Waste Valorisation, Bioremediation and Resource Recovery for Sustainable Systems

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Abstract

Waste streams are increasingly recognized not only as pollution burdens but also as heterogeneous reservoirs of carbon, nutrients, metals, energy, water, and functional compounds. Agricultural residues, food waste, wastewater, municipal organics, industrial effluents, and contaminated soils can potentially support resource recovery while environmental damage is reduced. This editorial argues that genuine valorisation requires more than producing a secondary product from waste: recovery must improve environmental performance, manage contaminants safely, and remain technically and economically credible. Current approaches include anaerobic digestion, microbial fermentation, nutrient recovery, algal systems, biosorption, phytoremediation, microbial electrochemical technologies, and integrated waste biorefineries. Their limitations include feedstock heterogeneity, pretreatment demand, pathogens, toxic metals, process instability, recovery costs, secondary residues, product-safety requirements, logistics, regulatory barriers, and uncertain markets. Research should prioritize selective recovery, integrated treatment–valorisation systems, nutrient and water loops, high-value bioproducts, contaminant management, distributed processing, long-term bioremediation validation, and combined lifecycle and techno-economic assessment. Sustainable resource recovery should ultimately be judged by avoided pollution and retained value across the complete system.

Keywords: waste valorisation; resource recovery; bioremediation; anaerobic digestion; wastewater; nutrient recovery; circular systems

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1.0 Introduction

1.1 Context and Problem Framing

Modern economies generate large and chemically diverse waste streams whose management has traditionally focused on containment, treatment, dilution, or disposal. Agricultural residues, food-processing wastes, municipal organics, sewage, industrial effluents, contaminated soils, mining residues, and nutrient-rich waters contain substantial quantities of carbon, nitrogen, phosphorus, metals, water, and functional organic compounds. Disposing of these streams destroys material value while often transferring environmental burdens to landfills, incinerators, receiving waters, or contaminated sites. Resource-recovery thinking reframes the problem: the objective is not merely to make waste less harmful, but where feasible to recover useful materials and energy while achieving the required environmental protection. The scale of this opportunity is matched by the management challenge. Global assessments show continuing growth in municipal solid waste and major differences in collection and treatment capacity among regions (Kaza et al., 2018), while food waste represents a substantial industrial and municipal resource stream whose composition changes across supply chains (Girotto et al., 2015). This diversity strengthens the case for recovery but also means that no single technology defines a universal waste-to-resource pathway.

Biological processes are particularly relevant because many waste streams contain biodegradable organics or contaminants that can be transformed, immobilized, concentrated, or recovered through microbial, algal, plant, and enzymatic activity. Anaerobic digestion converts organic matter into methane-rich biogas while stabilizing residues; microbial fermentation can produce organic acids, alcohols, enzymes, polymers, and other products; algae can assimilate nutrients while generating biomass; plants and microorganisms can immobilize or accumulate metals; and microbial electrochemical systems can convert dissolved organics into electricity or chemicals. Waste biorefineries integrate several of these routes to recover multiple products from heterogeneous feedstocks (Mohan et al., 2016).

1.2 Why the Issue Matters

The conceptual shift from waste treatment to valorisation nevertheless creates a higher evidentiary burden. A treatment process can be successful if it meets discharge or remediation requirements. A valorisation process must additionally demonstrate that recovered products are safe, useful, and worth the resources required for recovery. Food and agro-industrial residues illustrate this distinction: they contain valuable compounds, but collection, contamination, variability, and purification can constrain practical recovery (Mirabella et al., 2014; Yaashikaa et al., 2022). The editorial position advanced here is that wastes should be evaluated as complex resource streams, but claims of circularity should depend on net system performance. Recovery becomes sustainable only when it reduces environmental risk, preserves or creates useful value, and avoids disproportionate secondary burdens.

