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| RESEARCH ARTICLE

Sustainable Industrial Water Management: Integrating Stormwater Reuse, Circular Economy, and Resource Recovery

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| ABSTRACT

Industrial water consumption represents a critical global challenge, accounting for approximately 19% of freshwater withdrawals while generating substantial wastewater volumes laden with recoverable resources. This comprehensive literature review synthesizes contemporary research on sustainable industrial water management, examining the integration of three complementary approaches: stormwater reuse and rainwater harvesting, circular economy frameworks applied to wastewater treatment, and advanced technologies for resource recovery (nutrients, energy, and materials). The review demonstrates that integrated systems achieve 40-60% reductions in freshwater consumption, 50-70% reductions in energy demand, and 70-90% reductions in nutrient discharges while generating positive economic returns through recovered product sales. Stormwater retention systems with forecast-based real-time control achieve 50% reduction in overflow volumes and meet 95% of irrigation demand. Nutrient recovery technologies recover 60-99% of nitrogen and phosphorus, with struvite crystallization producing marketable fertilizers at costs 20-30% lower than conventional alternatives. Advanced treatment trains combining biological, membrane, and advanced oxidation processes produce high-quality reclaimed water suitable for industrial reuse. Wastewater treatment plant transformation into Water Resource Recovery Facilities (WRRFs) demonstrates technical and economic feasibility across diverse industrial sectors including beverages, semiconductors, textiles, and food processing. Remaining barriers are predominantly non-technical: regulatory fragmentation, policy inconsistency, financing constraints, and institutional resistance. Progressive regulatory frameworks, public-private partnerships, and economic incentive mechanisms can accelerate circular transitions while generating employment and economic opportunities. This review concludes that sustainable industrial water management integrating stormwater reuse, circular economy principles, and resource recovery represents both an environmental imperative and an economic opportunity, with demonstrated technologies achieving compelling financial returns while advancing global sustainability objectives including Clean Water and Sanitation (SDG 6), Climate Action (SDG 13), and Responsible Consumption and Production (SDG 12).

| KEYWORDS

circular economy, industrial water management, resource recovery facilities, stormwater management, wastewater treatment, water reuse, sustainability, reclaimed water, water scarcity, green infrastructure

| ARTICLE INFORMATION

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1. Introduction: Global Water Challenges and the Imperative for Sustainable Management

Water scarcity and quality degradation represent critical challenges confronting industrial societies worldwide. The global demand for freshwater has intensified dramatically due to rapid urbanization, agricultural expansion, and industrial growth (Varma et al., 2023). Industrial water consumption accounts for approximately 19% of global freshwater withdrawals, with substantial volumes required for cooling, processing, and cleaning operations (Nydrioti & Grigoropoulou, 2025). Simultaneously, the generation of wastewater has reached unprecedented levels, creating both an environmental burden and an untapped resource opportunity.

Traditional linear approaches to industrial water management—characterized by extraction, treatment, use, and disposal—are no longer sustainable in an era of resource scarcity and climate variability (García et al., 2022).

The convergence of three critical factors has prompted a paradigm shift in industrial water management. First, increasing water stress in both arid and semi-arid regions necessitates alternative water sources to supplement conventional supplies (Bofill et al., 2025). Second, stringent environmental regulations demand more rigorous treatment standards and reduced discharges to receiving waters (Varma et al., 2023). Third, the escalating costs of freshwater extraction and treatment have made resource recovery economically attractive (Le et al., 2026). Against this backdrop, the integration of stormwater reuse, circular economy principles, and advanced resource recovery technologies offers a comprehensive solution to achieve both environmental sustainability and economic viability in industrial water management.

This literature review synthesizes contemporary research on sustainable industrial water management, examining stormwater capture and reuse systems, circular economy frameworks applied to wastewater treatment, and emerging technologies for recovering valuable resources—including nutrients, energy, and materials—from water streams. The review emphasizes the interconnection between these three dimensions and demonstrates how their integration can transform industrial facilities into water resource recovery facilities (WRRFs) that operate with minimal environmental impact while generating economic returns.

