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Editorial

Emerging Technologies for Waste Treatment, Pollution Control and Resource Recovery

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Abstract

This Editorial introduces the Special Issue "Emerging Technologies for Waste Treatment, Pollution Control and Resource Recovery", which examines how contemporary environmental engineering is moving beyond conventional end-of-pipe treatment toward integrated, circular, and systems-oriented approaches. The collected contributions address sustainability innovation in textile manufacturing, life-cycle-informed PFAS removal from landfill leachate, fishbone-derived hydroxyapatite adsorbents for heavy metal removal, and constructed wetlands for azo dye degradation. Together, these studies demonstrate that effective waste treatment must be evaluated not only in terms of pollutant removal efficiency, but also by material circularity, secondary environmental burdens, operational feasibility, and long-term contaminant fate. This Editorial highlights key cross-cutting themes, including the valorization of residual materials, the importance of realistic matrices and field validation, and the need to integrate life cycle assessment, techno-economic analysis, and mechanistic investigation early in technology development. It further identifies major research gaps concerning spent media management, regeneration, toxicity, transformation products, and scale-up under variable operating conditions. Overall, this Special Issue proposes a framework in which emerging waste treatment technologies are understood as multifunctional environmental systems that support pollution control, resource recovery, and resilient circular economies.

Keywords: waste treatment; pollution control; resource recovery; circular economy; emerging environmental technologies

1. Introduction and Scope

The management of waste streams has entered a phase in which end-of-pipe treatment, pollution control, and resource recovery can no longer be considered separate tasks [1]. Increasingly complex wastewaters, persistent contaminants, and dispersed solid residues require technologies that not only remove pollutants but also reduce secondary burdens, recover value, and remain deployable under realistic operating constraints. This Special Issue of *Environments*, entitled "Emerging Technologies for Waste Treatment, Pollution Control and Resource Recovery", was conceived to stimulate research at precisely this interface: technologies and strategies that treat wastes while supporting circularity, environmental protection, and more resilient resource systems.

The contributions collected in this Special Issue address four complementary dimensions of this transition. First, a review of sustainability-oriented innovation in textile manufacturing examines how pre-consumer waste recovery, digitalization, product and process redesign, organizational innovation, and environmental remediation can enable

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circular patterns in a sector known for high water, energy, and chemical intensity. Second, a life cycle assessment of PFAS removal from landfill leachate shifts attention from treatment efficiency alone to the environmental trade-offs of alternative abatement routes. Third, a study on fishbone-derived hydroxyapatite demonstrates how biogenic residues can be converted into low-cost adsorbents for heavy metal removal. Finally, an investigation of constructed wetlands for azo dye removal provides mechanistic insight into plant–microbe interactions that enable low-energy treatment without external carbon addition. Together, these papers reflect a maturing research agenda: the most promising environmental technologies are those designed around pollutant fate, material circularity, process sustainability, and context-specific implementation.

Recent developments in waste treatment and pollution control have been driven by three converging needs. The first is the treatment of contaminants that are chemically persistent, biologically recalcitrant, or present in highly complex matrices, such as PFAS in landfill leachate and azo dyes in textile effluents [2–4]. The second is the replacement of virgin treatment materials with waste-derived or regenerable alternatives, thereby turning residual biomass or industrial by-products into functional adsorbents, catalysts, or construction materials [5,6]. The third is the need to quantify the whole system's impacts early in the technology development process. High removal efficiency is necessary but insufficient if achieved through excessive reagent use, high energy demand, non-regenerable sorbents, or problematic sludge streams. The papers in this Special Issue therefore contribute not merely as isolated case studies, but as examples of how waste treatment research is expanding toward system-level circular engineering.

2. Contributions

Butturi et al. provide the broadest systems perspective in this Special Issue by reviewing sustainability-oriented innovation in the textile manufacturing industry, with a focus on pre-consumer waste recovery and circular patterns. Their analysis identifies five innovation areas: Industry 4.0 and digital transformation; innovative product and process design and sustainable raw materials; the use of textile waste outside the textile value chain; waste recovery within the value chain and environmental remediation; and organizational or business model innovation. This contribution is valuable because it frames waste minimization as an upstream design and governance challenge rather than a solely downstream treatment problem. It also shows that circularity in textile manufacturing requires coordination across material selection, production planning, traceability, waste sorting, and inter-firm collaboration. The review highlights gaps that are highly relevant for the field: design for recyclability and durability must be implemented more systematically; the environmental consequences of novel materials and processes should be evaluated concurrently with their development; and industrial symbiosis and social innovation require deeper investigation.

Bedogni et al. address one of the most pressing issues in current leachate management: the removal of per- and polyfluoroalkyl substances from a complex landfill leachate matrix. The authors compared clariflocculation, single-step powdered activated carbon addition, double-step powdered activated carbon adsorption after clarification, and Fenton oxidation through laboratory experiments coupled with life cycle assessment. A key contribution of this paper is the methodology. By integrating categories for global warming, particulate matter formation, and human toxicity, the study demonstrates that treatment selection cannot be based solely on removal performance. The double-step adsorption approach was identified as the most promising option, combining PFAS removal efficiencies of 44.3–82.2% with the lowest environmental impact among the tested options, depending on carbon dosage. The paper also identifies activated carbon production, sludge disposal, and

sulfuric acid as major environmental hotspots. This result is particularly instructive: for persistent micropollutants, environmental optimization may require reducing the burden of the treatment supply chain as much as increasing contaminant removal.