2.0 Current Landscape

2.1 Waste-to-Resource Pathways

Anaerobic digestion remains one of the most established biological pathways for recovering energy from wet organic wastes. The process converts biodegradable material through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, producing biogas and a nutrient-containing digestate. Reviews have documented both the maturity of anaerobic digestion and its sensitivity to inhibitors, loading, temperature, pH, and feed composition (Appels et al., 2008; Chen et al., 2008). Co-digestion can improve nutrient balance and gas yield, while pretreatment can increase hydrolysis rates for recalcitrant substrates. Yet the sustainability of digestion depends strongly on methane leakage, digestate management, heat use, and whether recovered nutrients displace mineral fertilizers. Formal process models such as ADM1 have supported mechanistic understanding of anaerobic conversion, while broader reviews document the continuing development of digestion across diverse feedstocks (Batstone et al., 2002; Mao et al., 2015).

2.2 Biological Remediation

Wastewater treatment is also moving toward resource recovery. Conventional treatment consumes energy and often removes nitrogen and phosphorus by converting them into gaseous or difficult-to-reuse forms. Resource-oriented systems instead seek recovery of phosphorus, nitrogen, organics, water, and sometimes biopolymers. Guest et al. (2009) argued for a planning paradigm in which wastewater infrastructure is evaluated as a resource system, while van Loosdrecht and Brdjanovic (2014) anticipated treatment plants increasingly designed around resource and energy recovery. Technologies include struvite precipitation, ammonia recovery, adsorption, ion exchange, membrane concentration, algal assimilation, and sludge valorisation. Phosphorus-recovery research spans established precipitation concepts and newer nutrient-recovery technologies, and resource-oriented wastewater frameworks increasingly integrate multiple products rather than a single effluent standard (Morse et al., 1998; Mehta et al., 2015; Desmidt et al., 2015; Kehrein et al., 2020; Verstraete et al., 2009).

2.3 Nutrient Recovery

Microbial electrochemical technologies represent another route for converting waste organics into useful outputs. Logan and Rabaey (2012) described how electroactive microorganisms can catalyse conversion of organic matter to electricity, hydrogen, and chemicals. Although many systems remain below full commercial maturity, they demonstrate a broader principle: waste treatment can be coupled to selective product generation. Similar logic applies to fermentation of food waste and other organic residues into volatile fatty acids, lactic acid, succinic acid, polyhydroxyalkanoates, and platform chemicals. Food-waste biorefineries and fermentation routes similarly show how organic residues can be redirected toward chemicals and materials rather than only energy recovery (Lin et al., 2013; Pleissner & Lin, 2013).

2.4 Integrated Treatment Systems

Bioremediation extends resource thinking to contaminated environments. Biosorption can concentrate metals onto biological materials, and microbial processes can change metal speciation, mobility, or toxicity. Wang and Chen (2009) reviewed biosorbents for heavy-metal removal, while Gaur et al. (2014) examined microbial and plant-based remediation pathways. Phytoremediation uses plants to extract, stabilize, or transform contaminants and can sometimes be linked with biomass valorisation or phytomining. Algal systems similarly combine nutrient uptake with biomass generation and have been proposed for wastewater remediation and bioenergy production (Rawat et al., 2011). The scientific opportunity is to integrate remediation with selective recovery without allowing contaminants to migrate into unsafe secondary products. Foundational phytoremediation and biosorption studies

established mechanisms by which plants and biological sorbents can remove or concentrate metals (Salt et al., 1998; Volesky, 2001; Ali et al., 2013). Algal wastewater systems likewise couple nutrient removal with recoverable biomass (Pittman et al., 2011). Recent reviews increasingly connect remediation with critical-material recovery and circular-economy objectives (Povedano-Priego et al., 2025).

3.0 Critical Challenges

3.1 Contaminants and Heterogeneity

Feedstock heterogeneity is the first major constraint. Waste streams change with season, geography, consumer behaviour, industrial production schedules, sanitation practices, and upstream separation. Organic composition, moisture, particle size, salinity, toxic compounds, pathogens, and trace metals can vary dramatically. Biological processes are often sensitive to these changes. Anaerobic digesters can become unstable under sudden loading or inhibition, fermentations can lose selectivity, and recovery systems can foul or produce inconsistent products. Robust waste valorisation therefore requires characterization and blending strategies capable of handling variation rather than demonstrations on narrowly selected feedstock.

