy: Critical Perspectives on Prevention, Recovery, Treatment, and Resource Valorization

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## Abstract

Industrial waste management is often framed as technology selection, although sustainability depends on prevention, material quality, residual fate, and the displacement of primary production. This purposive critical integrative review examines industrial wastewater, sludges, and solid production residues using 106 cited sources: 42 retained papers from an initial 47-paper full-text collection and 64 complementary sources. It does not claim systematic or exhaustive coverage. The synthesis compares prevention, industrial symbiosis, treatment and recovery through functional equivalence, representative operating conditions, mass and energy balances, and life-cycle trade-offs. A retrospective audit identifies four retained studies at controlled-experiment level, one with continuous laboratory operation, one with field-pilot evidence, and one with enterprise-scale evidence; the other 35 provide review, observational, or modelling evidence rather than operational validation. High removal or yield can coexist with intensive chemical use, secondary residues, uncertain substitution, and fragile economics. The resulting five-gate framework operationalizes recurring evidence gaps through prevention, representative performance, residual and exposure control, life-cycle sustainability and economic additionality, and implementation feasibility. Its contribution is an evidence-linked checklist, not a new assessment method or validated technology ranking. Environmental LCA, techno-economic assessment, social LCA, and explicitly framed carbon accounting support the gates. Decisions should advance only when the information needed for the next commitment is available; unresolved safety or burden-transfer risks require redesign rather than an automatic move to more intensive treatment.

**Keywords:** industrial waste; waste prevention; circular economy; industrial symbiosis; resource recovery; industrial wastewater; life-cycle assessment; techno-economic assessment; zero-waste manufacturing

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## 1. Introduction

Industrial waste is not a single environmental problem but a family of material, chemical, biological, and informational failures distributed across production systems. A ton of

homogeneous metal scrap with a stable buyer is fundamentally different from a ton of saline wastewater containing trace metals, a solvent-rich sludge, a contaminated polymer mixture, or a variable organic residue. Treating these flows as an undifferentiated quantity obscures the properties that determine risk and recoverability: concentration, phase, toxicity, calorific value, moisture, variability, contamination, geographic dispersion, and temporal reliability. Earlier waste-management literature helped establish integrated planning and the waste hierarchy, but much of it was developed around municipal systems and is transferred to industry without sufficient attention to process specificity [1–3]. Industrial decisions require a more granular unit of analysis: the waste-producing operation and its connection to upstream design, on-site utilities, downstream markets, regulation, and neighboring facilities.

The conventional response has been to classify waste and then select a treatment technology. That response is necessary for existing liabilities, but it is an incomplete sustainability strategy. It takes the production process as fixed, treats waste as an inevitable output, and often measures success as percentage removal from a liquid or gas phase. Removal is not destruction. Adsorption moves contaminants into spent media; coagulation transfers them into sludge; membranes produce a cleaner permeate and a concentrated retentate; advanced oxidation can transform parent compounds while leaving energy use, salts, and intermediates outside the reported boundary. Thermal treatment reduces volume and may recover energy, yet also generates ash, air-pollution-control residues, and capital lock-in. Even recycling can circulate hazardous additives or stimulate demand for a waste stream whose prevention would have produced a larger benefit [4–6]. A credible critical review must therefore ask where pollutants and burdens go, not merely whether they disappear from the measured effluent.

Circular-economy and industrial-ecology research broadens the frame by emphasizing retained value, by-product exchange, and system-level resource productivity. Industrial symbiosis can connect one facility's residual heat, water, gas, mineral residue, or organic by-product to another facility's input. Recent work demonstrates sophisticated methods for mapping regional networks and evaluating their resilience, but it also reveals that exchange is conditional on quality, quantity, timing, distance, confidentiality, contracts, and regulatory definitions [7–9]. A technically possible match is not necessarily a durable transaction. Moreover, a dense network is not automatically circular: exchanges can be one-way, dependent on a single anchor firm, vulnerable to price changes, or dominated by low-value applications that delay rather than prevent disposal. Industrial symbiosis should therefore be evaluated as an adaptive socio-technical system rather than celebrated as a collection of bilateral exchanges.

Recent literature also expands the technical repertoire. Advanced membranes, electrochemical processes, cold plasma, engineered sorbents, anaerobic systems, biochar, and hybrid treatment trains promise higher removal, water reuse, and resource recovery. The strongest recent studies increasingly pair performance experiments with life-cycle assessment (LCA), techno-economic assessment (TEA), or optimization. These studies are valuable because they expose conflicts hidden by a single performance indicator. For photovoltaic industrial wastewater, routes with resource recovery can substantially reduce climate impacts, but chemical production remains a major hotspot [10]. In textile wastewater, a treatment train with the best effluent performance is not necessarily the least expensive or least burdensome option [11]. Secondary lead production achieves a large greenhouse-gas advantage over primary smelting, yet some toxicity, chemical-use, and water indicators can worsen [12]. Such results challenge the assumption that technology is sustainable because it is circular in material terms.

The evidence base remains difficult to compare. Removal efficiencies are reported at different influent concentrations, pH values, contact times, temperatures, adsorbent doses,

hydraulic retention times, and analytical endpoints. Reviews often reproduce maximum values without distinguishing real from synthetic wastewater, continuous from batch operation, or pilot from commercial scale. Economic analyses use different currencies, energy prices, lifetimes, discount rates, and credits for recovered products. LCA studies vary in functional unit, allocation, system boundary, background database, regional electricity mix, and treatment of avoided production. These differences are not minor methodological details; they can reverse rankings. An adsorbent that removes 100% of a dilute contaminant at high dosage may have a low mass-normalized capacity. A process that becomes profitable only by crediting unverified product sales or negative-emission benefits is not equivalent to a bankable full-scale installation. Critical synthesis requires attention to denominators, boundary choices, and evidence maturity.

This review therefore addresses four questions. First, where can process modification, material substitution, eco-design, and operational control prevent waste or reduce its hazardousness before treatment? Second, how do physical, chemical, biological, and thermal technologies compare when performance is interpreted together with inputs, secondary residues, robustness, and scale? Third, under what conditions do resource recovery, industrial symbiosis, and digital coordination produce additional environmental and economic value rather than burden shifting or circularity claims without verified outcomes? Fourth, what research and governance changes are required to move from laboratory efficacy to reliable industrial systems?

*Review Scope, Corpus Construction, and Appraisal*

This is a purposive critical integrative review of industrial wastewater, sludges, and solid residues generated by manufacturing and associated resource-processing operations. It addresses prevention and recovery decisions, not comprehensive coverage of every waste technology. Municipal collection, household behaviour, general air-pollution control, and clinical waste are outside the primary performance scope; selected adjacent-sector publications are used only as explicitly identified methodological analogies. The initial collection comprised 48 supplied article files in five thematic groups. One exact duplicate left 47 unique candidates, of which 42 are retained in the cited evidence set. The initial 95-reference bibliography comprised these 42 retained papers and 53 complementary sources. Eleven targeted additions during revision bring the cited total to 106, comprising 42 retained collection papers and 64 complementary sources. Appendix A gives the counts, source manifest, eligibility rules, and provenance limitations.

The initial collection was assembled purposively, not generated by a documented reproducible database search. Contemporaneous database exports, exact historical queries, search dates, and a record of independent second-author screening or extraction were not available for the retrospective audit; none is claimed here. The audit reconciled full-text files with the bibliography, checked the reviewer-identified quantitative claims against source passages and tables, and assigned source-type and operational-evidence codes. A dated, targeted public-source search on 14 September 2026 supplied missing assessment and decision-method literature (Appendix A.3). The blank extraction form is reproduced in Appendix B. Common appraisal questions cover function, feed, scale, duration, balances, product quality, residual fate, counterfactual, uncertainty, and conflicts in reporting, but their application is study-type specific: a review supports mechanisms and gaps; a model supports conditional scenarios; observational data support contextual associations; experiments support only the conditions tested. No numerical quality score, pooled effect, or independent duplicate extraction is claimed. Coverage is judged sufficient to develop a bounded decision checklist, not to estimate sector-wide performance or establish literature saturation. Table 1 summarizes the lens used in the critical review.

**Table 1.** Evaluative lens used in this critical review.

| Criterion | Decision Question | Minimum Credible Evidence | Frequent Red Flag | References |
|---|---|---|---|---|
| Prevention | Can generation, toxicity, or complexity be avoided? | Functional baseline; material-flow and hazard change; rebound check | Treatment is assumed before process or design alternatives are tested | [13,14] |
| Technical efficacy | Does the option achieve the required function under representative conditions? | Realistic feed; operating conditions; duration; recovery and product quality | Maximum removal from a dilute synthetic batch is generalized to industry | [15,16] |
| Residual control | Where do contaminants and mass go? | Closed mass balance; sludge, concentrate, off-gas, spent media, and toxicity data | Disappearance from one phase is described as destruction | [6,17] |
| System benefit | Are total burdens lower than the counterfactual? | Transparent functional unit, boundary, substitution ratio; environmental and social life-cycle assessment | Full virgin-production credit is assigned to a lower-quality output | [18–21] |
| Economic feasibility | Is the option viable without implausible revenue or omitted costs? | CAPEX, OPEX, replacement, downtime, residual cost, market and sensitivity analysis | Profit depends on unverified product or carbon-credit prices | [10,19] |
| Implementation | Can performance persist at scale? | Pilot or full-scale evidence; permits; skills; contracts; monitoring; contingency | A conceptual framework or simulation is presented as achieved performance | [9,22] |

Figure 1 organizes the order in which alternatives should be considered: prevent loss and hazardousness, retain useful material, recover resources, treat remaining contaminants, and control terminal residues. It is a hierarchy of options, not evidence of certification. Figure 2, introduced after the synthesis, instead tests whether a particular option has adequate evidence to proceed. The two figures are used together: select a hierarchy-consistent candidate with Figure 1, then interrogate its evidence and consequences with Figure 2. Feedback can reopen upstream design choices when downstream burdens prove unacceptable.

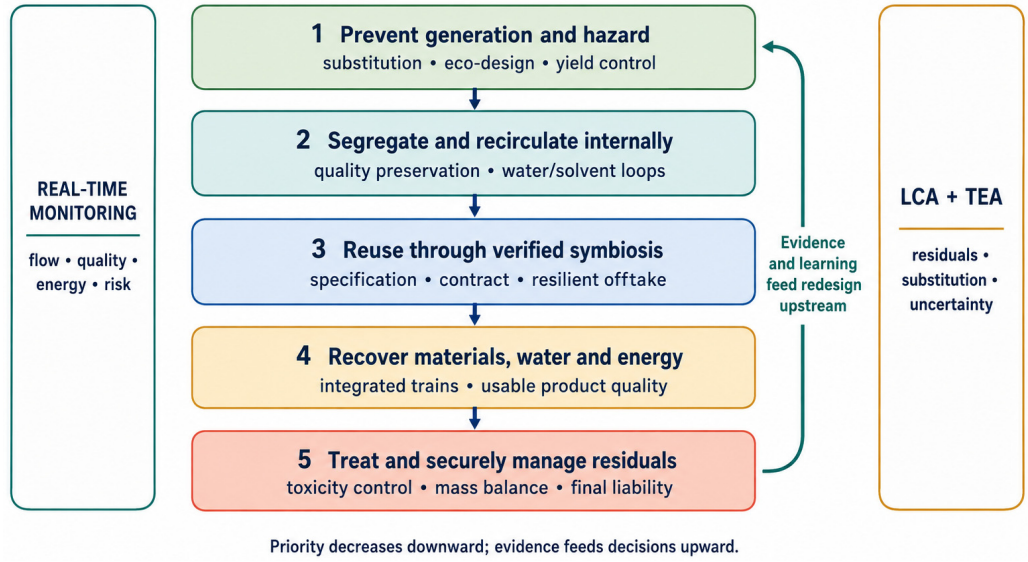


**Figure 1.** Industrial-waste hierarchy as an adaptive feedback system. This figure prioritizes management options; Figure 2 evaluates whether a selected option has adequate evidence for the next decision. The figures therefore describe option ordering and evidence checking, respectively.

## 2. Industrial Waste Heterogeneity, Risk, and System Boundaries

### *2.1. Waste Classification Is a Decision Variable, Not an Administrative Label*

Industrial waste is commonly classified by physical state, source sector, or hazardous status. These categories support reporting and compliance, but they are insufficient for technology selection. A liquid may be a pumpable wastewater, an unstable emulsion, an organic solvent suitable for distillation, or a slurry whose solids determine the viable recovery route. A "solid" residue may contain 60% moisture, release metals under acidic conditions, self-heat, or generate dust. Hazard classification may depend on concentration thresholds and leaching tests that do not capture long-term transformations. End-of-waste status can also change incentives: if a recovered output cannot meet product specifications or loses traceability, it remains a disposal liability even after substantial processing [6,23].

A decision-relevant characterization should combine at least five dimensions. The first is material value: concentration of metals, nutrients, polymers, organics, energy, or water that can displace a primary input. The second is hazard: acute and chronic toxicity, persistence, mobility, flammability, corrosivity, infectious potential, and incompatible mixtures. The third is treatability: particle size, solubility, biodegradability, salinity, buffering capacity, fouling propensity, and thermal behaviour. The fourth is logistics: generation rate, variability, storage stability, and distance to a user or treatment facility. The fifth is institutional fit: applicable permits, liability, product standards, chain-of-custody data, and market acceptance. These dimensions explain why a high theoretical recovery value does not guarantee a feasible recovery system.

Table 2 links representative waste streams to the properties that control management. The table deliberately avoids prescribing one "best available" technology. Instead, it shows how the same nominal stream can lead to different strategies. Metal-bearing wastewater at high concentration may justify selective precipitation or electrochemical recovery, whereas low concentrations in a complex matrix may require polishing and generate a better residual when managed as hazardous waste. Clean thermoplastic production scrap can often be mechanically recycled internally; mixed post-use plastics with unknown additives may require sorting, decontamination, or exclusion from sensitive applications. Homogeneous food-processing residues can support anaerobic digestion or biorefining; contaminated mixed organics may not.

**Table 2.** Waste-stream attributes that determine viable management pathways.

| Stream | Value-Bearing Attribute | Risk/Treatability Constraint | Decision Implication | References |
|---|---|---|---|---|
| Metal-bearing water/sludge | Recoverable metal concentration and selectivity | Mixed ions, chelants, pH, sludge leaching | Recover selectively at high concentration; polish dilute residuals; verify product purity | [12,24] |
| Oil-rich water/emulsion | Oil, water, and sometimes heat recovery | Droplet size, surfactants, salinity, dissolved organics | Use staged separation and pretreatment; manage concentrate and membrane fouling | [25,26] |
| Solvent/process liquor | High embodied energy and chemical value | Azeotropes, impurities, fire and exposure hazards | Segregate at source; distil or extract only where reuse specification is stable | [17,19] |
| Polymer/composite scrap | Polymer or fiber value; embodied energy | Additives, multilayers, degradation, unknown chemistry | Prioritize design and clean internal loops; restrict unsafe or low-quality circulation | [4,5,27] |
| Mineral residues | Aggregate, binder, or metal content | High mass, moisture, variability, leaching and durability | Local use can be favourable; test functional substitution and long-term fate | [28,29] |

**Table 2.** *Cont.*

| Stream | Value-Bearing Attribute | Risk/Treatability Constraint | Decision Implication | References |
|---|---|---|---|---|
| Organic residues | Biochemicals, nutrients, methane, heat, char | Moisture, pathogens, inhibitors, contaminants, seasonal supply | Cascade high-value recovery before energy; assure digestate/char quality | [30,31] |
| Hazardous legacy stocks | Potential metals or salts | Uncertain inventory, containment, exposure, mixed hazards | Risk-prioritize characterization; recovery must not destabilize containment | [32] |

### *2.2. Environmental Impact Depends on Fate, Exposure, and Substitution*

The impact of industrial waste is mediated by its fate and exposure pathway. Metals do not biodegrade and can accumulate in sediment or biosolids; persistent organics may transform into products with different toxicity; salts can impair freshwater ecosystems and limit biological treatment; oils reduce oxygen transfer and carry hydrophobic pollutants; fine particles and volatile compounds create occupational and regional air risks. Land disposal can isolate material in the short term but creates long-duration obligations for leachate, gas, and containment integrity [33,34]. Thermal treatment changes rather than eliminates the material balance, partitioning elements among flue gas, bottom ash, fly ash, and recovered metals. Accordingly, risk assessment must be connected to mass balance and speciation, not just total mass.

Recovery introduces a second question: what primary production is actually displaced? A recovered material that fails specification, travels long distances, or is used in a low-value application may provide less benefit than its tonnage suggests. Substitution is rarely one-to-one. Recycled polymer can lose mechanical properties or retain additives; mineral residues used in concrete can alter water demand, durability, or leaching; recovered nutrients may require concentration and quality assurance; waste-derived fuel can replace energy while increasing local emissions or ash. The de Azevedo et al. [35] analysis of industrial residues in cementitious composites illustrates the importance of local material performance and economic conditions. Recent coal-gangue research similarly indicates that modest substitution can retain useful strength, whereas high replacement levels can produce 20–30% strength losses and greater water absorption unless activation and mix design are optimized [29]. The avoided burden should therefore be based on demonstrated functional equivalence, not equal mass.

Polymer circulation illustrates why composition, and recovery yield must be assessed together. Mixed polymers, additives, multilayers, and contaminated feed can require separation and purification that offset nominal circular gains [4,5,27]. Laboratory process integration also shows why reaction conversion cannot stand in for saleable product recovery: Luo et al. couple PLA hydrolysis with electrodialysis and LCA, but recovery testing uses a simplified lactate solution rather than proving continuous processing of mixed industrial waste [36]. This is a controlled proof of integration with modelled system implications, not commercial validation. Product purity, residual salts, reagent recovery, and realistic feed variability remain part of the decision boundary.

### *2.3. Functional Units and Boundaries Can Reverse Conclusions*

Comparisons require a functional unit that reflects the service delivered. “One ton of waste treated” may be suitable for disposal systems, but it can mislead when influent concentration and treatment target differ. Wastewater technologies can be compared per cubic meter only when pollutant loads and effluent requirements are similar; otherwise

a load-based unit or multi-functional description is needed. Material recovery should account for quality-adjusted output. Product redesign may require a unit such as one service-year, one packaged delivery, or one component meeting a specified performance. Reusable packaging, for example, becomes advantageous only after enough reuse cycles to offset heavier production and return logistics, and actual loss and washing rates matter [37].