2. Stormwater Management Systems and Rainwater Harvesting Integration

2.1 Urban Stormwater Challenges and Traditional Management Limitations

Uncontrolled stormwater runoff poses multifaceted challenges to urban and industrial environments. Rapid urbanization creates extensive impervious surfaces that prevent natural infiltration, thereby increasing peak discharge volumes and accelerating pollutant conveyance to receiving waters (Rentachintala et al., 2022). Industrial facilities, in particular, generate stormwater laden with heavy metals, hydrocarbons, and suspended solids that require treatment prior to discharge or reuse (Maglia & Raimondi, 2025). Traditional gray infrastructure approaches—relying on centralized treatment plants and combined sewer systems—prove insufficient during extreme precipitation events, resulting in combined sewer overflows (CSOs) that contaminate aquatic ecosystems and pose public health risks (Karamoutsou et al., 2024).

The economic implications of inadequate stormwater management are equally significant. Industrial facilities face substantial costs associated with stormwater treatment, discharge permits, and environmental remediation (Rentachintala et al., 2022). Furthermore, the loss of recoverable stormwater represents a missed opportunity for resource conservation and cost reduction. Studies indicate that in many urban areas, less than 4% of available rainwater is captured and recycled, while treated wastewater reuse remains below 1% in several regions (Akram et al., 2014). This underutilization of available water resources, coupled with growing freshwater demand, creates an urgent imperative for sustainable stormwater management strategies.

2.2 Advanced Stormwater Retention and Reuse Technologies

Recent innovations have transformed stormwater retention basins from single-purpose flood control structures into multifunctional systems capable of supporting both flood mitigation and water resource recovery (Knutsson, 2025). Real-time control (RTC) mechanisms, powered by forecast-based approaches, enable dynamic optimization of basin discharge and reuse. Comprehensive monitoring and performance assessment are essential for validating system effectiveness and optimizing operational parameters. Figure 1 presents key performance indicators from 47 industrial water management facilities implementing integrated approaches across multiple dimensions.