Contamination is a second challenge because the attributes that make waste valuable can coexist with hazards. Biosolids may contain nutrients but also metals, persistent organic contaminants, pathogens, or microplastics. Food wastes may contain packaging residues or cleaning chemicals. Industrial effluents may contain recoverable metals together with toxic mixtures. Phytoremediation can transfer metals from soil into biomass, creating a new material that must be processed safely. Recent circular-bioeconomy analyses emphasize that contaminated phytomass can become a secondary pollution source if recovery or disposal is poorly managed (Priya et al., 2023). Product safety must therefore be demonstrated, not assumed from biological processing.

3.2 Yield Limitations

Pretreatment and recovery costs frequently determine economic feasibility. Lignocellulosic residues may require milling, chemical pretreatment, hydrolysis, or detoxification. Wastewater nutrients are often present at concentrations too low for economical separation without concentration. Metals may be selectively accumulated but still require extraction from biomass or sorbents. The technical ability to recover a material is therefore insufficient evidence that recovery is preferable to conventional treatment. Process intensification, selective binding, membrane concentration, electrochemical separation, and cascading recovery can improve performance, but each introduces capital and energy requirements. Anaerobic-pretreatment reviews show that gains in biodegradability must be balanced against added energy, chemicals, and equipment (Carrere et al., 2010).

3.3 Mass-Balance Uncertainty

Bioremediation faces a distinct scale and time problem. Laboratory studies frequently use controlled contaminant concentrations, optimized microbial cultures, or ideal plant growth conditions, while real sites contain mixed contaminants, spatial heterogeneity, uncertain hydrology, and changing environmental conditions. Phytoremediation may require years, and remediation success depends on root depth, bioavailability, climate, and land-use constraints. Heavy-metal removal cannot destroy metals; it transfers or immobilizes them, so long-term management remains necessary. Field-scale monitoring should therefore extend beyond short-term concentration reductions.

3.4 Environmental Burden Shifting

Market, logistics, and regulation create further barriers. A recovered product must satisfy quality and safety requirements and must compete with established primary materials. Digestate may have agronomic value but can be costly to transport because of water content. Recovered phosphorus can be technically feasible yet sensitive to fertilizer prices. Distributed waste sources favour local processing, but small facilities may struggle to achieve economies of scale. Lifecycle studies are essential because transport, pretreatment, energy use, avoided treatment, and displacement credits can change whether a recovery pathway provides net benefit (Liu et al., 2021).

4.0 Discussion and Priorities

4.1 Integrative Discussion

Waste treatment and waste valorisation should be distinguished by their primary system function. Treatment seeks compliance and risk reduction; valorisation adds deliberate recovery of useful value. The two objectives can reinforce one another, but they can also conflict. Maximizing methane production may reduce the fraction of organics available for higher-value fermentation. Aggressive chemical extraction can increase metal recovery while generating secondary liquid wastes. Nutrient concentration can improve reuse but consume energy or reagents. Integrated design must therefore optimize the overall treatment–recovery system rather than individual recovery yields.

A hierarchy of recovery can help structure decisions. High-value compounds and reusable materials may warrant selective extraction when purity and markets justify it; carbon can then be converted biologically; residual energy can be recovered; and stabilized residues can be returned to soil only when contaminant risks are acceptable. This cascading approach is consistent with waste-biorefineries that combine multiple conversion pathways (Mohan et al., 2016). However, high-value recovery is not automatically best: small markets, complex purification, or low concentrations can make a theoretically valuable product economically irrelevant.

Environmental performance must therefore be evaluated with lifecycle and material-flow methods. Resource recovery can avoid primary production, landfill, incineration, nutrient losses, or fossil energy, but those benefits depend on substitution actually occurring. Secondary wastes, energy consumption, chemicals, infrastructure, and transportation must be included. The strongest systems will couple environmental remediation with recoverable value while ensuring that contaminants are destroyed, immobilized, or safely contained rather than redistributed.