System boundaries are equally influential. A gate-to-gate study may identify on-site electricity and chemical use but omit production of equipment, upstream reagents, downstream residue treatment, infrastructure, or transport. Expansion or substitution credits can dominate results, especially for energy and recovered products. Waste heat may be treated as burden-free, even where its availability depends on a carbon-intensive anchoring process. Biochar may receive carbon storage credits without testing permanence or alternative uses of biomass. Recovered materials may receive full virgin-production credits although they displace only a lower-grade product. Economic studies can likewise exclude land, labor, maintenance, financing, quality control, downtime, and permit costs. High-quality decision support should report results with and without major credits, disclose the replacement ratio, and test plausible energy and commodity prices [18,19].

The conclusion is not that LCA or TEA is too uncertain to use. On the contrary, they are essential precisely because treatment moves burdens across processes and impact categories. Their role is not to produce a universal ranking but to make assumptions visible, identify hotspots, and test whether an option remains preferable under realistic variation. The most useful studies integrate performance, environment, and economics around the same mass and energy balance. Studies that attach generic impact factors to a maximum laboratory removal percentage provide much weaker evidence.

## 3. Prevention, Process Modification, Eco-Design, and Zero-Waste Manufacturing

### *3.1. Prevention Changes the Denominator*

Waste prevention is often endorsed rhetorically but underdeveloped analytically. Treatment studies begin with a fixed influent; symbiosis studies begin with an available by-product; recycling studies begin with an end-of-life material. Prevention asks whether flow, toxicity, or complexity can be avoided while preserving the production function. This changes the denominator from "waste treated" to "service or product delivered." Cleaner production may reduce raw material loss, water use, off-specification production, chemical inventories, packaging, trimming, and cleaning waste. It can also reduce the treatment capacity and risk controls required downstream. Because prevented waste is not measured at the treatment plant, its benefits can disappear from performance dashboards unless material-flow accounting is linked to production data.

The prevention hierarchy has four distinct mechanisms. Input substitution replaces hazardous or difficult-to-recover substances. Product and packaging design reduce material diversity and facilitate disassembly, repair, reuse, and high-quality recycling. Process intensification and operational control increase yield and reduce rejected batches, leaks, over-dosing, purge streams, and unnecessary water or energy. Business-model and supply-chain changes retain ownership, standardize components, introduce take-back, or shift from product sales to service provision. Deutz et al. [13] correctly framed waste management as a product-design requirement rather than an end-of-pipe responsibility. More recent circular-manufacturing models reinforce the connection among product architecture, operations, supplier coordination, reverse flows, and data, although many remain conceptual and lack longitudinal validation [38].

Prevention can create trade-offs. Replacing a hazardous solvent with water may increase energy for drying or wastewater volume. Lightweight packaging may become multilayered and harder to recycle. Longer-life products can use more material or impede

adoption of more efficient technologies. Tight internal water recycling can concentrate salts and organics, increasing corrosion, fouling, or purge-treatment difficulty. Lean production can reduce inventory yet create more frequent transport. The appropriate question is therefore whether a change lowers total life-cycle burden for a defined function, not whether it reduces one waste stream at the factory gate.

### *3.2. Process Modification and Internal Recirculation*

Process-level prevention begins with measurement. Submetering water, chemicals, energy, and yield by production step can reveal losses that aggregate facility data conceal. Statistical process control and predictive maintenance can reduce off-specification batches and catastrophic releases. Counter-current rinsing, dry cleanup before washing, optimized cleaning-in-place, bath-life extension, drag-out recovery, segregated collection, closed-loop cooling, and heat integration are mature measures with potentially rapid payback. Their limitations are context-specific: contaminant accumulation, cross-contamination, worker exposure, product-quality tolerances, and the cost of retrofitting legacy equipment.

Digital technologies improve visibility but do not independently create circularity. Sensors, industrial Internet of Things platforms, machine learning, and digital twins can forecast quality drift, locate leaks, schedule exchange, and optimize treatment. Fatimah et al. [39] and Mukherjee et al. [40] show the breadth of smart-waste applications, while Wang et al. [41] and Ali et al. [42] connect Industry 4.0 to industrial parks and circular practices. Yet econometric association, simulation, or prototype classification accuracy is not proof of net waste reduction. Digital systems consume equipment and energy, require interoperable data, and can amplify poor objectives. A model optimized for lowest treatment cost may favor dilution or off-site transfer unless material loss, toxicity, and life-cycle impacts are explicit constraints. Data quality, calibration, cybersecurity, workforce competence, and ownership of commercially sensitive flow data are practical adoption conditions.

Internal recirculation is generally more controllable than external exchange because the producer understands material provenance and can align schedules. However, repeated cycling can accumulate trace contaminants and degrade material properties. Closed-loop water systems need side-stream treatment and a managed purge. Polymer regrind requires limits on thermal history and contamination. Metal scrap recovery depends on alloy segregation. Solvent recovery requires analysis of azeotropes, stabilizers, and impurities. The prevention benefit should be quantified as avoided virgin input and avoided treatment, net of additional separation and quality-control burdens.

### *3.3. Eco-Design and Design for Recovery*

Eco-design determines what downstream systems can achieve. Design for disassembly reduces destructive joining and enables component reuse. Material simplification avoids incompatible polymers and problematic coatings. Standardized fasteners, modular components, accessible batteries, material passports, and reversible adhesives can improve repair and recovery. Extended producer responsibility (EPR) can align incentives by making producers financially or operationally responsible for end-of-life products, but policy design matters. A joint tax-subsidy model may increase collection and recycling, yet poorly calibrated fees can reward tonnage without rewarding durability, non-toxic composition, or closed-loop quality [43]. EPR performance therefore depends on eco-modulated fees, verified treatment, transparency, and enforcement against free riders and exports.

Plastics demonstrate why design must address both physical recyclability and chemical safety. A package can be sortable by polymer type while still containing additives that restrict recycled-content applications. Abbasi et al. [4] propose a framework for iden-

tifying chemicals of concern across the plastic value chain, and Jahnke et al. [5] call for simpler formulations, transparent composition, precycling, and cross-sector standards. These proposals challenge mass-based recycling targets. If hazardous or unknown additives circulate into toys, food-contact materials, building products, or informal recycling, a high recycling rate can increase exposure. Quality- and safety-adjusted indicators should accompany tonnage.

Textiles illustrate a different design problem: cutting layouts and product variety generate pre-consumer scrap even before consumer use. Zero-waste pattern cutting can integrate pattern geometry into aesthetic and production decisions, reducing offcuts but requiring designer skills, supplier coordination, and adaptation of automated cutting and sizing systems [44]. The approach is strongest when prevention is measured against marker efficiency and total material purchased, not showcased through individual garments. At scale, returns, mixed fibers, coatings, elastane, trims, and fast-fashion volume can overwhelm gains from efficient cutting. Design innovation must therefore be coupled to demand, durability, and reverse logistics.

Wind-tower manufacturing is retained as a bounded evidence-gap example, not a representative performance benchmark. Cases-Valbuena et al. identify only six eligible studies on paint sludge and welding slag valorization, with much of the usable evidence transferred from other manufacturing sectors [28]. Early construction-material results cannot establish the safety or durability of wind-sector residues with different formulations. The subsection therefore supports requirements for source-specific characterization and long-term leaching and durability tests, not an industry-wide claim of emissions reduction or commercial readiness.

### *3.4. Zero Waste as Direction, Metric, and Potential Distraction*

Zero waste is useful as a directional principle because it privileges prevention and system redesign. Pietzsch et al. [14] identify benefits, barriers, and critical success factors, while Zaman [22] distinguishes the emphases of industrial ecology, circular economy, and zero waste. Industrial ecology is strongest at process, facility, and network optimization; zero waste often emphasizes prevention, behavior, and local governance; circular economy spans value-retention strategies and business models. Their overlap is productive, but terminological convergence should not hide differences in scale and accountability.

As a literal performance claim, "zero waste" is problematic. Facilities may achieve zero waste to landfill by incinerating residues, exporting them, stockpiling uncertain by-products, or classifying low-value applications as recycling. Waste-prevention plans can also become aspirational when responsibility, indicators, and enforcement are weak [45]. A mass diversion rate assigns equal value to prevention, reuse, recycling, and energy recovery, although their environmental consequences differ. Pires and Martinho [46] provide a hierarchy-sensitive index, but any aggregate indicator depends on classification and data quality. A stronger industrial metric set includes waste intensity per functional output, hazardous-material intensity, virgin-material displacement, quality-adjusted recovery, residual toxicity, greenhouse-gas impact, water burden, and the fraction independently verified. It should also show absolute waste generation, because efficiency gains can be offset by production growth.

Empirical work on manufacturing firms suggests that zero-waste management and green innovative supply chains may improve environmental and operational performance through organizational capabilities [47]. This mechanism is plausible: firms need sensing, learning, supplier development, and reconfiguration to convert isolated practices into sustained results. Nevertheless, cross-sectional survey relationships are vulnerable to common-method bias, self-reporting, and reverse causality. High-performing firms

may adopt more visible green practices rather than the practices causing performance. Longitudinal data tied to audited material flows are needed.

Table 3 compares prevention strategies according to mechanism, evidence, and failure mode. The table emphasizes that prevention measures are not automatically superior; they earn priority because they can remove downstream burdens, but only when function, exposure, and rebound are assessed.

**Table 3.** Prevention and zero-waste strategies: mechanisms, benefits, and limitations.

| Strategy | Primary Mechanism | Potential Benefit | Critical Limitations or Test | References |
| --- | --- | --- | --- | --- |
| Material substitution | Replace hazardous or unrecoverable input | Lower toxicity and simpler downstream treatment | Check life-cycle trade-offs, product performance, and new exposure pathways | [4,5] |
| Yield/process control | Reduce off-specification output, leaks, purge, and over-dosing | Immediate raw material and treatment savings | Requires granular metering, operator capability, and normalized production baseline | [13,48] |
| Internal recirculation | Reuse water, solvent, scrap, or heat within facility | Preserves provenance and avoids transport | Contaminant accumulation and quality degradation require purge and monitoring | [38,39] |
| Eco-design/disassembly | Simplify materials, joining, repair, and component access | Higher reuse and closed-loop recovery | Benefits occur later and require supply-chain and product-standard alignment | [13,27] |
| EPR and take-back | Shift end-of-life responsibility and information upstream | Collection, design feedback, and financing | Flat fees and mass targets may reward low-quality recovery or exports | [43,49] |
| Zero-waste target | Mobilize prevention and hierarchy-based action | Cross-functional ambition and visibility | "Zero landfill" can mask incineration, transfer, or stockpiling; track absolute waste | [14,22] |
| Digital optimization | Predict loss, maintenance, quality drift, and exchange | Faster prevention and control decisions | Data quality, cybersecurity, rebound, and objective-function bias | [39,42] |

## 4. Industrial Symbiosis and Resource Exchange

### *4.1. From Matching Exercises to Resilient Networks*

Industrial symbiosis is commonly defined as the exchange of materials, water, energy, infrastructure, or services among otherwise separate organizations. Its intuitive appeal is strong: a by-product replaces a purchased input, reducing waste and virgin extraction. Early optimization studies focused on identifying matches and minimizing cost or environmental burden [50,51]. Recent research shows that a network is dynamic. Firms enter and exit; product specifications change; energy systems decarbonize; commodity prices fluctuate; and a waste producer may reduce its output through cleaner production. A resilient network must adapt without creating dependence on continued waste generation.

Domini et al. [7] combine material-flow and social-network analysis in a highly industrialized Italian region; Fric et al. [8] examine network complexity, cyclicality, and resilience. These are observational network analyses, not controlled demonstrations that additional exchanges caused environmental improvement. Palagonia et al. [9] synthesize 137 articles on policy, collaboration, information, technology, organization, and value, while Genc [52] uses ecological-network analogies to explore resilience. The reviews supply organizing concepts; the observational studies supply contextual patterns. Neither source type replaces measured displacement and post-implementation verification.

A practical exchange requires a specification, not just a material name. Quantity and composition must fit the receiving process; timing must match production schedules or

storage must be available; pretreatment and transport must not erase the benefit; liability for contamination must be assigned; and the exchange must remain viable under plausible price changes. Confidentiality can prevent disclosure of material composition. Regulatory status can make firms reluctant to accept a legally defined material as waste. Financing is difficult when payback depends on multiple firms with unequal bargaining power. Trust is necessary, but contracts, verification, and contingency plans are equally important.

The anchor-firm model can accelerate development because a large stable facility supplies heat, steam, water, carbon dioxide, or a high-volume by-product. It can also create systemic vulnerability. If the anchor shuts down, decarbonizes, changes feedstock, or internalizes the by-product, dependent firms lose a critical input. Fossil-refinery waste heat can support nearby users but risk locking the region into the refinery's operation. A resilience assessment should therefore simulate supplier loss, demand loss, transport interruption, quality deviation, and regulatory change. Agent-based modelling provides a useful laboratory for these dynamics, as shown by Fussone et al. [53], but simulated agents simplify negotiation, investment behavior, and regulatory uncertainty. Results should guide stress testing rather than be reported as forecast savings.

### *4.2. Measuring Additionality and Avoiding Low-Value Lock-In*

The environmental benefit of an exchange is the difference between two complete systems: management of the by-product without the exchange plus production of the displaced input, versus collection, conditioning, transport, use, and eventual fate with the exchange. If mineral residue replaces natural aggregate, the relevant displacement may be limited by strength, durability, density, and transport distance. If waste heat replaces natural gas, temperature grade, seasonal demand, infrastructure loss, and future grid decarbonization matter. If an organic by-product becomes animal feed or a biorefinery input, food-safety controls and the prior use of the residue matter.

Low-value applications can be environmentally sensible when they safely displace abundant primary material with little processing. They can also lock material into diffuse products, complicate later recovery, and create large future liabilities. Incorporating contaminated residues into construction materials may immobilize pollutants during use but disperse them across buildings and roads. Long-term leaching, demolition, and end-of-life management should be part of the assessment. The same caution applies to "downcycling" plastics and composites. Circularity should be evaluated over multiple cycles and uses, not at the first diversion from landfill.

Bai et al. [54] analyze 48 Chinese industrial-waste resource-utilization centers and link operational paradigms to multidimensional efficiency. The study contributes empirical scale beyond single exchanges, yet center-level efficiency depends on regional industrial structure and policy support. Efficiency scores are relative to the sampled frontier; they do not establish absolute sustainability or safe product quality. Case-specific text and indicator selection can also shape classification. The results are most useful for identifying organizational patterns and underperforming dimensions, not for declaring a universally optimal model.

Santana Filho et al. [55] propose a governance-centered rural biomass hub in Portugal. The proposal illustrates aggregation, shared infrastructure, and offtake coordination, but it is not operating evidence. Its headline annual carbon-saving estimate is not retained as a quantitative benchmark because the baseline, displacement assumptions, and calculation boundary are not sufficiently specified for independent reconstruction. A project appraisal would need a no-hub counterfactual covering existing biomass uses, transport, conversion, displaced products and energy, followed by measured updates during staged implementation.

Biorefinery integration can increase value by fractioning organic residues into fuels, chemicals, materials, nutrients, and energy rather than maximizing one output. Barathi et al. [56] synthesize industrial symbiosis, biorefineries, circular economy, and sustainable development goals, but the breadth of the framework creates an evaluation challenge. Adding pathways increases system flexibility and potential value while also increasing capital, pretreatment, process control, and market exposure. A robust biorefinery should be optimized for changing feedstock and product prices and should report what happens to water, nutrients, inhibitors, and unusable solids.

### *4.3. Governance and the Geography of Exchange*

Industrial symbiosis cannot be scaled by technology platforms alone. Coordinating organizations may map flows, convene firms, standardize data, resolve permits, aggregate small volumes, and help finance shared infrastructure. Public policy can support feasibility studies, common utilities, product standards, and risk-sharing, but subsidies should target verified additionality rather than the existence of an exchange. Munonye et al. [57] emphasizes the policy-to-practice gap, especially in developing and transitional economies. The gap reflects not only insufficient policy ambition but also enforcement capacity, informality, infrastructure, credit constraints, and uneven distribution of benefits.

Geography determines which exchanges work. Bulky, wet, low-value materials tolerate short distances; concentrated metals or specialty chemicals can justify longer transport. Heat is particularly local. Shared wastewater treatment may create economies of scale but can dilute source responsibility and expose biological systems to toxic shocks. Regional mapping should combine material quantity and quality with transport, utility corridors, water stress, community exposure, and future land use. Social network measures can identify brokers and isolated firms, but material-flow verification is still required.

The governance literature also warns against treating consensus as frictionless. Firms have different objectives and bargaining power. A waste producer may avoid disposal cost while the user bears quality risk. Communities may experience truck traffic or emissions while private firms capture value. Nuur et al. [58] show, in the mining context, that circular-economy language can legitimize continued extraction and shift attention from demand reduction and environmental justice. Similar caution applies to industrial-waste recovery generally. A circular project should disclose who owns the material, who bears liability, which primary activity is displaced, and how benefits and risks are distributed.

Industrial symbiosis is therefore best treated as a portfolio of verified exchanges within a regional transition strategy. Some exchanges will be temporary bridges while upstream processes change; others can support durable closed loops. Contracts should accommodate changing quantities, and infrastructure should avoid single-purpose lock-in where possible. Network performance should be reported as absolute virgin-material displacement, avoided treatment, net emissions, economic value, and resilience under disruption, not simply tons exchanged or number of participants.

## 5. Physical, Chemical, Biological, and Thermal Technologies

### *5.1. Technology Classes Are Functions Within Treatment Trains*

A treatment train should be designed from the waste characteristics and the required function, rather than by adding fashionable technologies. Decision methods and multi-criteria analysis support comparison, but transparent process models must generate the material and utility inventories used by those assessments [16,19]. Process systems engineering supplies this missing link. Water-pinch analysis targets reuse and regeneration subject to contaminant-load and concentration constraints [59]; heat-pinch analysis tests recovery against temperature-grade and heat-demand constraints. Simulation and constrained op-

timization then reconcile stream balances, equipment limits, recycle accumulation, and uncertainty. Value analysis is located where marginal changes in process streams or constraints create or destroy economic value [60]. Such targets are not automatically achievable plant savings: fouling, safety, operability, and retrofit constraints must be included before evaluating an integrated alternative.