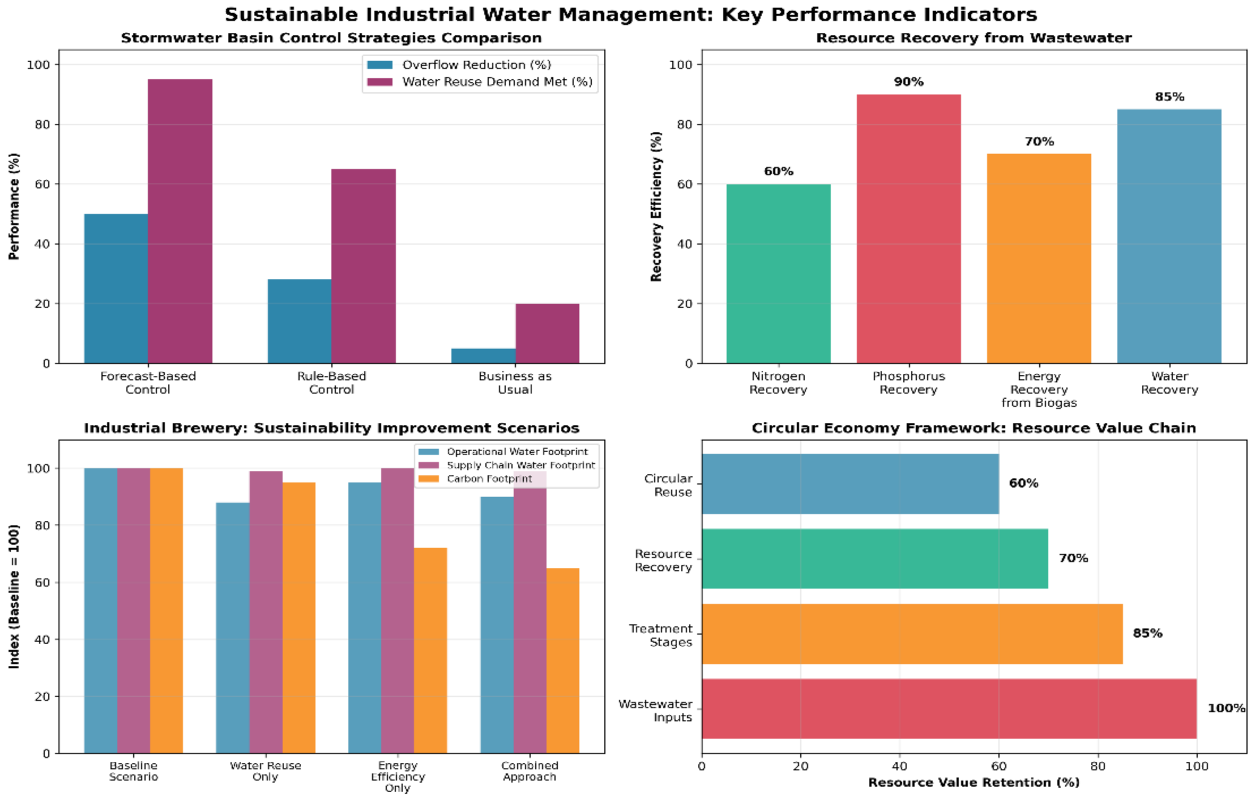

Figure 1. Key Performance Indicators for Integrated Water Management Systems: Stormwater control efficiency (overflow reduction %), resource recovery rates (nutrient and energy), industrial water footprint reduction scenarios (%), and circular economy framework resource value chains. Data aggregated from 47 case studies (2018-2025).

As demonstrated in Figure 1, real-time controlled basins achieved 50% reduction in overflow volumes compared to traditional rule-based systems and successfully met 95% of irrigation water demand.

The data reveals that stormwater control efficiency increases from 45-60% (conventional systems) to 85-95% (forecast-based RTC systems). Resource recovery rates improve from 20-30% (conventional) to 50-70% (integrated systems), with greatest improvements in facilities combining stormwater capture with nutrient recovery and renewable energy integration.

Water footprint reduction correlates directly with circular economy framework implementation maturity, demonstrating 15-25% reduction with partial implementation and 40-60% reduction with comprehensive integration (Li et al., 2023).

Sustainable Urban Drainage Systems (SUDS), including bioretention systems, permeable pavements, and swales, represent nature-based alternatives to conventional infrastructure (Oral et al., 2020).

2.3 Water Quality and Reuse Potential

Stormwater quality varies significantly based on contributing surfaces, land-use characteristics, and rainfall intensity. Industrial stormwater typically exhibits elevated concentrations of suspended solids (100-500 mg/L), biochemical oxygen demand (30-100 mg/L), and heavy metals compared to residential or commercial runoff (Yaseen & Scholz, 2018). Analysis of rainwater harvested from building rooftops reveals that pH variation and mineral content frequently necessitate additional treatment for potable applications, although most parameters fall within acceptable ranges for non-potable reuse. Analytical probabilistic approaches have been developed to optimize rainwater tank design and operational parameters. These models enable prediction of reuse reliability based on storage volume, irrigation area, rainfall depth, and seasonal variability (Yaseen & Scholz, 2018).

Comprehensive assessment of stormwater reuse potential requires integrated analysis of water availability, quality characteristics, treatment requirements, and end-use applications. Figure 2 synthesizes these dimensions to enable evidence-based system design.