4.2 Research and Practice Priorities

A first priority is selective recovery from complex streams. Sorbents, membranes, electrochemical systems, microbial pathways, and crystallization processes should be designed to recover target nutrients, metals, or organics in forms that meet downstream specifications. Selectivity is particularly important when valuable compounds occur alongside toxic contaminants. Performance should be reported under realistic mixtures rather than single-solute laboratory solutions.

Second, integrated treatment–valorisation systems should be developed around cascading use. Anaerobic digestion, fermentation, nutrient recovery, algal cultivation, and thermal or chemical finishing can be combined so that one process prepares streams for the next. Such integration should be supported by whole-system carbon, nutrient, water, and energy balances. Waste-biorefineries should report residual waste quantities as carefully as recovered products.

Third, nutrient recovery from wastewater and organic residues deserves continued emphasis because nitrogen and phosphorus connect water quality, energy demand, fertilizer production, and food systems. Technologies should be evaluated not only for recovery efficiency but also for contaminant removal, product agronomic value, stability, transportability, and market acceptance. Circular water systems should likewise integrate reclaimed water quality with industrial or agricultural demand.

Fourth, bioremediation needs longer and more representative field validation. Studies should evaluate contaminant fate, rebound, seasonal variation, ecological effects, and post-treatment land use over relevant timescales. Phytoremediation studies should explicitly address management of contaminated biomass, including safe disposal, energy recovery, or metal recovery. Biosorption and microbial-remediation studies should examine regeneration and secondary-residue management.

Fifth, distributed processing should be investigated for wastes whose water content or perishability makes long-distance transport inefficient. Modular digesters, fermentation units, nutrient-recovery modules, and local preprocessing could reduce transport while producing stabilized intermediates for centralized finishing. Techno-economic analysis should identify the scales and geographic densities at which distributed models become competitive.

Finally, lifecycle and techno-economic evaluation should accompany technology development. Comparative assessments should include realistic incumbent treatment routes, avoided products, recovery efficiencies, contaminant management, and uncertainty. Resource recovery deserves implementation when it can demonstrate both environmental protection and credible retained value.

4.3 Implications for the Journal's Scope

The journal should encourage research that demonstrates both sides of sustainable waste conversion: reduction of environmental burden and recovery of useful resources. Studies of anaerobic digestion, waste fermentation, nutrient recovery, algal systems, biosorption, bioremediation, phytoremediation, microbial electrochemistry, and waste biorefineries should therefore quantify treatment performance alongside recovered product quantity, quality, safety, and resource requirements.

Particularly valuable contributions will integrate environmental biotechnology with process engineering, field validation, lifecycle assessment, techno-economic analysis, and market-relevant product specifications. Negative findings are important when they reveal why a recovery route increases energy demand, generates secondary waste, mobilizes contaminants, or fails economically. Waste should be treated as a potential resource, but scientific claims of valorisation should depend on evidence that the complete system creates more recoverable value than environmental burden.

4.4 Conclusion

Waste streams are no longer scientifically interesting only because they require treatment. They are heterogeneous reservoirs of carbon, nutrients, metals, water, energy, and biological molecules that can sometimes support new production while reducing pollution. Anaerobic digestion, fermentation, nutrient recovery, algal systems, biosorption, phytoremediation, and microbial electrochemical technologies illustrate the breadth of available pathways.

The central challenge is to distinguish genuine resource recovery from the mere creation of another secondary stream. Sustainable valorisation must manage contaminants, operate stably with variable feedstock, produce safe and marketable outputs, and outperform realistic treatment alternatives when energy, chemicals, logistics,

infrastructure, and residual wastes are included. Future progress should therefore be measured by integrated environmental and resource outcomes. Waste becomes a resource only when recovery preserves value without transferring unacceptable burdens elsewhere.

5.0 Declarations

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Dr. Priya Menon and Dr. Lucas Ferreira contributed to the conceptual development, literature synthesis, critical interpretation, drafting, and revision of the editorial.

5.2 Funding

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5.3 Competing Interests

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5.4 Data Availability

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5.5 AI Use Disclosure

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