Equalization and segregation are often more important than novel reactors. Equalization dampens flow, pH, temperature, and pollutant shocks, permitting smaller and more stable downstream units. Source segregation prevents a dilute toxic stream from contaminating a large biodegradable flow and preserves concentrated materials for recovery. Oil–water separation protects membranes and biological processes. Solids removal reduces abrasive wear and chemical consumption. These operations may not produce headline removal efficiencies, yet their failure explains why laboratory technologies underperform at plant scale. Table 4 summarizes representative quantitative evidence from the selected studies. Values are retained with their key conditions and caveats because percentages without denominators are not comparable. The table includes both experimental and modelled studies but labels them accordingly. It is not a league table; it demonstrates why removal, capacity, energy, cost, scale, and residual management must be read together.

**Table 4.** Representative quantitative performance and the conditions that limit interpretation.

| Study/Stream | Evidence | Configuration and Basis | Reported Performance/Basis | Resource or Cost/Basis | Interpretation | References |
|---|---|---|---|---|---|---|
| Produced water | R | Review; diverse feeds, units and scales. | No common feed or endpoint; pooled maxima are not retained. | Energy/cleaning percentages lack a harmonized comparator. | Mechanism and integration guidance only; no single operational level assigned to a mixed review. | [26] |
| Photovoltaic wastewater | L4 + M | Fluorine pilot: 30 days, 1 t/h. Route inventory uses 1 kg $F^-$ and 1 kg $NH_3$-N loads. | Routes 1–4: 27.73/17.64/ 11.58/11.56 kg $CO_2$-eq on that combined inventory basis. | Total internal + external costs: Route 3 CNY 42.36; Route 4 CNY 84.82, on the same basis; not CNY/$m^3$. | Pilot applies to fluorine recovery; whole-route comparisons include literature inputs and product credits. | [10] |
| Textile scenarios | M | Reference flow 13.7 $m^3$/h; FU 13,700 kg wastewater (one hour). | Source Table 2: Scenario 4 COD 3.17 and $BOD_5$ 0.14 mg/L; source Table 4 conflicts on COD. | Facility CAPEX EUR 0.75–2.7 million; OPEX EUR 0.274–2.6 million/year. | No secure single final COD is asserted; scenario outcomes are not independently verified plant guarantees. | [11] |
| Integrated textile treatment | L3 + M | 125-day synthetic-feed laboratory UASB; lab polishing/pyrolysis; projected 50 $m^3$/day. | Combined laboratory effluent: COD 49.8 mg/L; $NH_4$-N 1.36 mg/L. | Projected IRR 13%; payback 5.43 years; −6.63 kg $CO_2$-eq/$m^3$ influent under source credits. | L3 describes the continuous reactor, not a full commercial train. The commercial energy claim lacks an explicit denominator. | [31] |
| Food-waste biochar | L2 | 600 °C pyrolysis; dilute batch adsorption; adsorbent dose 2 g/L. | Pb removal up to 100%; phenol up to 82%, relative to initial dissolved concentration; capacities 0.376 and 0.238 mg/g adsorbent. | No verified plant cost or LCA advantage from a waste feedstock alone. | Removal fraction is not throughput or capacity; activation, washing, real-feed competition and spent media matter. | [30] |
| Industrial COD sorption | L2 | Batch dose series; initial COD 250 mg/L. | At 3 g/L: reported capacity ≈80.5 mg/g; 96.8% removal implies ≈80.7 mg/g. | 484 mg/g reported elsewhere cannot be coupled to the 3 g/L condition without clarification. | Section 5.3 shows the balance check; provenance and linked-condition reporting require clarification. | [61] |

**Table 4.** *Cont.*

| Study/Stream | Evidence | Configuration and Basis | Reported Performance/Basis | Resource or Cost/Basis | Interpretation | References |
|---|---|---|---|---|---|---|
| Cobalt recovery | L2 | Batch wastepaper-cellulose sensor; electroplating and battery-waste matrices. | Reported removal: 95.77% and 78.15% of initial Co(II), respectively; seven reuse cycles. | Percentages are removal from test liquids, not purified-product recovery yields. | Pretreatment, masking chemicals, sensor fate and continuous operation remain unresolved. | [24] |
| Nitrogen | R | Review of removal/recovery; full-scale survey added as a qualified comparator. | No universal energy/cost percentage retained; removal to $N_2$ is not product recovery. | Product value requires accepted purity and a market; no common cost denominator across routes. | Mixed industrial/municipal evidence; the review itself receives no L1–L6 operational level. | [62,63] |
| Lead production | L5 + M | Enterprise comparison; FU 1 ton lead. | Primary 1.84; secondary 0.51 t $CO_2$-eq/t Pb (reported reduction 72.18%). | Operating profit: USD 262.55 vs. 241.92/t Pb; carbon profitability USD 0.14 vs. 0.47/kg $CO_2$-eq. | Single enterprise; no independent L6 validation; capital, labor and maintenance excluded from profit. | [12] |
| Coal-gangue concrete | R | Review; replacement basis and mix design differ among studies. | Pooled strength/absorption maxima are not treated as a common benchmark. | No uniform avoided-cement or aggregate credit without equal product function. | Source, replacement basis, curing, durability and leaching prevent a universal optimum. | [29] |
| Waste-heat regeneration | L2 | Bench liquid-desiccant tests with simulated industrial waste heat. | Preheating from 60 to 80 °C increased regeneration rate ≈30–35% relative to the 60 °C case. | Not a measured full-plant energy saving or waste-treatment yield. | Utility-integration analogy only; heat grade, availability and counterfactual use matter. | [64] |

Evidence codes: L2, controlled experiment; L3, continuous laboratory component; L4, real-feed field pilot; L5, industrial case; M, modelled assessment; R, review. A review is deliberately not assigned a fictitious operational level. "+M" limits the operational code to measured components. Currency values remain in the source currency and price basis; no exchange-rate or inflation harmonization is implied. FU = functional unit; GWP = global-warming potential; COD = chemical oxygen demand; $BOD_5$ = five-day biochemical oxygen demand; CAPEX/OPEX = capital/operating expenditure.

### *5.2. Physical Separation and Membranes*

Physical processes exploit size, density, phase, volatility, magnetic behavior, or interfacial properties. Screens, cyclones, sedimentation, dissolved-air or induced-gas flotation, centrifuges, filters, and membranes are established because they are rapid and controllable. Their sustainability depends on the fate of the separated fraction. Concentrating oil, solids, or metals can enable recovery, but a contaminated concentrate remains a liability. Cleaning water, backwash, filter media, antiscalants, and energy belong in the balance.

Produced water illustrates staged separation, but the evidence used here is a review rather than one harmonized experiment [26]. Bulk oil separation, flotation, membranes, and polishing perform different functions on feeds whose salinity, dissolved organics, emulsifiers, scale-forming ions, and oil-droplet sizes vary by field and production age. Oil-removal, recovery, energy-saving and cleaning percentages from these studies do not provide comparable benchmarks because their conditions and denominators are insufficiently harmonized. The review supports treatment-train logic and identifies advanced-hybrid scale-up gaps; site design still requires representative feed, explicit endpoints, measured auxiliary demand, and concentrate management.

Membranes provide compact, modular separation and can produce high-quality water. Microfiltration and ultrafiltration remove particles, emulsions, and macromolecules; nanofiltration and reverse osmosis reject dissolved species; membrane distillation and electrodialysis address high salinity or selective ion transport. The trade-off is concentration

polarization, fouling, scaling, pressure or thermal demand, membrane replacement, and concentrate management. Detailed organic characterization of industrial process water is therefore a design requirement, not an academic refinement [65]. Total organic carbon alone cannot predict fouling when molecular size, hydrophobicity, charge, and interactions with salts control deposition.

Membrane performance is frequently reported as rejection percentage, but recovery ratio and concentrate quality may be more decision-relevant. Ninety-nine percent rejection at low water recovery can create a large residual volume; higher recovery reduces liquid volume but increases osmotic pressure and scaling. Cleaning restores flux at the cost of chemicals, downtime, and membrane aging. Long-duration tests should report permeability decline, cleaning frequency, irreversible fouling, specific energy, water recovery, solute mass balance, and concentrate fate. Pilot operation through seasonal and production-cycle variation is more valuable than a short stable-feed experiment.

Physical beneficiation also supports solid-waste recovery. Crushing, grinding, sieving, density, magnetic, electrostatic, and sensor-based sorting can liberate and separate metals, minerals, polymers, and components. Yet comminution consumes energy and may generate respirable dust or reduce particles to sizes that complicate later separation. Automated sorting and artificial intelligence can improve recognition, but accuracy under clean benchmark images does not establish recovery purity in dirty, overlapping, rapidly moving industrial streams [66]. A sorting system should report throughput, recovery, purity, false rejection, contamination tolerance, maintenance, and downstream product acceptance.

### *5.3. Chemical Precipitation, Coagulation, Oxidation, and Electrochemical Systems*

Chemical treatment is indispensable where pollutants are non-biodegradable, toxic, colloidal, or recoverable through selective reactions. Neutralization, precipitation, coagulation–flocculation, ion exchange, solvent extraction, adsorption, advanced oxidation, and electrochemical processes can achieve stringent targets. Their shared weakness is dependence on reagents and the production of secondary streams. Stoichiometric demand may be small relative to actual use because competing ions, buffering, and mixing inefficiencies consume chemicals. Sludge quantity, dewaterability, leachability, and disposal classification should accompany water-quality results.

Metal precipitation is robust at sufficiently high concentration, but mixed metals have overlapping pH windows and hydroxide sludge can be voluminous. Sulfide precipitation can achieve lower dissolved concentrations but introduces odor and toxicity risks. Selective crystallization, electrodeposition, or ion exchange can produce a more valuable output when concentration and composition justify the added control. Waste-derived sorbents can reduce raw-material cost, yet acid or alkaline activation, washing, regeneration, and spent-media management can dominate their footprint.

El Gamal and Gomaa [61] report high COD removal by maize-tassel activated carbon, but the reported capacities should not be combined without their dose basis. Their dose experiment gives approximately 464 mg/g at 0.5 g/L and 80.5 mg/g at 3 g/L, whereas the paper also presents 484 mg/g alongside its optimized-performance discussion. At an initial COD of 250 mg/L, 96.8% removal and a dose of 3 g/L imply approximately 80.7 mg/g through $q = (C_0 - C_e)/\text{dose}$, not 484 mg/g. This calculation checks the compatibility of the stated conditions; it does not disprove a capacity measured at another dose or a separately fitted isotherm parameter. The wastewater provenance is also described as a juice factory in the materials section and as a fertilizer factory in the collection description. Consequently, the source is retained as controlled batch evidence with insufficiently linked reporting for independent comparison, not as a design-capacity or cost benchmark. Broader biochar modelling reviews likewise do not substitute for reproducible real-effluent trials [67].

Sieradzka et al. [30] produced activated biochar from food-industry wastes by pyrolysis at 600 °C for ten minutes. Char yields were about 22–26%, and the highest reported Brunauer–Emmett–Teller surface area reached 557 $m^2/g$. Under dilute test conditions and a dose of 2 g/L, removal reached 100% for lead and 82% for phenol, yet fitted maximum capacities were only about 0.376 and 0.238 mg/g, respectively. This apparent contrast matters: high percentage removal was driven partly by low solute mass relative to sorbent dose. Concentrated activating agents, washing, char yield, and absence of real-wastewater validation weaken claims of immediate industrial sustainability. The appropriate next step is not another equilibrium test but continuous columns using competitive real matrices, regeneration cycles, leachability assessment, and cradle-to-grave comparison with commercial carbon.

Alatawi et al. [24] convert wastepaper cellulose into a cobalt-detecting and -removing nanosensor. Reported removal reached 95.77% for electroplating wastewater and 78.15% for battery waste, with reuse over seven cycles. The use of real matrices and recovery concept strengthens the study relative to synthetic-only adsorption work. However, batch operation, acid pretreatment, nanoparticle synthesis, and the use of concentrated masking agents create scale and safety questions. A circular claim requires recovery of cobalt in a saleable form, recovery or safe management of the sensor material, and an assessment of chemical and water inputs.

Advanced oxidation processes generate highly reactive species through ozone, ultraviolet light, peroxide, photocatalysis, Fenton chemistry, cavitation, plasma, or electrochemical reactions. They are useful for refractory organics and toxicity reduction, especially as pretreatment or polishing. Complete disappearance of a parent compound does not demonstrate mineralization. Total organic carbon, chemical oxygen demand, toxicity, by-products, and energy per order should be reported. Chloride, carbonate, turbidity, and natural organic matter can quench radicals or form unwanted products.

Cold plasma is retained as an emerging oxidation example supported here by one review [68], not as a mature industrial comparator. Reactor geometry, gas composition, influent concentration, and the distinction between parent-compound disappearance and mineralization prevent transfer of a reported maximum to a plant design. The decisive evidence would be a real-effluent pilot reporting the same endpoint and load as ozone or electrochemical alternatives, with complete auxiliary energy, off-gas, by-product toxicity, electrode life, and continuous operating duration.

Electrochemical technologies can avoid bulk chemical addition by generating coagulants or oxidants in situ, recovering metals at electrodes, or moving ions through selective membranes. Their performance depends on conductivity, electrode material, current density, mass transfer, passivation, and electricity carbon intensity. Electrode consumption is a reagent even when it is not dosed from a tank. Studies should report Faradaic efficiency, specific energy per mass removed or recovered, electrode loss, sludge composition, and performance under intermittent renewable power where relevant.

### *5.4. Biological Conversion and Nature-Based Systems*

Biological treatment is attractive for biodegradable organics and nutrients because microorganisms perform transformations under comparatively mild conditions. Aerobic systems are robust but consume aeration energy and generate biomass. Anaerobic systems produce methane and less sludge but require stable temperature, longer start-up, and protection from toxic shocks. Biofilms can retain slow-growing organisms; membrane bioreactors improve solids separation but introduce fouling; constructed wetlands and phytoremediation offer low-energy polishing but require land and may accumulate contaminants in biomass.

Industrial wastewater challenges biological assumptions. High salinity, solvents, metals, antibiotics, dyes, temperature, and rapidly changing loads can inhibit communities. Chemical oxygen demand does not indicate biodegradability, and color removal can occur by adsorption to sludge rather than degradation. Pilot studies should report acclimation, shock recovery, sludge yield, microbial stability, toxicity, and fate of sorbed contaminants. Reviews reporting "greater than 90% removal" across biofiltration systems are useful for identifying mechanisms but cannot support design without loading, media, empty-bed contact time, humidity, nutrient balance, and duration [69].

Nitrogen treatment requires a distinction between destruction of reactive nitrogen and recovery of a usable nitrogen product. The broad technology review [62] is supplemented by Lackner et al.'s survey of 14 full-scale partial nitritation/anammox installations [63]. That survey provides operating experience on solids, aeration control, and nitrate accumulation, but much of the wider deployment described concerns municipal sidestreams; it does not establish equivalent performance for saline, toxic, or dilute industrial feeds. Full-scale anammox experience also demonstrates nitrogen removal, not fertilizer recovery. Recovery by stripping, membrane contactors, electrodialysis, adsorption, or crystallization remains conditional on concentration, impurities, reagent demand, and an accepted product. This retained corpus is insufficient to rank those recovery routes across industrial sectors.

Dadebo et al. [31] combine a biochar-amended upflow anaerobic sludge blanket reactor, phytoremediation, and co-pyrolysis. The anaerobic reactor operated for 125 days with synthetic textile wastewater, supporting continuous laboratory evidence (L3) for that component; the complete commercial train was modelled, not demonstrated. Combined laboratory treatment achieved an effluent COD of 49.8 mg/L and ammonium of 1.36 mg/L. For a projected 50 $m^3$/day installation, the study reports an internal rate of return of 13%, a payback period of 5.43 years, and a net climate result of −6.63 kg $CO_2$-eq per $m^3$ of influent wastewater under its specified energy, product, and disposal credits. Laboratory concentrations and projected economics must not be presented as measurements from one operating plant. Real-feed variability, land demand, contaminated biomass and char, and verified offtake remain unresolved.

The case also illustrates why hybrid systems can outperform unit technologies. Anaerobic treatment removes biodegradable load and produces energy; plants or wetlands polish nutrients and residual organics; pyrolysis stabilizes some biomass and produces char and gas. However, integration creates interfaces, including harvesting, dewatering, transport, drying, pyrolysis emissions, char quality, and the return of condensates, each of which needs a mass balance. A process becomes circular only when the recovered energy and products are used and the remaining contaminants are safely controlled.

### *5.5. Thermal Treatment, Waste-to-Energy, Pyrolysis, and Waste Heat*

Thermal processes include drying, evaporation, distillation, combustion, gasification, pyrolysis, hydrothermal treatment, vitrification, and thermal desorption. They can destroy organics, reduce volume, recover solvents or energy, and stabilize residues. They are also capital- and energy-intensive and redistribute non-volatile elements into solid residues. Feed moisture, ash, chlorine, sulfur, metals, and calorific value strongly affect performance.

Incineration is established for hazardous and municipal wastes, but its sustainability is context-dependent. Modern air-pollution control reduces emissions while producing concentrated residues that require management. Energy recovery depends on lower heating value, plant efficiency, utilization of heat, and the displaced energy mix. Comparisons should account for recycling foregone, auxiliary fuel, reagent production, bottom and fly ash, metal recovery, and long-term capacity commitments. Abbasi [70] challenges optimistic waste-to-energy claims, whereas Moya et al. [71], Li et al. [72], and Ionescu et al. [73] show

that energy recovery can contribute within integrated systems. The apparent disagreement reflects different waste composition, infrastructure, energy systems, and boundaries. Incineration is most defensible for residual, non-recyclable, adequately characterized waste after prevention and recovery, not as a demand source requiring continued waste generation.

Pyrolysis and gasification are frequently described as material recovery because they produce char, oil, or gas. Product labels do not establish product value. Oils can be oxygenated, unstable, contaminated, or require upgrading; gas may be consumed internally; char can contain metals or persistent organics. Yield and energy balance vary with feed, moisture, temperature, heating rate, residence time, and reactor design. Biochar can provide sorption or soil functions, but contaminant leaching and carbon permanence must be demonstrated. Plastic pyrolysis may tolerate mixed streams but can concentrate chlorine, bromine, metals, and additives in products or residues. It should be compared with design changes, mechanical recycling, and safer material selection, not only landfill.