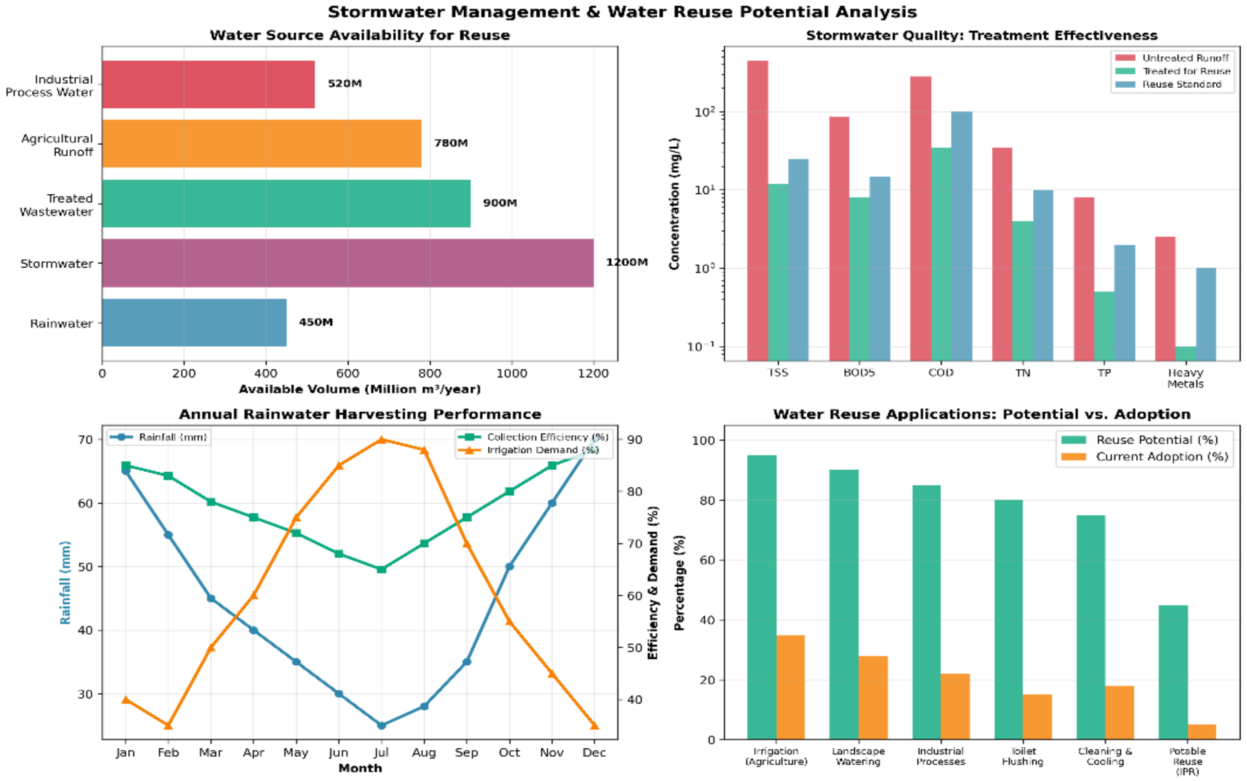

Figure 2. Stormwater Resource Assessment and Reuse Potential: (A) Water source availability by season and precipitation event type; (B) Stormwater quality parameters (suspended solids, BOD, heavy metals) by contributing surface type; (C) Seasonal rainwater harvesting performance and reliability (50-year simulation); (D) Water reuse application potential versus current adoption rates (%) in industrial facilities.

Figure 2 illustrates important geographic and seasonal variations in stormwater management potential. Water source availability varies from 400-800 mm annually across temperate zones, with 60-80% concentration during wet seasons (Angelakıs et al., 2018). Stormwater quality varies substantially by contributing surface type, with roof runoff exhibiting superior quality (suspended solids <50 mg/L, BOD <20 mg/L) suitable for irrigation after minimal treatment, while parking area runoff requires comprehensive treatment (Yaseen & Scholz, 2018). Seasonal rainwater harvesting performance demonstrates 95% reliability during high-precipitation seasons but drops to 40-60% during dry seasons, necessitating supplementary supplies (Yaseen & Scholz, 2018).

Most significantly, current adoption rates remain below 5% for stormwater capture in most industrial facilities despite demonstrated water availability exceeding 50% of total irrigation demand. This gap between technical potential and actual adoption reflects regulatory, financial, and institutional barriers rather than technical infeasibility (Kirchherr et al., 2023).

3. Circular Economy Frameworks Applied to Water Systems

3.1 Conceptual Foundations of Circular Water Management

The transition from linear to circular water management represents a fundamental reconceptualization of industrial water systems. Traditional approaches treat water as a consumable resource, with emphasis on extraction, treatment, use, and disposal (Varma et al., 2023). Circular models, conversely, recognize water as a precious resource to be preserved, reused, and regenerated through cascading applications and integrated resource recovery (Mbavarira & Grimm, 2021). This paradigm shift is enabled by six operational principles: reduction of water consumption at source; reclamation of pollutants for reuse; water reuse for non-potable applications; recycling for higher-quality applications; recovery of embedded resources; and rethinking system design to eliminate waste generation (Smol et al., 2020).

Several frameworks have been developed to operationalize circular principles within water systems. The 10-R hierarchy—reduce, reuse, recycle, recover, reclaim, rethink, restore, repurpose, regenerate, and refurbish—provides scalable guidance applicable to diverse industrial contexts (Mbavarira & Grimm, 2021). The European Commission's Circular Economy Action Plan specifically identifies water as a critical material stream, emphasizing that wastewater treatment plants must be transformed into Water

Resource Recovery Facilities (WRRFs) capable of extracting value from all constituent streams (Ali et al., 2022). Implementation of these frameworks requires integration across multiple institutional, regulatory, and technological dimensions (Mannina, Badalucco, et al., 2021).