Moreno Carpinteyro et al. provide a resource-recovery perspective by converting fishbone waste from different species into hydroxyapatite-based adsorbents for Cr^{3+}, Ni^{2+}, and Zn^{2+} removal. The study is notable for its head-to-head comparison across fish species, pretreatment routes, calcination, pH conditions, and contact times. Non-calcined materials were especially effective for Ni^{2+} and Zn^{2+} removal at natural and acidic pH, whereas calcined samples were more suitable for Cr^{3+} adsorption under alkaline conditions. Megrim- and hake-derived materials emerged as particularly promising adsorbents, with removal efficiencies reaching up to 99.99% under selected conditions. Beyond the high efficiencies, the broader insight is that "waste-derived adsorbent" is not a uniform category. Precursor origin, mineral structure, calcination history, pH, and metal speciation all govern performance. The study therefore advances the field by linking circular material sourcing to the chemical selectivity and operational windows required for water treatment applications.

Soda et al. examine a different class of emerging technology: nature-based, low-energy treatment through constructed wetlands. Their study of the removal of Reactive Orange 16 and Reactive Black 5 demonstrates that vegetation can markedly enhance azo dye decolorization without external carbon supplementation. Vegetated wetland systems achieved 60–95% removal of Reactive Orange 16 and up to 98% removal of Reactive Black 5, outperforming unplanted controls. Importantly, dye-decolorizing bacteria, including Priestia megaterium and Clostridium spp., were isolated under anaerobic conditions from vegetated systems despite oxic bulk dissolved oxygen levels. The authors propose that vegetation creates localized reductive microenvironments and supplies endogenous organic carbon that supports anaerobic azo bond reduction within otherwise oxic systems. This mechanistic interpretation is significant because it explains how plant–microbe interactions can be used as a substitute for external chemical inputs, and supports the design of decentralized systems for warm regions and infrastructure-limited settings.

Across these contributions, several cross-cutting themes emerge. First, treatment technologies increasingly need to be assessed in relation to their position within a circular value chain. Textile waste recovery reduces future pollutant loads; fishbone-derived hydroxyapatite converts residue into a treatment material; and constructed wetlands use biological processes to reduce reliance on reagents. Second, pollutant removal must be coupled with fate analysis. PFAS, metals, and azo dyes differ profoundly in mobility, persistence, transformation pathways, and end-of-life risks; consequently, successful removal from water is only one stage of environmental protection. Third, technology comparison requires standardized functional units, realistic matrices, and transparent accounting of secondary emissions, sludge management, sorbent production, regeneration, and disposal. These themes represent the intellectual contribution of this Special Issue: emerging technologies must be evaluated as integrated environmental systems rather than isolated unit operations.

3. Knowledge Gaps and Future Research Directions

The papers in this Special Issue also clarify several gaps that should guide future research. The first gap concerns scale and matrix realism. Laboratory studies remain essential for mechanistic understanding and controlled comparison, but field-scale validation is needed for variable leachates, industrial effluents, mixed-metal wastewaters, and seasonally changing constructed wetlands. Real matrices introduce competing ions, natural organic matter, suspended solids, fluctuating pH, temperature fluctuations, hydraulic instability, and shifts in the biological community that can alter treatment performance.

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The second gap is the long-term fate of captured contaminants and spent treatment media. Adsorbents loaded with heavy metals, PFAS-rich sludge, and dye transformation products can create secondary management challenges [7]. Future work should therefore prioritize regeneration, desorption, metal recovery, safe immobilization, ecotoxicity, and end-of-life pathways [8]. For waste-derived materials, circularity should include not only the use of a residual feedstock but also the responsible management or reuse of the spent adsorbent.

The third gap is mechanistic resolution. Future constructed wetland studies would benefit from microscale redox measurements, root exudate characterization, microbial omics, and transformation-product analysis. Similarly, adsorbent studies should integrate surface chemistry, competitive adsorption, metal speciation, and repeated-cycle stability. For PFAS treatment, high-resolution analysis of compound classes, precursors, short-chain species, and residual toxicity will be essential for evaluating performance beyond aggregate removal metrics.

Finally, environmental assessment should be embedded earlier in the technology design process [9]. Prospective life cycle assessment, techno-economic analysis, uncertainty assessment, and scenario modeling can identify burden shifting before scale-up. Digital tools, including data-driven optimization, traceability systems, and process monitoring, can connect material flows with treatment performance and sustainability indicators [10]. Such integration will allow future technologies to be optimized simultaneously for removal efficiency, resource recovery, greenhouse gas emissions, toxicity, cost, operability, and social acceptance.

4. Conclusions and Outlook

This Special Issue demonstrates that emerging technologies for waste treatment, pollution control, and resource recovery are evolving toward integrated, multifunctional systems. The contributions span upstream circular innovation in textile manufacturing, life-cycle-informed PFAS abatement, waste-derived adsorbents for metal removal, and nature-based dye treatment. Although these topics differ in scale, matrix, and mechanism, they share a common direction: environmental technologies must be effective, low-impact, resource-conscious, and adaptable to real-world constraints.

Looking forward, the field should move beyond proof-of-concept demonstrations toward robust design frameworks that couple mechanistic understanding with systems assessment. The most impactful advances will likely arise from hybrid approaches: combining biological and physicochemical treatment, linking pollutant removal with material recovery, designing waste-derived adsorbents for regeneration, and using digitalization to connect supply-chain circularity with treatment operation. We hope that this Special Issue will stimulate further research and collaboration among scientists, engineers, industry practitioners, and policymakers working to transform waste streams from liabilities into resources while protecting environmental and human health.

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