Thermal integration can reduce external utility demand, but heat quality and integration constraints matter. Liu et al. [64] experimentally compare bench-scale liquid-desiccant regeneration strategies driven by simulated industrial waste heat (L2), rather than reporting a purely modelled study. Raising solution-preheating temperature from 60 to 80 °C increased regeneration rate by about 30–35% in those tests, with diminishing returns at higher temperatures. This peripheral utility example illustrates the importance of usable heat grade; it does not demonstrate full-scale waste-treatment savings. Pinch targets must be reconciled with real heat availability, exchanger losses, fouling, and the counterfactual use of that heat [59,60].

Boichenko et al. [74] compare literature-derived fuel properties across 17 lipid feedstocks; no new experimental measurements were made. The paper is therefore treated as review evidence for feedstock selection, not as validation of industrial conversion yields or emissions. Waste-lipid availability, prior uses, pretreatment, catalyst consumption, and product specifications would need separate plant-level assessment before a fuel route could pass the decision gates.

### *5.6. Comparing Technologies Without False Precision*

Table 5 compares technology functions and recurring trade-offs. The table avoids universal rankings because industrial decisions are multi-stage and context-sensitive. Physical processes are often essential for segregation and concentration; chemical processes handle toxic and refractory compounds; biological processes efficiently transform biodegradable loads; thermal processes manage high-energy or recalcitrant residues and recover energy or products. Hybrid trains exploit complementarity but create more interfaces and control requirements.

**Table 5.** Cross-technology trade-offs in industrial waste treatment.

| Technology Function | Strength | Main Input/Burden | Residual or Failure Mode | Best-Fit Role | References |
|---|---|---|---|---|---|
| Physical separation | Rapid, established, often preserves recoverable material | Pumping, pressure, cleaning, media and space | Concentrate, backwash, fouling, low selectivity for dissolved species | Front-end segregation, concentration and protection of downstream units | [26,65] |
| Chemical precipitation/coagulation | Robust for metals, colloids and variable loads | Acid/base, salts, coagulants, mixing | Sludge quantity, dewatering, leaching and reagent impurities | Bulk removal where selective recovery is not economic | [16,24] |

**Table 5.** *Cont.*

| Technology Function | Strength | Main Input/Burden | Residual or Failure Mode | Best-Fit Role | References |
|---|---|---|---|---|---|
| Adsorption/ion exchange | Polishing and potential selectivity | Media manufacture, regeneration chemicals, pressure drop | Spent media, desorbate, capacity loss in mixed matrices | Low residual concentrations after bulk load removal | [30,61] |
| Advanced oxidation/electrochemical | Refractory organics, disinfection, selective redox | Electricity, oxidants, electrodes, catalysts | Intermediates, salts, electrode loss, incomplete mineralization | Pretreatment or polishing with toxicity and energy verification | [10,68] |
| Aerobic/anaerobic biological | Efficient biodegradable-load conversion; anaerobic energy recovery | Aeration or heat, nutrients, start-up and process control | Biomass, methane leakage, inhibition, sorbed contaminants | Stable biodegradable streams with shock protection | [31,69] |
| Membranes | Compact, modular, high-quality water and selective concentration | Pressure/heat, antiscalants, cleaning and replacement | Concentrate, fouling, scaling and membrane waste | Reuse and recovery trains with viable concentrate endpoint | [26,65] |
| Thermal conversion | Volume reduction, organic destruction, solvent, energy and product recovery | Heat, air control, drying, capital | Ash, char/oil quality, air-control residues and lock-in | Dry, energy-rich, hazardous or recalcitrant residuals after prevention | [19,70] |

Three principles support fair comparison. First, evaluate equal service: the same pollutant load, effluent or product specification, and reliability. Second, include utilities and residuals: electricity, heat, chemicals, water, media, sludge, concentrate, off-gas, and replacement parts. Third, distinguish evidence maturity: equilibrium batch tests, continuous laboratory reactors, pilots with real feed, demonstrations, and commercial systems do not carry the same decision weight. A technology can be scientifically promising and operationally immature at the same time.

## 6. Resource Recovery and Circular Valorization

### *6.1. Recovery Function*

Resource recovery turns a management cost into a potential product, but the recovered function must be defined. Water can be reused for cooling, rinsing, boilers, irrigation, or process contact, each with different specifications. Metals may be recovered as mixed sludge, salt, oxide, or pure metal with very different values. Nitrogen can become ammonium sulfate, ammonia water, struvite, or gaseous nitrogen. Carbon can be methane, volatile fatty acids, polymers, char, or carbon dioxide. A "recovery rate" without product form, purity, stability, and user is incomplete.

The strongest projects begin with receiving specifications and design backward. This reduces the risk of producing a secondary material that is technically recoverable but commercially unusable. It also clarifies monitoring and liability. Product standards should include contaminants that could circulate through repeated loops. End-of-waste rules can enable markets, but premature reclassification can transfer risk from regulated waste systems to product users [6].

### *6.2. Metals and Mineral Residues*

Metals have high theoretical circularity because elements remain recoverable, yet dispersion, alloying, oxidation, and contamination reduce practical yields. End-of-life vehicle systems show that collection and dismantling policy affect recovery as much as separation technology [75–77]. Informal handling, exports, missing components, and mixed shredding streams can limit high-quality recycling. Design for disassembly and material identification improve both economics and safety.

The enterprise comparison by Wang et al. [12] provides L5 industrial-case evidence with modelled life-cycle impacts, not independent L6 verification. Reported climate impacts are 1.84 and 0.51 t $CO_2$-eq per ton of lead for primary and secondary production, respectively. The corresponding operating-profit estimates are USD 262.55 and 241.92 per ton of lead; the reported carbon-profitability ratios are USD 0.14 and 0.47 per kg $CO_2$-eq, respectively. These accounting results use the study's prices and exclusions, including capital, labor, and maintenance, and should not be interpreted as complete investor returns. Secondary production also shifts burdens toward some reagent and water categories, demonstrating why a climate advantage is not sufficient evidence of overall sustainability.

Mineral residues such as slag, ash, red mud, coal gangue, and construction fines are high-volume materials whose recovery depends strongly on transport and product function. The coal-gangue review [29] illustrates trade-offs between replacement, activation, strength, and water uptake, but its heterogeneous mixes do not establish a universally optimal replacement fraction. A comparison must specify mass- or volume-based substitution, particle size, mix formulation, curing, testing age, and the required structural function. Grinding, heat or chemical activation can improve reactivity while adding burdens. Long-term leaching, dimensional stability, relevant radiological risks, durability and demolition-phase recovery remain essential acceptance criteria.

The wind-residue example in Section 3.3 illustrates the same limitation: short-term construction-material performance and cross-sector analogies cannot establish long-term leaching safety, durability, or industrial transferability [28]. A source-specific acceptance specification is necessary before a construction outlet counts as verified recovery.

### *6.3. Water, Nutrients, Organics, and Energy*

Water reuse can reduce abstraction and discharge simultaneously, especially in water-stressed regions. Its net benefit depends on treatment intensity and distribution. High-purity reuse may require reverse osmosis, advanced oxidation, and disinfection even when a lower-grade application is available nearby. Fit-for-purpose cascades using high-quality water for sensitive operations and lower-quality water for washing, cooling, or utilities can avoid over-treatment. Salt accumulation and concentrate management remain central constraints.

Nutrient recovery is attractive because nitrogen and phosphorus production has significant energy and resource burdens. Recovery is easiest from concentrated streams such as digestate, source-separated urine, or certain industrial liquors. Dilute wastewater may be better treated biologically unless local fertilizer value, water scarcity, and discharge requirements justify concentration. Kasiński et al. [62] show that new membrane, electrochemical, adsorption, and crystallization methods expand the technical set, but comparisons need product purity, chemical demand, energy, and contaminant transfer.

Organic industrial residues can support anaerobic digestion, fermentation, composting, feed, extraction, or thermochemical conversion. The hierarchy among these depends on food/feed safety, biochemical composition, moisture, stability, and markets. Anaerobic digestion is mature for wet biodegradable flows and produces dispatchable biogas, but digestate nutrients and contaminants determine whether it is a fertilizer or waste. Biorefineries may extract higher-value compounds before energy recovery. D'Adamo and Sassanelli [78] discuss biomethane communities, while Morone and Imbert [79] emphasize stakeholder acceptance in the circular bioeconomy. Social acceptance is linked to odor, traffic, land application, and trust in product safety, not merely general support for renewable energy.

Oil and gas residues include drilling fluids, produced water, sludge, catalysts, contaminated soils, and chemical containers. Shahbaz et al. [25] emphasize value recovery

and context-specific pathways. Nurjaya et al. [80] estimate greenhouse-gas emissions from hazardous-waste management and transport in an oil and gas operation using Tier 1 factors for 2020–2024. Such inventories help identify dominant waste and logistics sources, but Tier 1 coefficients have limited facility specificity and may omit process emissions or differences among treatment technologies. Decisions should progress from screening inventories to measured activity data and technology-specific factors.

Yang et al. [32] combine inventories and assumptions to estimate stockpiled hazardous residues and discuss storage and governance risks. This is observational and estimation evidence (O), not a measured inventory of all industrial sites or validation of a treatment process. Because the source includes mixed waste categories, its national headline total is not used here as an industrial-only burden. Its relevant contribution is the need to disclose inventory coverage, changing generation coefficients, stockpile condition, and the uncertainty in long-term leakage and responsibility.

### *6.4. Cascades, Multiple Cycles, and Terminal Residues*

Circular systems degrade as materials move through cycles. Fibers shorten, polymers oxidize, alloys accumulate tramp elements, and nutrients acquire contaminants. A cascade can retain value by directing material from high- to lower-specification uses, but every cascade has a terminal residue. Good design identifies that residue and its safe endpoint at the start. It also avoids contaminating large clean stocks with small hazardous inputs.

Economic viability is also material- and context-specific. Sadhukhan and Sekar [81] examine mechanical recycling of clinical plastics and identify sensitivity to electricity, labor, chemicals, and gate fees. This adjacent-sector TEA is used only to illustrate cost-boundary and market questions; clinical segregation and decontamination conditions are not transferred to industrial polymer streams as evidence of safety. For industrial residues, verified sorting, traceability, product specifications, contamination control, and realistic sale prices are separate requirements. Likewise, the PLA hydrolysis/electrodialysis example [36] shows why reaction yield, product recovery, and process-wide benefit must be distinguished.

## 7. Life-Cycle Sustainability and Techno-Economic Assessment

### *7.1. Technical Performance and System-Level Consequences*

Removal efficiency answers a narrow question: what fraction of a measured constituent left a defined stream during a defined period? Industrial investment requires broader answers. How much energy, reagent, water, land, and labor were required? What residuals were created? Did the system meet its target reliably under variable loads? What equipment and replacement materials are needed? Which environmental burdens are reduced or increased? Who purchases the recovered output, at what specification and price? LCA and TEA connect these questions, but only if they use the same process model and do not hide uncertain credits.

Su et al. [10] combine plant inventories, a 30-day field pilot for fluorine recovery at 1 ton/hour, and literature-derived ammonia-recovery inputs. The pilot component supports L4 evidence; the four-route LCA and economic comparison remain modelled (M). Section 2.3 of the source defines pollutant-mass functional units of 1 kg fluoride ($F^-$) and 1 kg ammonia nitrogen ($NH_3$-N), rather than 1 $m^3$ wastewater. On the source's combined route-inventory basis for those two loads, reported GWP values are 27.73, 17.64, 11.58, and 11.56 kg $CO_2$-eq for Routes 1–4. Reported total internal-plus-external costs are CNY 42.36 for Route 3 and CNY 84.82 for Route 4 on that same inventory basis. These are not stand-alone costs per kilogram of either pollutant and have not been converted to CNY/$m^3$.

The small GWP difference between Routes 3 and 4 should not be treated as a robust ranking without uncertainty analysis; chemical inputs and credited products remain decisive.

Amato et al. [11] use an industrially informed scenario model with a functional unit of 13,700 kg of textile wastewater, corresponding to one hour at the reference facility's 13.7 $m^3$/h flow. The four alternatives were not demonstrated as parallel full-scale plants (M). A source-table conflict prevents quoting a single secure final COD value: Table 2 reports Scenario 4 COD of 3.17 mg/L and $BOD_5$ of 0.14 mg/L, whereas Table 4 reports approximately 0.1 mg/L under COD. Table 4 of this review therefore identifies the source's detailed Table 2 values and flags the disagreement rather than asserting a single verified effluent value. Reported capital costs are EUR 0.75–2.7 million and annual operating costs EUR 0.274–2.6 million for the modelled facility, not per functional unit. This study is useful for conditional comparisons of treatment intensity and reuse function, not as an independently verified effluent guarantee.

Dadebo et al. [31] go further by linking experimental performance to a scaled process, LCA, and TEA. The integration is exemplary in structure, but its optimistic net greenhouse-gas result and profitability depend on synthetic-feed performance and credits. The correct interpretation is conditional: if real wastewater maintains biological and polishing performance, if recovered energy and char meet usable specifications, and if land and residual controls are feasible, the route could be attractive. Sensitivity analysis should identify the minimum methane yield, char price, operating availability, and carbon credit needed for viability.

Wang et al. [12] show why circular options should be compared across impact categories. Secondary lead reduces climate impact by 72.18% per ton, yet chemical and water burdens can be higher. Climate-only procurement would miss this shift. Conversely, rejecting secondary production because one toxicity-related category worsens could preserve much larger primary-mining burdens. The appropriate response is targeted improvement of the secondary route, coupled with collection and occupational controls, while retaining the climate and resource benefits.

Table 6 brings these studies together. Their absolute values should not be compared across rows because functional units and systems differ. The transferable information lies in hotspot patterns, boundary choices, and the way environmental and economic rankings diverge.

**Table 6.** How integrated LCA and TEA change technology interpretation.

| Case | Environmental Result | Economic Result | Hotspot or Sensitivity | Decision Implication | References |
|---|---|---|---|---|---|
| Photovoltaic wastewater | Pilot-informed model: Routes 3–4 ≈ 58.3% below Route 1 on source pollutant-load basis (1 kg $F^-$ and 1 kg $NH_3$-N). | Route 3 CNY 42.36 vs. Route 4 CNY 84.82: total internal + external costs on that same combined inventory basis, not CNY/$m^3$. | Chemical production and recovery assumptions | Environmental winner and cost winner differ; optimize reagent system | [10] |
| Textile scenarios | Modelled treatment comparison; conflicting COD entries in source Tables 2 and 4 are flagged, not treated as a secure guarantee. | 13.7 $m^3$/h model facility: CAPEX EUR 0.75–2.7 million; OPEX EUR 0.274–2.6 million/year. | Required effluent function, energy and chemical intensity | Avoid treatment intensity that exceeds the discharge/reuse requirement | [11] |
| Integrated textile valorization | Modelled −6.63 kg $CO_2$-eq/$m^3$ with energy/product credits | IRR 13%; payback 5.43 y at 50 $m^3$/d | Real-feed performance, capacity factor, char/energy value | Promising pilot candidate; not yet bankable full-scale evidence | [31] |

**Table 6.** *Cont.*

| Case | Environmental Result | Economic Result | Hotspot or Sensitivity | Decision Implication | References |
|---|---|---|---|---|---|
| Primary vs. secondary lead | 1.84 vs. 0.51 t $CO_2$-eq/t Pb: reported 72.18% climate reduction; L5 enterprise inputs plus model. | Primary vs. secondary operating profit USD 262.55 vs. 241.92/t Pb; carbon profitability USD 0.14 vs. 0.47/kg $CO_2$-eq. | Chemical/water burdens; omitted capital/labor/ maintenance | Retain secondary route while targeting category-specific hotspots | [12] |
| Waste-derived sorbents | High batch removal is possible | Low-cost claims rely on waste feedstock and regeneration | Activation, washing, low capacity, scale and spent media | Require cradle-to-grave column comparison with commercial media | [30] |

### *7.2. Common Modelling Choices That Bias Results*

Attributional and consequential LCA answer different questions. Attributional assessment describes burdens assigned to a product or service within a specified existing system, commonly using average supply data and stated allocation rules. Consequential assessment estimates changes caused by a decision relative to an explicit counterfactual, requiring assumptions about affected marginal suppliers, displaced products, and market or capacity responses. System expansion alone does not demonstrate that a study is consequential: the complete modelling question, data choices, and substitution logic must agree. Both framings should disclose recycling treatment and co-product credits, with sensitivity to alternative assumptions [18,19,82].

For attributional inventories, avoid allocation where feasible through process subdivision; otherwise justify physical or economic relationships. For consequential comparisons, specify the marginal activity displaced by each additional usable unit and test partial substitution, market saturation, and alternative fates. Marginal allocation or marginal-value analysis must be defined explicitly: an incremental economic value from process optimization [60] is not automatically a carbon-allocation factor. Gate 4 should keep value-based operating decisions separate from environmental inventory conventions. A recovered ton that is contaminated, unsold, or less functional than virgin material cannot receive an unexplained one-for-one credit.

Electricity and heat assumptions are equally important. Electrochemical and thermal processes can look favorable under low-carbon power and unfavorable under fossil-intensive grids. Waste-heat use may be credited as free but can require exchangers, pumps, backup heat, and downtime accommodation. Decarbonization changes the comparison over the asset lifetime. Scenario analysis should therefore include current and prospective energy mixes rather than a single static factor.

Corporate carbon reporting is a related but different accounting task. The GHG Protocol Scope 3 Standard addresses value-chain inventories, including purchased goods and services (Category 1), third-party treatment of waste generated in operations (Category 5), and end-of-life treatment of sold products (Category 12), where applicable [83]. A waste-recovery decision may change these categories as well as the firm's Scope 1 and 2 emissions. The reporting entity, organizational boundary, activity data, emission factors, and allocation between actors should be stated. Project-level avoided emissions from displacing virgin material should be reported separately, not deducted from the Scope 3 inventory as an offset [82]. Double claiming should be checked explicitly when supplier and customer both describe the same circular exchange.

TEA often gives greater precision than the evidence supports. Capital cost scaled by a generic exponent does not capture site preparation, corrosion-resistant materials, explosion protection, redundancy, wastewater variability, instrumentation, engineering,

contingency, permitting, and commissioning. Operating costs should include labor, maintenance, replacement media and membranes, sludge and concentrate treatment, laboratory analysis, insurance, and downtime. Revenue should be limited by product specification, market size, transport, and price volatility. Financing and discount rates should reflect technology maturity.

Uncertainty analysis should focus on decision sensitivity, not decorate a point estimate. Parameters most likely to reverse a choice include feed concentration and variability, recovery yield, product price, electricity and chemical cost, treatment capacity factor, residual disposal fee, replacement interval, and substitution credit. A technology that remains preferable across plausible ranges has stronger evidence than one with an attractive base case and fragile assumptions. Kiskira et al. [19] appropriately integrate LCA, TEA, multicriteria decision analysis, and digital tools across circular industrial processes; the next step is standardization around shared mass balances and uncertainty reporting.

### *7.3. Social Life-Cycle Assessment and Integrated Sustainability*

Environmental LCA and TEA do not, by themselves, establish social acceptability. Social life-cycle assessment (S-LCA) supplies a structured way to examine workers, local communities, supply-chain actors, consumers where relevant, and society along the same life cycle. UNEP's guidelines distinguish approaches and their limitations rather than prescribing one universal indicator score [21]. For this review's decision context, the proposed application is to map stakeholders and high-risk process stages, select context-appropriate indicators, document the data source and reference condition, and assess how the alternative changes exposure, labor conditions, access to livelihoods, participation, and distribution of benefits.

The mathematics of life-cycle sustainability assessment discussed by Sadhukhan et al. [20] demonstrates the importance of connecting technical models, environmental inventories, life-cycle costs, and social supply-chain information. It supports an integrated assessment architecture, not the inference that an economically attractive recovery process is socially preferable. Here, life-cycle sustainability assessment (LCSA) means interpreting those complementary dimensions under an aligned function, boundary, and time horizon; no new composite LCSA score is calculated for the reviewed technologies.

For an industrial pilot, a practical social inventory could record measured or monitored exposure, lost-time incidents, training and protective measures, employment quality and displacement, contractor conditions, truck traffic, community complaints, consultation access, and the distribution of costs and revenues. These are proposed project-specific indicators, not outcomes measured across the present corpus. Sector or country hotspot data can screen priorities but cannot establish actual site conditions; worker and community evidence should be collected with appropriate consent, confidentiality, and grievance safeguards. Identify who experiences an impact, rather than averaging across affected groups.

Gate 4 should present the environmental, financial, and social results side by side, report incompatible boundaries and missing data, and show the sensitivity to value judgements. If MCDA is used, disclose normalization, weights, stakeholder participation, and whether a ranking changes under reasonable alternatives. Legal compliance, severe safety risks, and fundamental labor protections are non-compensatory conditions: a large climate credit cannot cancel their failure. Gate 5 then assigns responsibility for mitigation and verifies outcomes during implementation. This closes the methodological gap between the review's discussion of a just transition and its decision requirements.

## 8. Digitalization, Governance, and Implementation

### *8.1. Data Infrastructure for Material Accountability*

Industrial circularity depends on knowing what a flow contains, where it is, and how it changes. Digital manifests, sensor networks, enterprise-resource-planning integration, material passports, and chain-of-custody systems can reduce information loss. Real-time monitoring can detect pH, conductivity, flow, turbidity, temperature, gas composition, tank level, or equipment condition. Machine learning can infer difficult-to-measure properties and predict fouling or quality deviations. Blockchain may preserve records, but it cannot verify inaccurate input; physical sampling, calibration, and audit remain essential.

The strongest use of digitalization is closed-loop control: a sensor triggers process adjustment, segregation, maintenance, or rejection before waste is created or contaminated. The weakest use is a dashboard that reports tonnage after the fact. Smart-collection and automated-sorting studies demonstrate technical possibilities [66,84], but much of this evidence originates in municipal systems and cannot be transferred uncritically to variable industrial streams. Industrial applications should be evaluated by avoided loss, recovery purity, downtime, and life-cycle burden, not model accuracy alone. Error costs must also reflect risk: a false negative for a hazardous contaminant is not equivalent to a missed recyclable item.

Data sharing is difficult in symbiosis networks because flow composition and quantity may reveal production secrets. Governance arrangements can use standardized descriptors, trusted intermediaries, tiered access, and aggregated reporting. Palagonia et al. [9] identify coordination and information as critical issues, and Santana Filho et al. [55] place governance at the center of hub design. Data platforms should define ownership, liability, cybersecurity, update frequency, and who pays for verification.

### *8.2. Policy Instruments and Market Formation*

Regulation establishes the minimum acceptable endpoint, but circular systems also need product standards, procurement, infrastructure, and credible liability rules. Landfill taxes and disposal bans can shift waste toward recovery, yet without capacity and enforcement they can encourage stockpiling, illegal transfer, or low-quality outlets. Subsidies can accelerate demonstration but may preserve uneconomic processes. Recycled-content requirements create demand but must include quality and chemical-safety safeguards.

Policy instruments interact rather than operate independently. Energy, climate, waste, industrial, and trade measures can reinforce or undermine one another [85]. Industrial-park assessment shows the value of screening site-specific impacts before selecting interventions [86], while circular business-model cases emphasize that value proposition, delivery, and capture must change together [87]. Reviews integrating life-cycle thinking, EPR, and industrial symbiosis similarly show that responsibility and inter-firm exchange need shared governance architecture [49].

EPR is most effective when fees vary by durability, repairability, material complexity, hazardous content, and verified recovery. Flat fees weakly influence design. Deposit-refund systems improve collection of high-value products, while take-back can support manufacturer learning. E-waste studies underline that awareness and professional expectations do not by themselves guarantee safe collection and high-quality recovery [88]. Reverse logistics depends on volume, distance, backhaul, condition assessment, and information [89]. Behavioral adoption also depends on organizational culture and supply-chain relationships [90]. Policy should address small and medium-sized firms that lack capital and specialist staff, potentially through shared services and industrial-park infrastructure. The economic value of recycling policy is also context-sensitive: crises and market disruptions can reveal benefits that static commodity-price comparisons miss [91].

Policy transfer needs caution. A measure that works in a dense industrial region with reliable utilities, testing laboratories, enforcement, and finance may fail where those institutions are absent. Governance recommendations in this review are therefore context-dependent and mainly supported by conceptual, review, and observational evidence, rather than causal evaluations of policy effectiveness [9,57,58].

### *8.3. Organizational Capability and Just Transition*

Technology adoption is an organizational change. Operators need training; maintenance and laboratory functions need resources; procurement must accept secondary inputs; designers need feedback from treatment and recovery; finance teams must evaluate uncertain revenue; and regulators need capacity to verify claims. AlSheyadi et al. [47] identify green dynamic capabilities as a mediator between zero-waste and supply-chain practices and firm performance. Although the survey design limits causal inference, the organizational mechanism is convincing: sensing, seizing, and reconfiguring capabilities explain why identical equipment produces different results across firms.

Distributional impacts should be assessed through an explicit social-life-cycle method, not inferred from tons recycled or jobs announced. Automation may reduce hazardous sorting and also displace workers; formalization may improve protection but remove livelihoods without transition support. Gate 4 therefore requires the stakeholder and indicator assessment described in Section 7.3, while Gate 5 requires accountable implementation, participation, transparent siting, grievance procedures, and monitoring. Neither lower GHG emissions nor financial profit offsets an unresolved serious occupational or community risk [21,58].

## 9. Evidence Quality and the Laboratory-to-Industry Gap

### *9.1. Recurrent Weaknesses*

The literature is rich in proof-of-concept performance and thin in independent, long-duration, full-scale evidence. Adsorption studies often use a single solute in deionized water, high sorbent dose, controlled pH, and equilibrium times that are impractical for continuous flow. Oxidation studies report parent-compound disappearance without mineralization or toxicity. Biological studies use synthetic wastewater and stable temperature. Material-valorization studies test early strength but not durability, leaching, demolition, or multiple recycling cycles. Reviews may combine maxima across incompatible conditions, creating unrealistic expectations.

Scale introduces nonlinear problems: mixing, heat and mass transfer, pressure drop, clogging, fouling, corrosion, media attrition, sensor drift, and maintenance access. Laboratory energy meters may exclude pumps, air compression, feed preparation, cleaning, and standby. Batch regeneration can be chemically intensive. Pilot success under a narrow feed window does not ensure annual reliability. Technology readiness should therefore be linked to evidence type and operational duration.

Economic evidence is frequently modelled from experimental yield without a bankable product. Revenue for recovered char, chemicals, nutrients, or metals may use commodity prices despite lower purity and small local demand. Negative-emission or avoided-disposal credits can dominate profitability. Conversely, studies may omit valuable risk reduction, compliance assurance, water security, or avoided production downtime. TEA should disclose both direct cash flow and broader external benefits rather than mixing them.

LCA studies often stop at climate change. Chemical toxicity, ecotoxicity, water scarcity, land, resource depletion, and local air pollution can alter the conclusion. Inventory uncertainty is especially high for novel chemicals, nanomaterials, and waste-derived products. Circularity metrics based on mass do not resolve these gaps. Colasante et al. [92]

show how national circularity performance depends on indicator choice, and Zoboli et al. [93] connect circular business models with energy policy; both reinforce the need for multi-dimensional assessment.

### *9.2. A Transparent Evidence Ladder*

Table 7 defines six operational levels consistently: L1, mechanism or material characterization; L2, controlled batch or short-run experiment; L3, continuous laboratory operation with a balance and stated feed; L4, field pilot with real industrial feed; L5, integrated industrial demonstration or enterprise-scale case; and L6, independently verified commercial operation. These are evidence descriptors, not certified technology-readiness levels. Commercial scale without independent verification is not L6. A paper receives the highest directly documented experimental or operating level for the relevant component, not for every extrapolated part of a treatment train. Reviews/conceptual syntheses (R), non-operational models or prospective assessments (M), and observational, survey, or inventory analyses (O) are recorded separately. A combined label such as L4 + M explicitly separates a pilot measurement from an LCA projection.

**Table 7.** Six operational evidence levels, their limits, and the next validation step. Counts refer only to the 42 retained papers in the initial full-text collection.

| Level/Count | Direct Evidence Required | Limit on Interpretation | Next Decisive Step | References |
|---|---|---|---|---|
| L1/0 | Mechanism or material characterization. | No treatment throughput, durability or system benefit established. | Controlled experiment with stated feed and material balance. | [17,19] |
| L2/4 | Controlled batch or short-run experiments with defined conditions. | Cannot establish continuous industrial reliability. | Continuous testing, competitive matrix, cycles and balances. | [24,30,61,64] |
| L3/1 | Continuous laboratory component, stated feed/duration and a balance. | Not validation of all linked components or a commercial-scale model. | Real-feed field pilot over representative production cycles. | [31] |
| L4/1 | Field-pilot operation on real industrial feed. | Short pilot operation is not long-term commercial availability. | Integrated demonstration including utilities, residuals, maintenance and full costs. | [10] |
| L5/1 | Integrated industrial demonstration or enterprise operating case. | One enterprise and modelled impacts do not establish independent commercial verification. | Independent audit, replication and post-implementation monitoring. | [12] |
| L6/0 | Commercial operation independently verified against a baseline, with residual and performance records. | Even verified site results need transferability checks. | Continuing surveillance and multi-site comparison. | [9,19] |

The retrospective audit of the 42 retained collection papers yields L1 = 0, L2 = 4, L3 = 1, L4 = 1, L5 = 1, and L6 = 0. The remaining 35 comprise R = 23, M = 4, and O = 8. Each paper is counted once in this primary classification; the modelling qualifiers attached to three operational papers do not create additional papers. Appendix A.4 provides the

paper-level classification and its rationale. The 64 complementary sources are not included in this operational denominator; they provide background, methods, or explicitly qualified sector examples, and their number must not be represented as additional industrial validation.Counts use one primary code per retained paper. R = 23, M = 4, O = 8 lie outside the operational ladder, giving 42 in total. L3, L4, and L5 papers also carry modelling qualifiers; those qualifiers are not extra papers. "Independent" means verification separate from the process developer or originating study, not peer review alone.

Methodological quality also varies among reviews. Structured searches, explicit inclusion criteria, quality assessment, and reproducible extraction strengthen confidence. Arksey and O'Malley [94] provide a foundational scoping framework. Palagonia et al. [9] analyze 137 articles systematically; Zaman [22] applies PRISMA and principal-component analysis to 108 sources; Kiskira et al. [19] screen 412 records to 116; and Cases-Valbuena et al. [28] show transparently that only six studies meet their narrow question. Narrative reviews remain useful for mechanisms and terminology, but they should not establish industry-wide performance. Accordingly, Semrau and Horzela-Miś [48], Ijimdiya et al. [95], Radu et al. [96], and Eržen et al. [49] are used primarily for framing and reported trends, not as proof of full-scale outcomes.

### *9.3. Study Limitations*

The corpus is purposive, predominantly recent, and unequally distributed across topics. It cannot support publication-frequency estimates, pooled effects, literature saturation, or universal technology rankings. The 47 screened candidates are not 47 included performance studies: 42 were retained, and only seven contain operational evidence classifiable at L2–L5; none meets the independent-commercial-verification criterion for L6 (Table 7; Appendix A.4). These counts reflect this collection, not the availability of industrial evidence worldwide. Recent publication and early-online status do not increase maturity. Review summaries, surveys, simulations, and enterprise-informed LCA each answer different questions. Nitrogen recovery, plasma, and wind-sector residue claims have therefore been narrowed; plant-level prevention, long-duration symbiosis, occupational outcomes, and independent full-scale verification remain underrepresented. Historical database search logs and independent duplicate extraction are not available, and the current retrospective audit cannot repair that provenance limitation. The framework is an unvalidated synthesis of recurrent decision problems; prospective testing with industrial assessors, documented disagreements, and post-deployment outcomes is still needed.

## 10. An Integrated Decision Framework

The five-gate framework in Figure 2 is derived by mapping recurring weaknesses in the reviewed evidence to the information needed before a decision advances (Table 8).

Low-quality substitution and neglected prevention motivate Gate 1; unrepresentative feeds and scale extrapolation motivate Gate 2; incomplete balances and transferred contamination motivate Gate 3; uncertain product credits, costs, and distributional impacts motivate Gate 4; and unreliable markets, governance, and operation motivate Gate 5. This is an interpretive synthesis, not a statistically derived or externally validated framework.

The framework does not claim that prioritization, gates, or integrated sustainability are new. The waste hierarchy orders management preferences; conventional stage-gate processes organize commitments and learning [97]; and the revised safe-and-sustainable-by-design framework already integrates safety, life-cycle environmental assessment, and expanded socio-economic considerations [98]. The narrower contribution here is to translate these established ideas into a waste-specific evidence checklist: preserve feed and performance denominators, separate operational maturity from model credibility, track

pollutants through recovered products and residuals, and test actual displacement before granting circularity credit. These requirements connect options in Figure 1 to the assessment methods in Section 7. They supplement, rather than replace, process design, permitting, SSbD, LCA, or investment appraisal.

Gate 1 prevention and hazard reduction. Define the production function and ask whether material loss, water use, toxicity, or complexity can be eliminated through substitution, product design, yield improvement, maintenance, segregation, or business-model change. Report absolute and intensity-based change to detect rebound.

Gate 2 representative technical performance. Characterize flow, concentration, variability, and contaminants that affect operation. Test the technology under realistic loads and required specifications. Report recovery, purity, reliability, energy, chemicals, water, and duration. A maximum batch value is insufficient.

Gate 3 residual and exposure control. Complete the mass balance. Identify concentrate, sludge, off-gas, spent media, biomass, ash, cleaning waste, and transformation products. Test toxicity, leaching, occupational exposure, and safe terminal management. Recovery that exports risk fails this gate.

**Table 8.** Derivation and practical use of the five gates. Advancement criteria refer to the proposed next commitment, not automatic authorization for deployment.

| Gate | Recurring Evidence Problem | Minimum Decision File | Advancement/Hold Criterion | References |
|---|---|---|---|---|
| 1. Prevention | Circular design or survey claims do not demonstrate absolute source reduction. | Equal production function; baseline mass/hazard inventory; prevention alternatives; absolute and intensity indicators. | Proceed when feasible prevention has been assessed and the remaining stream is justified; redesign if the project depends on avoidable waste. | [22,44,47] |
| 2. Performance | Dilute batches, ambiguous dose/capacity and synthetic-feed extrapolation. | Feed variability; operating window; component-specific L1–L6 code; balances; product quality; reliability; source locations. | Evidence must match the next commitment. A bounded pilot may resolve uncertainty; batch maxima cannot authorize full investment. | [24,30,31,61] |
| 3. Residuals/exposure | Recovered products may recirculate chemicals; mass can migrate to concentrate, ash or media. | All output streams; toxicity/leaching; worker exposure; secondary-waste route; hazard controls. | Hold for missing hazardous outputs or unacceptable exposure; no credit for simply moving contamination. | [4,5,28] |
| 4. System additionality | Product credits, incomplete costs and omitted social impacts can reverse the result. | Aligned LCA, TEA/life-cycle costing and S-LCA; counterfactual; attributional/consequential choice; sensitivity; separate Scope 3 inventory. | Proceed only with defensible functional equivalence and an explicit trade-off decision; unresolved serious safety/rights harm is non-compensatory. | [10–12,20,21,82,83] |
| 5. Delivery/adaptation | Network matches, prospective hubs and enterprise cases do not guarantee durable operation. | Permits, offtake and quality contracts; skills; monitoring owner; independent verification plan; contingency and feed-reduction scenarios. | Deployment requires accountable controls and feasible operation; otherwise retain a conditional hold or redesign. | [7–9,12,53,55] |

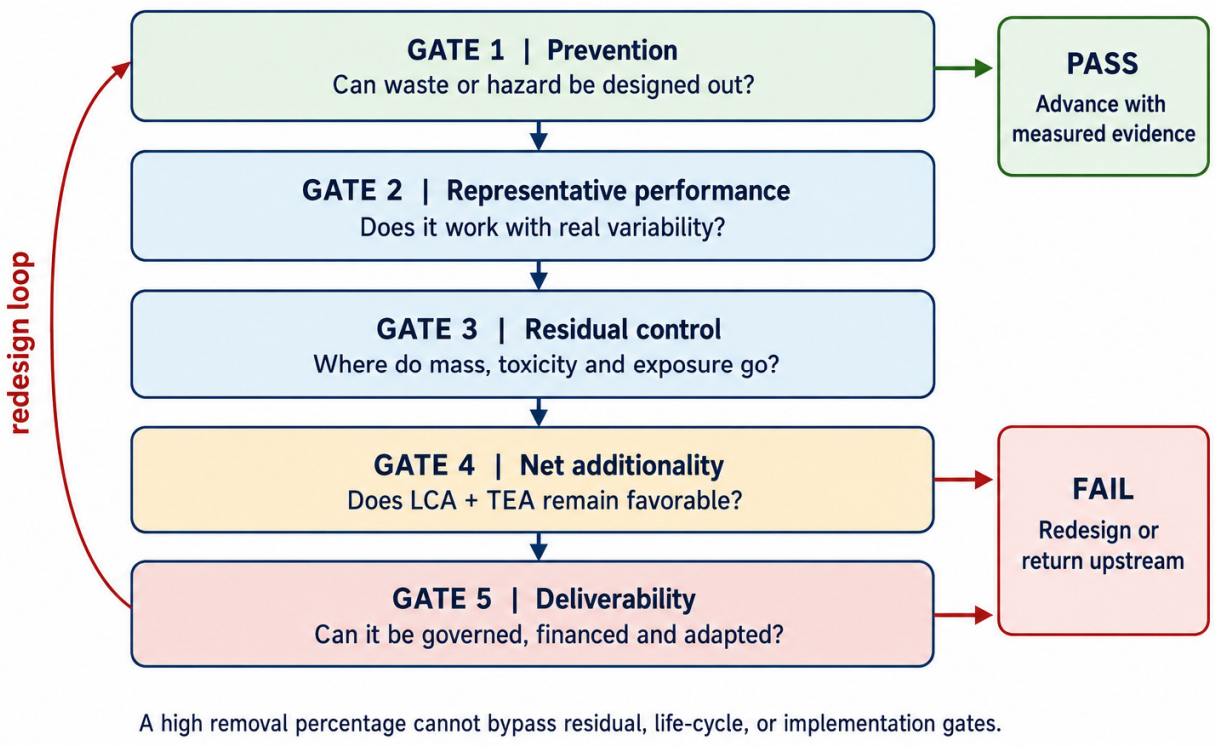


**Figure 2.** Five-gate evidence-checking framework for industrial-waste decisions. Figure 1 prioritizes alternatives; these gates assess the selected alternative. Gate 4's life-cycle test includes environmental LCA, social LCA, and economic assessment. Table 8 supplies the evidence links, required information, and advancement criteria that operationalize the diagram.

Gate 4 life-cycle sustainability and economic additionality. Compare equivalent functions against a defined counterfactual using aligned environmental LCA, TEA/life-cycle costing, and social LCA. State attributional or consequential framing and report corporate Scope 3 implications separately from project avoided emissions. Test product quality and displacement, capital, labor, maintenance, downtime, residual costs, market uncertainty, and stakeholder impacts. Do not compensate for unacceptable safety or rights-related harm with a favourable aggregate score.

Gate 5 scale, governance, and adaptability. Confirm permits, standards, monitoring, data ownership, contracts, skills, infrastructure, community acceptance, and contingency arrangements. Pilot the integrated train with real feed. Design for changing waste quantity and composition so the system does not depend on continued waste generation.

Figure 3 translates the gates into a decision-readiness profile. Three dimensions must improve together: technical robustness, net system benefit, and institutional deliverability. A study with high removal but low readiness is a research candidate; a mature process with poor net benefit is a redesign candidate; an attractive model without contracts or product standards is an implementation-development candidate. Only options with credible performance across all three dimensions should proceed to full investment.

Practical use should begin by defining the decision being authorized: a bench experiment, a pilot, procurement, or full investment. For each project, record the process owner, data owner, assessor, baseline, source version, uncertainty, and unresolved condition at every gate. Table 8 sets minimum information and example advancement criteria. An early project may proceed to a bounded experiment to resolve an uncertainty; it has not thereby passed the deployment gate. Safety and legal failures require redesign or rejection. Unresolved performance or market assumptions justify a conditional hold with a specified test and decision date. Reassess the gates when feed, energy supply, product markets,

or regulation changes. The proposed checklist has not yet been prospectively tested for inter-assessor agreement or predictive validity.

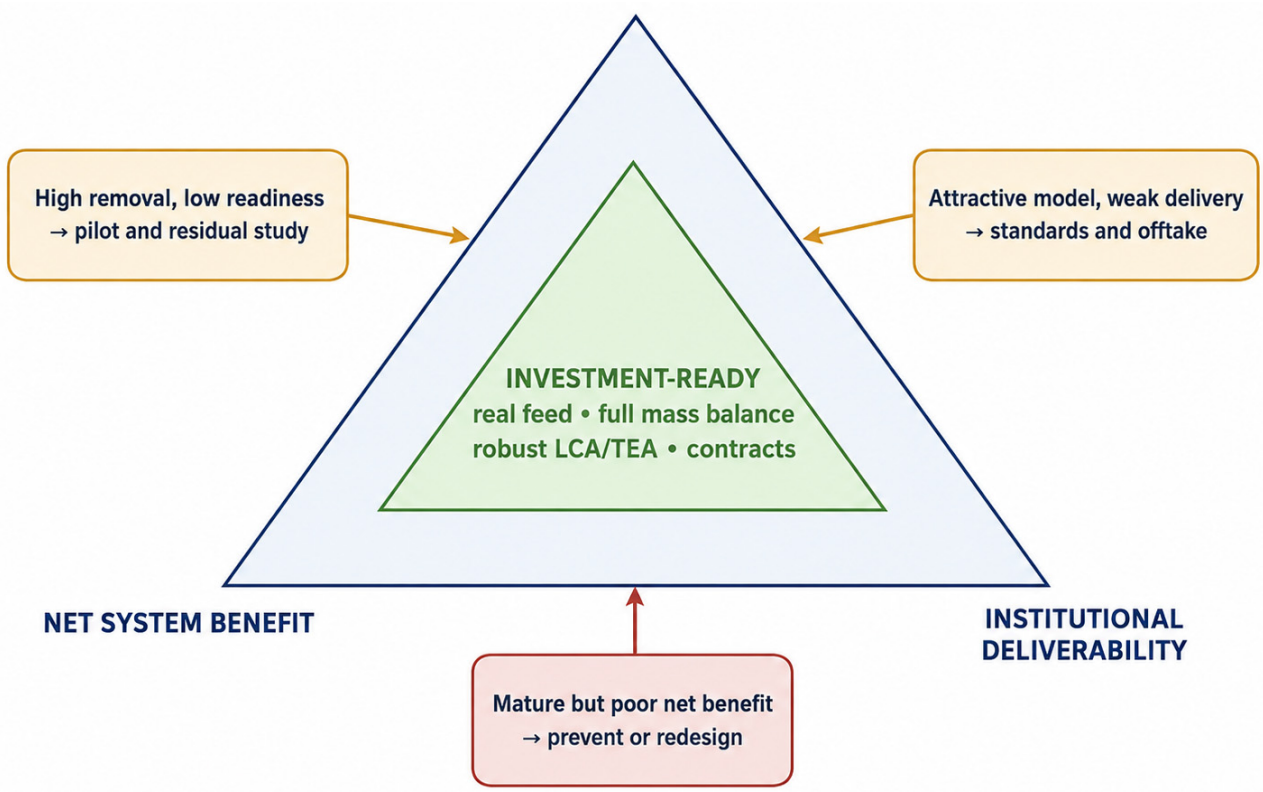


**Figure 3.** Decision-readiness profile for industrial-waste technologies.

## 11. Conclusions

For industrial wastewater, sludges, and solid production residues, circularity is a system outcome rather than a removal percentage or diversion rate. The most transferable finding of this purposive review is that prevention, functionally usable recovery, and safe residual management must be evaluated together. Laboratory studies reveal mechanisms and operating constraints; pilot and enterprise cases reveal additional integration burdens. Neither recent publication nor detailed modelling substitutes for independent operational verification.

The proposed contribution is a traceable decision checklist that connects those recurring evidence gaps to established process integration, environmental and social life-cycle assessment, economic analysis, and governance practice. It is not a universal technology ranking or a validated replacement for those methods. Priority research should pair representative continuous trials with closed material and energy balances, product-quality and exposure testing, conservative substitution scenarios, and complete costs. Prospective application of the gates across several industrial sites would test whether they improve decisions and identify where their requirements need adaptation.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A. Corpus Provenance, Eligibility, and Retrospective Audit

### *Appendix A.1. Scope and Provenance*

The audit reconstructs the evidence set from the supplied full-text files and the submitted bibliography; it does not reconstruct an undocumented historical database search. The initial five groups were thematic selections supplied during manuscript development. No contemporaneous Scopus, Web of Science, PubMed, or other database export was available, and no claim that those databases were searched is made. Historical search terms, dates, screening totals before the supplied files, and independent second-author checks cannot be inferred from publication dates or reference lists. The revision-stage checks and searches below are distinct from that initial selection.

Initial retained full-text publications are dated 2025–2026. The complementary literature supplies earlier concepts, methods, sector context, and specific comparisons; the revised reference list spans 1990–2026. Its role is not equivalent to additional full-text operational validation. A source can be recent and still serve only a conceptual function. Full-text availability in the original five groups, rather than methodological quality or publication age alone, defines membership of the initial collection. The distinction is therefore provenance-based, while interpretation is governed by study type and reporting.

### *Appendix A.2. Eligibility, Inclusion Decisions, and Coverage*

For the retrospective synthesis, include industrial wastewater, sludges, production residues, or clearly labelled transferable decision methods. A technical claim must have an identifiable stream, endpoint and source location; a conceptual paper may be retained for framing without being treated as quantitative validation. Exclude exact duplicates; predominantly municipal studies without a specific methodological role; descriptive overviews lacking traceable support for the intended claim; and a closely related conference study when it cannot be treated as independent confirmation. Exclusion here is a decision about use in this review, not a finding of research misconduct or a comprehensive quality verdict. Reporting ambiguity in an otherwise relevant experimental paper leads to a qualified use, not automatic exclusion.

| Collection Stage | Files/Papers | Interpretation |
| --- | --- | --- |
| Supplied files | 48 | Five groups: 10, 8, 7, 15, 8 files. |
| Unique candidates | 47 | One exact duplicate of the textile-design paper removed. |
| Retained collection papers | 42 | Groups retain 10, 7, 4, 15, 6 papers, respectively. |
| Excluded unique candidates | 5 | Paper-level reasons recorded in Appendix A.4. |
| Original complementary sources | 53 | 95 original references minus 42 retained collection papers. |
| Targeted revision additions | 11 | Assessment, integration, decision-method and qualified sector literature. |
| Revised cited sources | 106 | 42 retained collection + 64 complementary; not 106 industrial trials. |

Selection coverage was assessed by whether the corpus exposed the principal decision problems prevention, performance transfer, residual fate, substitution, cost, and implementation not by a claim of database completeness, saturation, or minimum references per subsection. Plasma and wind residues remain limited examples; nitrogen recovery is not quantitatively ranked. Observational manufacturing and network studies cannot establish causal plant-level savings. Quantitative statements with unresolved denominators or conflicting source entries are omitted or explicitly qualified. These restrictions narrow the inference to decision criteria for industrial wastewater and solid residues.

*Appendix A.3. Documented Revision-Stage Search and Appraisal*

Targeted searches were conducted on 14 September 2026 through a public web-search index, followed by primary publisher pages, institutional repositories and official method guidance. No licensed bibliographic database search or PRISMA-style record flow was performed. The following reproducible query strings record the substantive routes leading to the additions; spelling variants and direct DOI/title lookups were used for metadata verification. There was no publication-year restriction for foundational methods. Only sources with an identifiable methodological or explicitly bounded application role were added. Search-engine result counts were not used as screening denominators.

| Purpose | Exact Substantive Query/Direct Lookup | Selected Additions |
| --- | --- | --- |
| Reviewer-specified methods | 10.1016/j.jclepro.2021.127457; 10.1002/cssc.202500503; 10.3390/en15238974 | LCSA, integrated PLA recovery and clinical-plastics economic analogy [20,36,81]. |
| Process integration | “industrial wastewater” “pinch analysis” “value analysis” process integration; “Wang” “Smith” “Wastewater minimisation” “1994” | Water-pinch method [59]. |
| Marginal/value analysis | “Value Analysis of Complex Systems and Industrial Application to Refineries” doi | Process value analysis [60]. |
| Social assessment | site.unep.org “Guidelines for Social Life Cycle Assessment” “2020” | UNEP social-LCA guidance via Life Cycle Initiative [21]. |
| Carbon accounting | “attributional” “consequential” “scope 3” GHG Protocol; site.ghgprotocol.org “Corporate Value Chain” “Scope 3” “avoided emissions” | Official Scope 3 and inventory/project-accounting guidance [82,83]. |
| Decision-framework comparison | “Stage-gate systems” “1990” Cooper DOI; site.publications.jrc.ec.europa.eu “Safe and sustainable by design” “2022” | Stage-gate method and current revised JRC SSbD framework [97,98]. |
| Mature nitrogen comparator | “Full-scale partial nitritation/anammox experiences” doi | Full-scale application survey [63], explicitly not industrial-only recovery evidence. |

Appraisal used a common question set but not a common numerical score. Experiments were checked for feed, control, scale, duration, measurement basis and residuals; models for inventory provenance, boundary, credits, sensitivity and extrapolation; observational papers for population, association versus causation and inventory assumptions; and reviews for search transparency, underlying evidence heterogeneity and the limits of secondary claims. Background methods were checked for relevance to the cited method-

ological statement, not assigned a treatment performance score. Reviewer-flagged numbers were checked against the retained source text and tables; the completed audit examples are in Appendix C. No independent duplicate screening or extraction is claimed, and the count assignments remain open to reassessment if additional operating or provenance records become available.

*Appendix A.4. Paper-Level Manifest and Evidence Counts*

The manifest lists all 47 unique candidates. Included references identify their complete bibliographic entries. L1–L6 classify the highest directly documented operational component, not an entire modelled value chain. R = review/conceptual synthesis; M = non-operational model/prospective assessment; O = observational, survey, inventory or secondary-data analysis. O + M retains O as the primary count; operational "+M" papers retain their operational primary code. "Excluded" papers are not added back to the cited evidence total merely by being named in this manifest.

| ID/Group | Paper/Reference | Code | Audited Use and Limitation |
|---|---|---|---|
| C01/G1 | Bai et al. (2025) [54] | O | Comparative indicators for 48 resource-utilization centers; observational efficiency analysis. |
| C02/G1 | Ali et al. (2025) [42] | O | BRICS econometric associations; not a controlled industrial intervention. |
| C03/G1 | Domini et al. (2025) [7] | O | Regional material-flow and social-network case analysis. |
| C04/G1 | Fric et al. (2025) [8] | O | Network-structure analysis; no process intervention trial. |
| C05/G1 | Fussone et al. (2025) [53] | M | Agent-based industrial-symbiosis simulation. |
| C06/G1 | Barathi et al. (2026) [56] | R | Broad symbiosis/biorefinery/circular-economy synthesis. |
| C07/G1 | Palagonia et al. (2025) [9] | R | Systematic industrial-symbiosis barriers review. |
| C08/G1 | Genc (2025) [52] | R | Ecological-network analogy review for industrial systems. |
| C09/G1 | Munonye et al. (2025) [57] | R | Policy-to-practice industrial-symbiosis review. |
| C10/G1 | Santana Filho et al. (2025) [55] | M | Prospective biomass-hub governance and scenario proposal, not an operating facility. |
| C11/G2 | Abbasi et al. (2026) [4] | O | Chemical-prioritization framework using existing composition/hazard data; no operating plant. |
| C12/G2 | Jahnke et al. (2025) [5] | R | Cross-sector plastics perspective; no new process operation. |
| C13/G2 | Cases-Valbuena et al. (2026) [28] | R | Six-study sector review; substantial cross-sector transfer. |
| C14/G2 | Chun et al. (2025) [99] | O | Single footwear-factory material-flow/DPSIR case. |
| C15/G2 | Barua (2025) [100]; Emerging Technologies for Sustainable Treatment of Industrial Wastewater | Excluded | Barua: broad technology overview without sufficient traceable performance evidence. |
| C16/G2 | Nurjaya et al. (2026) [80] | M | Hazardous-waste GHG estimates from activity data and emission factors; not measured treatment emissions. |

| ID/Group | Paper/Reference | Code | Audited Use and Limitation |
|---|---|---|---|
| C17/G2 | Yang et al. (2025) [32] | O + M | National stockpile inventory/mixed-method analysis with estimation assumptions; no process validation. |
| C18/G2 | Ijimdiya et al. (2026) [95] | R | Circular-economy/climate narrative synthesis. |
| C19/G3 | Yılmaz Gözene et al. (2025) [44] | R | Narrative zero-waste garment-design review; second file is an exact duplicate. |
| C20/G3 | Semrau et al. (2026) [48] | Excluded | Waste reduction and process innovation overview. |
| C21/G3 | Semrau et al. (2026) [48] | R | Narrative waste-reduction and process-innovation overview. |
| C22/G3 | AlSheyadi et al. (2025) [47,101] | Excluded | Al Sheyadi et al. conference paper: related author group/topic/population; not counted as independent confirmation of journal study. |
| C23/G3 | Zaman (2026) [22] | R | Systematic conceptual comparison of IE, CE, and zero waste. |
| C24/G3 | AlSheyadi et al. (2025) [47] | O | Manufacturing-manager survey/SEM; associations, not measured waste reduction. |
| C25/G4 | Su et al. (2025) [10] | L4 + M | 30-day industrial fluorine-recovery pilot; four-route LCA/TEA model. |
| C26/G4 | Liu et al. (2026) [64] | L2 | Controlled bench regeneration with simulated waste-heat supply. |
| C27/G4 | Ali et al. (2025) [68] | R | Review of plasma studies; no new operating demonstration. |
| C28/G4 | Amato et al. (2025) [11] | M | Industrial inputs and literature-informed treatment scenarios; complete trains not demonstrated in parallel. |
| C29/G4 | Dadebo et al. (2026) [31] | L3 + M | 125-day continuous laboratory UASB on synthetic feed; other components at laboratory scale; commercial train projected. |
| C30/G4 | Alatawi et al. (2025) [24] | L2 | Batch cobalt removal and reuse tests, including real matrices. |
| C31/G4 | Shanmughan et al. (2025) [67] | R | Review of sludge biochar and AI-based adsorption research. |
| C32/G4 | Adepitan et al. (2026) [26] | R | Review of produced-water treatment routes. |
| C33/G4 | Wang et al. (2026) [29] | R | Review of coal-gangue aggregate and binder studies. |
| C34/G4 | Kiskira et al. (2026) [19] | R | Structured review of circular process optimization and assessment methods. |
| C35/G4 | Boichenko et al. (2025) [74] | R | Literature-derived comparison of 17 biodiesel feedstocks; no original experiments. |
| C36/G4 | Kasiński et al. (2025) [62] | R | Review of nitrogen removal and recovery technologies. |
| C37/G4 | Sieradzka et al. (2025) [30] | L2 | Batch adsorption on activated food-waste chars in dilute solutions. |
| C38/G4 | El Gamal et al. (2025) [61] | L2 | Batch COD sorption; dose/capacity and provenance qualifications retained. |
| C39/G4 | Das et al. (2025) [69] | R | Industrial biofiltration narrative review. |
| C40/G5 | Wang et al. (2026) [12] | L5 + M | Enterprise production inventories and residual pathways; LCA/economics modelled; no independent verification. |

| ID/Group | Paper/Reference | Code | Audited Use and Limitation |
|---|---|---|---|
| C41/G5 | Nuur et al. (2026) [58] | R | Critical mining/circularity perspective; conceptual contribution. |
| C42/G5 | Karmakar et al. (2026) [27] | R | Design-for-recyclability and polymer-processing review. |
| C43/G5 | Radu et al. (2025) [96] | R | Review of sustainable polymer processing. |
| C44/G5 | Eržen et al. (2026) [49] | R | Life-cycle thinking/EPR/symbiosis conceptual review. |
| C45/G5 | Setyadi et al. (2025) [38] | R | Unvalidated circular-operations framework. |
| C46/G5 | Zero-waste cities (2025) [102] | Excluded | Zero-waste-cities study: explicitly municipal focus, outside primary industrial scope. |
| C47/G5 | Circular sustainability in organic chemical industry; waste943.pdf | Excluded | Organic-chemical-industry conference overview: insufficiently reproducible synthesis/reporting. |

Primary classification totals: L1 0; L2 4; L3 1; L4 1; L5 1; L6 0; R 23; M 4; O 8. Total retained = 42. The duplicate textile-design files share identical content and are represented once. Three operating papers combine measurements with prospective LCA/TEA (L3 + M, L4 + M, L5 + M); one inventory paper has O + M. These qualifiers do not inflate the denominator.

The original 53 complementary references are [1–3,6,13–18,23,25,33–35,37,39–41,43,45,46,50,51,65,66,70–73,75–79,84–94,100,103–109]. The 11 revision additions are [20,21,36,59,60,63,81–83,97,98]. These sources support background, assessment methods and qualified comparisons; the detailed operational count above is deliberately restricted to the auditable initial full-text collection.

## Appendix B. Blank Evidence-Extraction Matrix

Use one copy per source. The final column is intentionally blank for extraction. Record "not reported", "not applicable", or "not independently verified" rather than imputing values. Include each quantity's denominator and exact source location. Record actual checking, not a presumed second review.

| Figure | 1. | Extraction Entry |
|---|---|---|
| Identity and provenance | Source ID; full citation/DOI; file version; source location; search/retrieval date; initial group; inclusion/exclusion reason. | |
| Purpose and design | Research question; sector/country; study design; R/M/O or L1–L6 code and rationale; component to which the code applies. | |
| Waste and function | Waste origin, composition and variability; real/synthetic feed; initial concentration/load; flow; function and comparator. | |

| **Figure** | **1.** | **Extraction Entry** |
|---|---|---|
| Operating conditions | Batch/continuous; scale/capacity; duration; temperature; pH; dose; pressure/current; retention time; cycles; downtime. | |
| Measured performance | Removal, mineralization and recovery kept separate; output concentration; capacity/yield; purity; uncertainty; sample size; exact table/page. | |
| Balances and utilities | Inputs/outputs; mass-balance closure; energy and water; chemicals; gross/net recovery; all units and denominators; missing flows. | |
| Residuals and exposure | Sludge, concentrate, spent media, biomass, ash, off-gas; transformation products; toxicity/leaching; worker/community exposure; terminal fate. | |
| Environmental assessment | FU/reference flow; boundary/time horizon; attributional/consequential framing; allocation; displaced activity/quality; impact methods; uncertainty. | |
| Economic assessment | Currency and price year; capacity and availability; CAPEX/OPEX; labor/maintenance/replacement; revenue; gate fees; residual costs; financing assumptions. | |
| Social assessment | Stakeholders; reference situation; labor/exposure/distribution indicators; data provenance; participation; hotspot versus measured site data. | |
| Validation and transfer | Evidence level; independence; controls; real-feed representativeness; technology and institutional limits; conditional versus achieved claims. | |
| Critical synthesis | Claim supported; gate(s) informed; conflicting figures/locations; unresolved denominator; proposed next test; evidence weight and rationale. | |
| Extraction checking | Extractor/date; checker/date if actually performed; disagreement and resolution; reason for any unverified field. | |

## Appendix C. Targeted Quantitative Verification Record

| Source Location | Verification Finding | Treatment in the Revision |
| --- | --- | --- |
| Su et al. [10], Sections 2.2, 2.3 and 4.1 | Pilot: 30 days, 1 t/h. FU declarations are 1 kg $F^-$ and 1 kg $NH_3$-N. Route 3/4 combined total costs: CNY 42.36/84.82. | State the combined pollutant-load inventory basis, not $m^3$. Separate fluorine pilot evidence from whole-route modelling. |
| Dadebo et al. [31], abstract; Sections 2.2 and 2.3 and energy discussion | 125-day laboratory reactor on synthetic feed; laboratory COD 49.8 mg/L. LCA FU 1 $m^3$ influent. The 14.66 kWh passage lacks an explicit denominator. | Retain normalized modelled GHG result and projected 50 $m^3$/day economics; remove the unsupported energy amount. |
| Santana Filho et al. [55], abstract and Table 8 | 120 kt $CO_2$/year is a prospective headline, without a sufficiently traceable baseline and displacement calculation for this comparison. | Remove the headline saving; retain the governance proposal and specify the counterfactual required. |
| El Gamal and Gomaa [61], materials/collection descriptions and dose experiment | 464 mg/g at 0.5 g/L and 80.5 mg/g at 3 g/L are dose-specific. At 250 mg/L initial COD and 96.8% removal, q ≈80.7 mg/g at 3 g/L. A separate 484 mg/g value must not be coupled to that dose. | Show the check and distinguish condition-specific capacity from other maxima/fitted parameters. Describe provenance/reporting as insufficiently linked, not misconduct. |
| Amato et al. [11], Tables 2 and 4; Section 2.2 | Table 2 Scenario 4: COD 3.17 mg/L, $BOD_5$ 0.14 mg/L. Table 4 places ≈0.1 mg/L under COD. Reference flow: 13.7 $m^3$/h; FU 13,700 kg. | Withdraw unqualified COD ≈0.1 mg/L. Identify the detailed Table 2 values and explicitly flag the source-table conflict. |
| Wang et al. [12], life-cycle and economic comparison | FU: 1 t lead. Climate: 1.84/0.51 t $CO_2$-eq/t Pb. Profit: USD 262.55/241.92 per t Pb; carbon profitability: USD 0.14/0.47 per kg $CO_2$-eq. | Keep units and ordering explicit. Do not treat operating-profit calculations with excluded costs as full investment returns. |

This appendix records targeted checks prompted by the review. It is not a claim that every input in every cited publication has been independently replicated. Precision is retained where needed to identify the reported value; it is not an endorsement of its uncertainty or transferability.

## References


1. Marshall, R.E.; Farahbakhsh, K. Systems approaches to integrated solid waste management in developing countries. *Waste Manag.* **2013**, *33*, 988–1003. [CrossRef] [PubMed]
2. Wilson, D.C.; Rodic, L.; Cowing, M.J.; Velis, C.A.; Whiteman, A.D.; Scheinberg, A.; Vilches, R.; Masterson, D.; Stretz, J.; Oelz, B. 'Wasteaware' benchmark indicators for integrated sustainable waste management in cities. *Waste Manag.* **2015**, *35*, 329–342. [CrossRef] [PubMed]
3. Asefi, H.; Shahparvari, S.; Chhetri, P. Advances in sustainable integrated solid waste management systems: Lessons learned over the decade 2007–2018. *J. Environ. Plan. Manag.* **2020**, *63*, 2287–2312. [CrossRef]
4. Abbasi, G.; Las Heras Hernández, M.; Hauser, M.J.; Bourgé, É.; Harju, M.; Nikiforov, V. Towards safe plastic recycling: A novel framework for identifying chemicals of concern in plastic waste. *Environ. Int.* **2026**, *209*, 110177. [CrossRef] [PubMed]
5. Jahnke, A.; Beck, A.J.; Becker, R.L.; Bedulina, D.; Braun, U.; Gerdts, G.; Hildebrandt, L.; Joerss, H.; Korduan, J.; Laforsch, C.; et al. Perspective article: Multisectoral considerations to enable a circular economy for plastics. *J. Hazard. Mater.* **2025**, *496*, 139326. [CrossRef] [PubMed]
6. Johansson, N.; Forsgren, C. Is this the end of end-of-waste? Uncovering the space between waste and products. *Resour. Conserv. Recycl.* **2020**, *155*, 104656. [CrossRef]
7. Domini, M.; Vahidzadeh, R.; Vaccari, M.; Sbaffoni, S.; De Marco, E.; Beltrani, T.; Bertanza, G. Regional industrial symbiosis networks for waste minimisation: A case study from Italy. *J. Environ. Manag.* **2025**, *394*, 127376. [CrossRef] [PubMed]
8. Fric, U.; Levnajić, Z.; Modic, D.; Rončević, B. Industrial symbiosis networks supporting circularity: Understanding complexity, cyclicality and resilience. *Environ. Technol. Innov.* **2025**, *37*, 104026. [CrossRef]
9. Palagonia, C.; Michelini, L.; Mattelin-Pierrard, C. Spanning industrial symbiosis within the circular economy: Critical issues and future research agenda. *J. Ind. Ecol.* **2025**, *29*, 746–765. [CrossRef]
10. Su, P.; Li, L.; Zhou, H.; Li, H.; Zhu, W.; He, H.; Ai, J.; Zhang, W. Environmental and economic sustainability of novel photovoltaic industrial wastewater treatment systems from a life-cycle perspective. *Environ. Res.* **2025**, *272*, 121157. [CrossRef] [PubMed]
11. Amato, A.; Merli, G.; Prisciandaro, M.; Ayedi, K.; Innocenzi, V. Environmental sustainability assessment of different strategies for the treatment of wastewater from textile industry. *J. Environ. Chem. Eng.* **2025**, *13*, 118761. [CrossRef]
12. Wang, L.; Wei, Q.; Cai, K.; Ma, Y.; Song, Q.; Xu, H.; Li, J. Circular economy strategies in metal production: A comparative environmental and economic analysis of primary lead and secondary lead smelting in China. *J. Clean. Prod.* **2026**, *572*, 148926. [CrossRef]
13. Deutz, P.; Neighbour, G.; McGuire, M. Integrating sustainable waste management into product design: Sustainability as a functional requirement. *Sustain. Dev.* **2010**, *18*, 229–239. [CrossRef]
14. Pietzsch, N.; Ribeiro, J.L.D.; de Medeiros, J.F. Benefits, challenges and critical factors of success for Zero Waste: A systematic literature review. *Waste Manag.* **2017**, *67*, 324–353. [CrossRef] [PubMed]
15. Schoeman, Y.; Oberholster, P.; Somerset, V. A decision-support framework for industrial waste management in the iron and steel industry: A case study in Southern Africa. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100097. [CrossRef]
16. Adar, E.; Delice, E.K.; Adar, T. Prioritizing of industrial wastewater management processes using an integrated AHP–CoCoSo model: Comparative and sensitivity analyses. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 4691–4712. [CrossRef]
17. Sharma, P.; Gaur, V.K.; Gupta, S.; Varjani, S.; Pandey, A.; Gnansounou, E.; You, S.; Ngo, H.H.; Wong, J.W.C. Trends in mitigation of industrial waste: Global health hazards, environmental implications and waste derived economy for environmental sustainability. *Sci. Total Environ.* **2022**, *811*, 152357. [CrossRef] [PubMed]
18. Iqbal, A.; Liu, X.; Chen, G.H. Municipal solid waste: Review of best practices in application of life cycle assessment and sustainable management techniques. *Sci. Total Environ.* **2020**, *729*, 138622. [CrossRef] [PubMed]
19. Kiskira, K.; Plakantonaki, S.; Gerolimos, N.; Kalkanis, K.; Sfyroera, E.; Coelho, F.; Priniotakis, G. Life cycle optimization of circular industrial processes: Advances in by-product recovery for renewable energy applications. *Clean Technol.* **2026**, *8*, 5. [CrossRef]
20. Sadhukhan, J.; Sen, S.; Gadkari, S. The mathematics of life cycle sustainability assessment. *J. Clean. Prod.* **2021**, *309*, 127457. [CrossRef]
21. United Nations Environment Programme. *Guidelines for Social Life Cycle Assessment of Products and Organisations 2020*; UNEP: Nairobi, Kenya, 2020. Available online: https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/ (accessed on 14 September 2026).
22. Zaman, A. Are industrial ecology, circular economy and zero waste converging or diverging frameworks for sustainable resource and waste management? *Circ. Econ. Sustain.* **2026**, *6*, 192. [CrossRef]
23. Ragossnig, A.M.; Schneider, D.R. Circular economy, recycling and end-of-waste. *Waste Manag. Res.* **2019**, *37*, 109–111. [CrossRef] [PubMed]
24. Alatawi, I.S.S.; Almughathawi, R.; Madkhali, M.M.M.; Alshammari, N.M.; Alaysuy, O.; Mogharbel, A.T.; Hosni, M.; El-Metwaly, N.M. Sustainable waste-derived cellulose-based nanosensor for cobalt ion detection, removal, and recovery from industrial effluents and battery wastes. *J. Water Process Eng.* **2025**, *70*, 106974. [CrossRef]

25. Shahbaz, M.; Rashid, N.; Saleem, J.; Mackey, H.; McKay, G.; Al-Ansari, T. A review of waste management approaches to maximise sustainable value of waste from the oil and gas industry and potential for the State of Qatar. *Fuel* **2023**, *332*, 126220. [CrossRef]
26. Adepitan, O.L.; Alabi, O.O.; Deigh, C.; Gbadeyan, O.J. Systems-level optimization of hybrid produced water treatment systems for sustainable oil and gas production: A review of current technologies. *Glob. Chall.* **2026**, *10*, 202500575. [CrossRef] [PubMed]
27. Karmakar, P.D.; Jeevananda, T.; Pal, A. Engineering strategies for circular polymer systems: A review of recycling technologies and process innovations. *Polym. Eng. Sci.* **2026**, *66*, 4885–4912. [CrossRef]
28. Cases-Valbuena, L.; Terrados-Cristos, M.; Díaz-Piloñeta, M.; Álvarez-Cabal, V.; Rey-Díaz, A. Valorization pathways of industrial waste from the wind energy sector: A systematic review. *Sustain. Mater. Technol.* **2026**, *47*, e01879. [CrossRef]
29. Wang, Y.; Zhu, L.; Xue, Y. A comprehensive review on dual-pathway utilization of coal gangue concrete: Aggregate substitution, cementitious activity activation, and performance optimization. *Buildings* **2026**, *16*, 302. [CrossRef]
30. Sieradzka, M.; Jerzak, W.; Mlonka-Mędrala, A.; Marszałek, A.; Dudziak, M.; Kalemba-Rec, I.; Błoniarz, A.; Reinmöller, M.; Kopia, A.; Nowak, W.; et al. Valorisation of food industry waste into high-performance biochar for environmental applications. *Sci. Rep.* **2025**, *15*, 11580. [CrossRef] [PubMed]
31. Dadebo, D.; Ibrahim, M.G.; Fujii, M.; Nasr, M. Feasibility of anaerobic digestion/phytoremediation/co-pyrolysis pathway for textile industrial wastewater valorization: Performance, life cycle assessment, and techno-economics. *J. Environ. Chem. Eng.* **2026**, *14*, 121251. [CrossRef]
32. Yang, Y.; Qian, C.; Liu, Y.; Xie, M.; Yang, R.; Wei, T.; Wang, S.; Xu, Y.; Liu, Z. Characteristics, status and management of stockpiled hazardous waste: A case study of China. *Environ. Dev. Sustain.* **2025**. [CrossRef]
33. Naveen, B.P.; Mahapatra, D.M.; Sitharam, T.G.; Sivapullaiah, P.V.; Ramachandra, T.V. Physico-chemical and biological characterization of urban municipal landfill leachate. *Environ. Pollut.* **2017**, *220*, 1–12. [CrossRef] [PubMed]
34. Nanda, S.; Berruti, F. Municipal solid waste management and landfilling technologies: A review. *Environ. Chem. Lett.* **2021**, *19*, 1433–1456. [CrossRef]
35. de Azevedo, A.R.G.; Costa, A.M.; Cecchin, D.; Pereira, C.R.; Marvila, M.T.; Adesina, A. Economic potential comparative of reusing different industrial solid wastes in cementitious composites: A case study in Brazil. *Environ. Dev. Sustain.* **2022**, *24*, 5938–5961. [CrossRef]
36. Luo, H.; Yang, D.; Sadhukhan, J.; Costica, V.; Dorey, R.; Song, Q.; Titirici, M.-M. Process integration and life-cycle assessment of moist-solid hydrolysis of polylactic acid with lactic acid recovery via electrodialysis. *ChemSusChem* **2025**, *18*, e202500503. [CrossRef] [PubMed]
37. Coelho, P.M.; Corona, B.; ten Klooster, R.; Worrell, E. Sustainability of reusable packaging–Current situation and trends. *Resour. Conserv. Recycl. X* **2020**, *6*, 100037. [CrossRef]
38. Setyadi, A.; Pawirosumarto, S.; Damaris, A. Embedding circular operations in manufacturing: A conceptual model for operational sustainability and resource efficiency. *Sustainability* **2025**, *17*, 6737. [CrossRef]
39. Fatimah, Y.A.; Govindan, K.; Murniningsih, R.; Setiawan, A. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *J. Clean. Prod.* **2020**, *269*, 122263. [CrossRef]
40. Mukherjee, A.G.; Wanjari, U.R.; Chakraborty, R.; Renu, K.; Vellingiri, B.; George, A.; Sundara Rajan, C.R.; Gopalakrishnan, A.V. A review on modern and smart technologies for efficient waste disposal and management. *J. Environ. Manag.* **2021**, *297*, 113347. [CrossRef] [PubMed]
41. Wang, Y.; Ren, H.; Dong, L.; Park, H.S.; Zhang, Y.; Xu, Y. Smart solutions shape for sustainable low-carbon future: A review on smart cities and industrial parks in China. *Technol. Forecast. Soc. Change* **2019**, *144*, 103–117. [CrossRef]
42. Ali, M.U.; Khan, I.; Khan, H. Leveraging Industry 4.0 technologies and industrial symbiosis: Advancing circular economy practices in BRICS economies. *J. Environ. Manag.* **2025**, *383*, 125471. [CrossRef] [PubMed]
43. Chang, X.; Wu, J.; Li, T.; Fan, T.J. The joint tax-subsidy mechanism incorporating extended producer responsibility in a manufacturing-recycling system. *J. Clean. Prod.* **2019**, *210*, 821–836. [CrossRef]
44. Yılmaz Gözene, H.; Halaçeli Metlioğlu, H. Zero waste approach in sustainable fashion design: Designer perspective for pre-consumer waste management. *J. Text. Eng.* **2025**, *32*, 79–93. [CrossRef]
45. Johansson, N.; Corvellec, H. Waste policies gone soft: An analysis of European and Swedish waste prevention plans. *Waste Manag.* **2018**, *77*, 322–332. [CrossRef] [PubMed]
46. Pires, A.; Martinho, G. Waste hierarchy index for circular economy in waste management. *Waste Manag.* **2019**, *95*, 298–305. [CrossRef] [PubMed]
47. AlSheyadi, A.; Abbas, H.; Baawain, A.; Saeed, A. Linking zero-waste management and green innovative supply chains to sustainable performance: The mediating role of green dynamic capabilities in manufacturing firms. *Sustainability* **2025**, *17*, 10348. [CrossRef]
48. Semrau, J.; Horzela-Miś, A. Strategies for reducing and valorizing industrial waste in the context of sustainable development and Industry 4.0. *Sci. Pap. Silesian Univ. Technol. Organ. Manag. Ser.* **2026**, *245*, 463–473. [CrossRef]

49. Eržen, B.; Deniz, Ş.; Aydoğmuş, E.; Kar, F.; Arslanoğlu, H. Integrating life cycle thinking and extended producer responsibility into industrial symbiosis: A review of circular economy approaches. *Circ. Econ. Sustain.* **2026**, *6*, 90. [CrossRef]
50. Huang, L.; Zhen, L.; Yin, L. Waste material recycling and exchanging decisions for industrial symbiosis network optimization. *J. Clean. Prod.* **2020**, *276*, 124073. [CrossRef]
51. Zhao, Y.; Yu, M.; Kong, F.W.; Li, L.H. An emergy ternary diagram approach to evaluate circular economy implementation of eco-industrial parks. *Clean Technol. Environ. Policy* **2019**, *21*, 1433–1445. [CrossRef]
52. Genc, O. Harmony in industry and nature: Exploring the intersection of industrial symbiosis and food webs. *Circ. Econ. Sustain.* **2025**, *5*, 79–100. [CrossRef]
53. Fussone, R.; Sammatrice, C.; Cannella, S.; Dominguez, R. Enhancing circular economy through industrial symbiosis: An agent-based simulation analysis of supply chain dynamics. *Sustain. Oper. Comput.* **2025**, *6*, 130–139. [CrossRef]
54. Bai, Y.; Wang, N.; Xie, S.; Zhang, J. Paradigm and efficiency of industrial waste resource utilization: Evidence from China. *J. Environ. Manag.* **2025**, *380*, 124922. [CrossRef] [PubMed]
55. Santana Filho, J.J.; Gaspar, P.D.; do Paço, A.; Marcelino, S.M. Governance-centred industrial symbiosis for circular economy transitions: A rural forest biomass hub framework proposal. *Sustainability* **2025**, *17*, 5659. [CrossRef]
56. Barathi, A.; Kundu, D.; Pooja, K.; Surya, M.; Jacob, S.; Samanta, P.; Kumar, V.; Kuila, A. Toward sustainable industry: Integrating industrial symbiosis, biorefineries, and circular economy for SDG alignment. *Sustain. Energy Fuels* **2026**, *10*, 1816–1842. [CrossRef]
57. Munonye, W.C.; Ajonye, G.O.; Akinloye, O.A. Industrial symbiosis in circular economies through policy and practice for waste-to-resource innovation. *Discov. Sustain.* **2025**, *6*, 1371. [CrossRef]
58. Nuur, C.; Karabag, S.F.; Feldmann, A. Circular economy in the extractive frontier: Tensions and pathways for transformative change in mining. *Extr. Ind. Soc.* **2026**, *25*, 101764. [CrossRef]
59. Wang, Y.P.; Smith, R. Wastewater minimisation. *Chem. Eng. Sci.* **1994**, *49*, 981–1006. [CrossRef]
60. Sadhukhan, J.; Zhang, N.; Zhu, X.X. Value analysis of complex systems and industrial application to refineries. *Ind. Eng. Chem. Res.* **2003**, *42*, 5165–5181. [CrossRef]
61. El Gamal, G.A.; Gomaa, A.M. Performance of maize tassel activated carbon for COD removal from industrial wastewater under optimized conditions. *Sci. Rep.* **2025**, *15*, 24902. [CrossRef] [PubMed]
62. Kasiński, S.; Kowal, P.; Czerwionka, K. Advanced technologies for nitrogen removal and recovery from municipal and industrial wastewater. *Materials* **2025**, *18*, 1422. [CrossRef] [PubMed]
63. Lackner, S.; Gilbert, E.M.; Vlaeminck, S.E.; Joss, A.; Horn, H.; van Loosdrecht, M.C.M. Full-scale partial nitritation/anammox experiences—An application survey. *Water Res.* **2014**, *55*, 292–303. [CrossRef] [PubMed]
64. Liu, B.; Liu, Z.; Weng, C.; Wang, Y.; Sun, Y.; Wu, W.; Zhai, C. Performance-oriented evaluation of regeneration strategies from industrial waste heat to chemical energy with preheating and internal heating. *Energy* **2026**, *349*, 140673. [CrossRef]
65. Minier-Matar, J.; AlShamari, E.; Raja, M.; Khan, F.; Al-Maas, M.; Hussain, A.; Adham, S. Detailed organic characterization of process water to evaluate reverse osmosis membrane fouling in industrial wastewater treatment. *Desalination* **2024**, *572*, 117128. [CrossRef]
66. Wilts, H.; Garcia, B.R.; Garlito, R.G.; Gómez, L.S.; Prieto, E.G. Artificial intelligence in the sorting of municipal waste as an enabler of the circular economy. *Resources* **2021**, *10*, 28. [CrossRef]
67. Shanmughan, B.; Nighojkar, A.; Kandsubramanian, B. Advancements in characterization techniques, empirical models, and artificial intelligence for comprehensive understanding of heavy metal adsorption on sewage sludge biochar. *Waste Manag. Bull.* **2025**, *3*, 193–206. [CrossRef]
68. Ali, N.N.; Alayan, H.M.; AbdulRazak, A.A.; Jalil, R.R.; Al-Sheikh, F. A review of recent advances in cold plasma technology in the oil industry: A sustainable alternative for phenol degradation to conventional treatment methods. *Desalin. Water Treat.* **2025**, *323*, 101289. [CrossRef]
69. Das, A.; Mishra, S. Reimagining biofiltration for sustainable industrial wastewater treatment. *Discov. Sustain.* **2025**, *6*, 826. [CrossRef]
70. Abbasi, S.A. The myth and the reality of energy recovery from municipal solid waste. *Energy Sustain. Soc.* **2018**, *8*, 14. [CrossRef]
71. Moya, D.; Aldás, C.; López, G.; Kaparaju, P. Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. *Energy Procedia* **2017**, *134*, 286–295. [CrossRef]
72. Li, Y.; Zhao, X.; Li, Y.; Li, X. Waste incineration industry and development policies in China. *Waste Manag.* **2015**, *46*, 234–241. [CrossRef] [PubMed]
73. Ionescu, G.; Rada, E.C.; Ragazzi, M.; Mărculescu, C.; Badea, A.; Apostol, T. Integrated municipal solid waste scenario model using advanced pretreatment and waste to energy processes. *Energy Convers. Manag.* **2013**, *76*, 1083–1092. [CrossRef]
74. Boichenko, S.; Yakovlieva, A.; Zubenko, S.; Shkilniuk, I. Physical, chemical, and performance properties of biodiesel fuels: A comparative study of lipid-based feedstocks. *Energies* **2025**, *18*, 4274. [CrossRef]

75. Sakai, S.i.; Yoshida, H.; Hiratsuka, J.; Vandecasteele, C.; Kohlmeyer, R.; Rotter, V.S.; Passarini, F.; Santini, A.; Peeler, M.; Li, J.; et al. An international comparative study of end-of-life vehicle (ELV) recycling systems. *J. Mater. Cycles Waste Manag.* **2014**, *16*, 1–20. [CrossRef]
76. Soo, V.K.; Peeters, J.; Compston, P.; Doolan, M.; Duflou, J.R. Comparative Study of End-of-Life Vehicle Recycling in Australia and Belgium. *Procedia CIRP* **2017**, *61*, 269–274. [CrossRef]
77. Rosa, P.; Terzi, S. Improving end of life vehicle's management practices: An economic assessment through system dynamics. *J. Clean. Prod.* **2018**, *184*, 520–536. [CrossRef]
78. D'Adamo, I.; Sassanelli, C. Biomethane community: A research agenda towards sustainability. *Sustainability* **2022**, *14*, 4735. [CrossRef]
79. Morone, P.; Imbert, E. Food waste and social acceptance of a circular bioeconomy: The role of stakeholders. *Curr. Opin. Green Sustain. Chem.* **2020**, *23*, 55–60. [CrossRef]
80. Nurjaya, L.A.N.W.; Nurherdiana, S.D.; Saputro, E.A.; Jalil, M.J. Greenhouse gas emissions estimation of hazardous waste in oil and gas industry for 2020–2024. *Environ. Prog. Sustain. Energy* **2026**, *45*, e70334. [CrossRef]
81. Sadhukhan, J.; Sekar, K. Economic conditions to circularize clinical plastics. *Energies* **2022**, *15*, 8974. [CrossRef]
82. Greenhouse Gas Protocol. Inventory and Project Accounting: A Comparative Review. 2023. Available online: https://ghgprotocol.org/blog/inventory-and-project-accounting (accessed on 14 September 2026).
83. World Resources Institute; World Business Council for Sustainable Development. *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*; WRI: Washington, DC, USA; WBCSD: Geneva, Switzerland, 2011. Available online: https://ghgprotocol.org/corporate-value-chain-scope-3-standard (accessed on 14 September 2026).
84. Sheng, T.J.; Islam, M.S.; Misran, N.; Baharuddin, M.H.; Arshad, H.; Islam, M.R.; Chowdhury, M.E.H.; Rmili, H.; Islam, M.T. An Internet of Things Based Smart Waste Management System Using LoRa and Tensorflow Deep Learning Model. *IEEE Access* **2020**, *8*, 148793–148811. [CrossRef]
85. Antonioli, D.; Borghesi, S.; D'Amato, A.; Gilli, M.; Mazzanti, M.; Nicolli, F. Analysing the interactions of energy and climate policies in a broad policy 'optimality' framework: The Italian case study. *J. Integr. Environ. Sci.* **2014**, *11*, 205–224. [CrossRef]
86. Shayesteh, A.; Koohshekan, O.; Khadivpour, F.; Kian, M.; Ghasemzadeh, R.; Pazoki, M. Industrial waste management using the rapid impact assessment matrix method for an industrial park. *Glob. J. Environ. Sci. Manag.* **2020**, *6*, 261–274. [CrossRef]
87. Urbinati, A.; Rosa, P.; Sassanelli, C.; Chiaroni, D.; Terzi, S. Circular business models in the European manufacturing industry: A multiple case study analysis. *J. Clean. Prod.* **2020**, *274*, 122964. [CrossRef]
88. Appolloni, A.; D'Adamo, I.; Gastaldi, M.; Santibanez-Gonzalez, E.D.R.; Settembre-Blundo, D. Growing e-waste management risk awareness points towards new recycling scenarios: The view of the Big Four's youngest consultants. *Environ. Technol. Innov.* **2021**, *23*, 101716. [CrossRef]
89. Julianelli, V.; Caiado, R.G.G.; Scavarda, L.F.; Cruz, S.P.d.M.F. Interplay between reverse logistics and circular economy: Critical success factors-based taxonomy and framework. *Resour. Conserv. Recycl.* **2020**, *158*, 104784. [CrossRef]
90. Kumar, A.; Moktadir, M.A.; Khan, S.A.R.; Garza-Reyes, J.A.; Tyagi, M.; Kazançoğlu, Y. Behavioral factors on the adoption of sustainable supply chain practices. *Resour. Conserv. Recycl.* **2020**, *158*, 104818. [CrossRef]
91. Ko, S.; Kim, W.; Shin, S.C.; Shin, J. The economic value of sustainable recycling and waste management policies: The case of a waste management crisis in South Korea. *Waste Manag.* **2020**, *104*, 220–227. [CrossRef] [PubMed]
92. Colasante, A.; D'Adamo, I.; Morone, P.; Rosa, P. Assessing the circularity performance in a European cross-country comparison. *Environ. Impact Assess. Rev.* **2022**, *93*, 106730. [CrossRef]
93. Zoboli, R.; Mazzanti, M.; Paleari, S.; Bonacorsi, L.; Chioatto, E.; D'Amato, A.; Ghisetti, C.; Maggioni, M.A.; Zecca, E.; Pareglio, S. Energy and the circular economy: Filling the gap through new business models within the EGD. In *FEEM Report No. 13*; Fondazione Eni Enrico Mattei: Milan, Italy, 2020. Available online: https://ssrn.com/abstract=3780085 (accessed on 27 August 2026).
94. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 19–32. [CrossRef]
95. Ijimdiya, S.J.; Kumarasamy, M.V.; Adu, J.T.; Pandi, D. Role of the circular economy framework for sustainable waste management and climate change mitigation. *Sustainability* **2026**, *18*, 1946. [CrossRef]
96. Radu, I.-C.; Vadureanu, A.-M.; Cozorici, D.-E.; Blanzeanu, E.; Zaharia, C. Advancing sustainability in modern polymer processing: Strategies for waste resource recovery and circular economy integration. *Polymers* **2025**, *17*, 522. [CrossRef] [PubMed]
97. Cooper, R.G. Stage-gate systems: A new tool for managing new products. *Bus. Horiz.* **1990**, *33*, 44–54. [CrossRef]
98. Garmendia Aguirre, I.; Abbate, E.; Bracalente, G.; Mancini, L.; Cappucci, G.M.; Tosches, D.; Rasmussen, K.; Sokull-Kluettgen, B.; Rauscher, H.; Sala, S. *Safe and Sustainable by Design Chemicals and Materials: Revised Framework (2025)*; Publications Office of the European Union: Luxembourg, 2025; p. JRC143022. [CrossRef]
99. Chun, W.S.; Phu, V.L. Adopting DPSIR approach to the valuation of circular economy strategy on solid waste of the footwear sector in Vietnam. *IOP Conf. Ser. Earth Environ. Sci.* **2025**, *1540*, 012020. [CrossRef]

100. Barua, S. Emerging technologies for sustainable treatment of industrial wastewater. *Int. J. Technol. Manag. Hum.* **2025**, *11*, 94–104. [CrossRef]
101. Al Sheyadi, A.; Awain, A.M.B.; Abbas, H. Zero Waste Management Towards Environmental and Operational Performance: The Mediating Role of Green Innovative Supply Chain Management. *IOP Conf. Ser. Earth Environ. Sci.* **2025**, *1520*, 012009. [CrossRef]
102. Makan, A.; Salama, Y.; Mamouni, F.Z.; Makan, M. Towards Zero-Waste Cities: An Integrated and Circular Approach to Sustainable Solid Waste Management. *Sustainability* **2025**, *17*, 7884. [CrossRef]
103. Aivalioti, M.; Cossu, R.; Gidarakos, E. New opportunities in industrial waste management. *Waste Manag.* **2014**, *34*, 1737–1738. [CrossRef] [PubMed]
104. De Almeida, S.T.; Borsato, M. Assessing the efficiency of End of Life technology in waste treatment—A bibliometric literature review. *Resour. Conserv. Recycl.* **2019**, *140*, 189–208. [CrossRef]
105. Gonçalves, A.T.T.; Moraes, F.T.F.; Marques, G.L.; Lima, J.P.; Lima, R.d.S. Urban solid waste challenges in the BRICS countries: A systematic literature review. *Rev. Ambient. Água* **2018**, *13*, e2157. [CrossRef]
106. Fuldauer, L.I.; Ives, M.C.; Adshead, D.; Thacker, S.; Hall, J.W. Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. *J. Clean. Prod.* **2019**, *223*, 147–162. [CrossRef]
107. Fuss, M.; Vasconcelos Barros, R.T.; Poganietz, W.R. Designing a framework for municipal solid waste management towards sustainability in emerging economy countries—An application to a case study in Belo Horizonte (Brazil). *J. Clean. Prod.* **2018**, *178*, 655–664. [CrossRef]
108. Azevedo, B.D.; Scavarda, L.F.; Caiado, R.G.G.; Fuss, M. Improving urban household solid waste management in developing countries based on the German experience. *Waste Manag.* **2021**, *120*, 772–783. [CrossRef] [PubMed]
109. Chaudhary, P.; Garg, S.; George, T.; Shabin, M.; Saha, S.; Subodh, S.; Sinha, B. Underreporting and open burning—The two largest challenges for sustainable waste management in India. *Resour. Conserv. Recycl.* **2021**, *175*, 105865. [CrossRef]


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