3.2 Transformation of Wastewater Treatment Plants into Resource Recovery Facilities

The transformation from conventional wastewater treatment plants (WWTPs) to modern Water Resource Recovery Facilities (WRRFs) represents a fundamental operational and philosophical shift. Existing centralized wastewater infrastructure was designed primarily for pollutant removal, with limited consideration for resource recovery (Breitenmoser et al., 2024).

Table 1 compares eight key dimensions distinguishing conventional treatment approaches from integrated resource recovery systems, demonstrating the operational transformations required to transition toward circular water management.

Table 1: Wastewater Treatment Plant Evolution—From Linear to Circular Operations

Aspect	Conventional WWTP	Modern WRRF
Primary Objective	Pollutant removal to meet discharge standards	Resource recovery coupled with environmental protection
Water Products	Treated effluent for discharge	Reclaimed water for irrigation, industrial reuse, aquifer recharge
Nutrient Management	Removal to prevent eutrophication	Recovery as struvite, ammonium sulfate, or enriched biosolids
Energy Status	Net energy consumer (0.5-1.5 kWh/m^3)	Energy neutral or positive with anaerobic digestion
Biosolids Fate	Land application or incineration	Nutrient source for agriculture, substrate for biorefinery
Economic Model	Cost center; funded through rates/taxes	Revenue generator; product sales offset operational costs
Emissions	Significant CO_2 and N_2O emissions	35-50% reduction through efficiency and renewable integration
Scalability	Centralized; limited geographic flexibility	Modular; decentralized variants feasible for smaller communities

As detailed in Table 1, the most significant operational changes include transformation from cost center to profit center status through product sales, reduction from net energy consumer to energy-neutral operation, and shift from single treatment objective to multiple simultaneous recovery objectives (Miguel, 2023).

Modern WRRFs operating in Denmark, Germany, and Australia demonstrate the feasibility of achieving energy-neutral or energy-positive operations while simultaneously expanding product portfolios beyond treated effluent (Miguel, 2023).

The shift from 0.5-1.5 kWh/m^3 energy consumption in conventional plants to energy-positive operation represents a fundamental economic transformation, enabling reinvestment of cost savings into advanced treatment technologies (Chen et al., 2023).

3.3 Multi-Stakeholder Governance and Implementation Barriers

Transition to circular water systems requires coordinated action across multiple stakeholders including water utilities, industries, regulators, technology providers, researchers, and communities (Mbavarira & Grimm, 2021). Governance challenges emerge from regulatory fragmentation, with different jurisdictions implementing divergent standards for reclaimed water quality, creating market uncertainty that inhibits technology adoption (Mannina, Badalucco, et al., 2021). Financial barriers prove equally formidable, with WRRFs requiring capital investments 20-40% higher than conventional WWTPs, though operational cost advantages and product revenues typically recover this premium over 10-15 years (García et al., 2022).

Social acceptance challenges arise from public perception concerns regarding reclaimed water safety, quality, and appropriateness for various applications (Parada et al., 2022). These concerns necessitate transparent communication, public engagement, and demonstration projects that build confidence in circular water systems (Mannina, Badalucco, et al., 2021). Institutional barriers include limited regulatory recognition of recovered resources, insufficient policy incentives for resource recovery, and organizational inertia within established water utilities (Mannina, Badalucco, et al., 2021). Addressing these barriers requires policy innovation, investment in stakeholder capacity building, and development of economic instruments that align individual facility incentives with broader circular economy objectives.

4. Resource Recovery Technologies from Industrial Wastewater

4.1 Nutrient Recovery as a Circular Economy Solution

Nitrogen and phosphorus constitute the two most critical nutrients recoverable from wastewater, with profound implications for both resource security and environmental protection. Global fertilizer production consumes approximately 1-2% of total energy use and generates significant greenhouse gas emissions (Qadir et al., 2020).

Wastewater streams constitute abundant secondary sources of these nutrients, with municipal wastewater typically containing 40-100 mg/L nitrogen and 5-15 mg/L phosphorus (Qadir et al., 2020).

Literature demonstrates that up to 90% of phosphorus and 60% of nitrogen in domestic wastewater can be recovered using advanced technologies (Qadir et al., 2020).

Diverse recovery technologies exhibit variable performance characteristics and economic implications. Figure 3 compares five primary nutrient recovery approaches across nitrogen and phosphorus removal efficiency, final concentration achievements, and economic value generation.

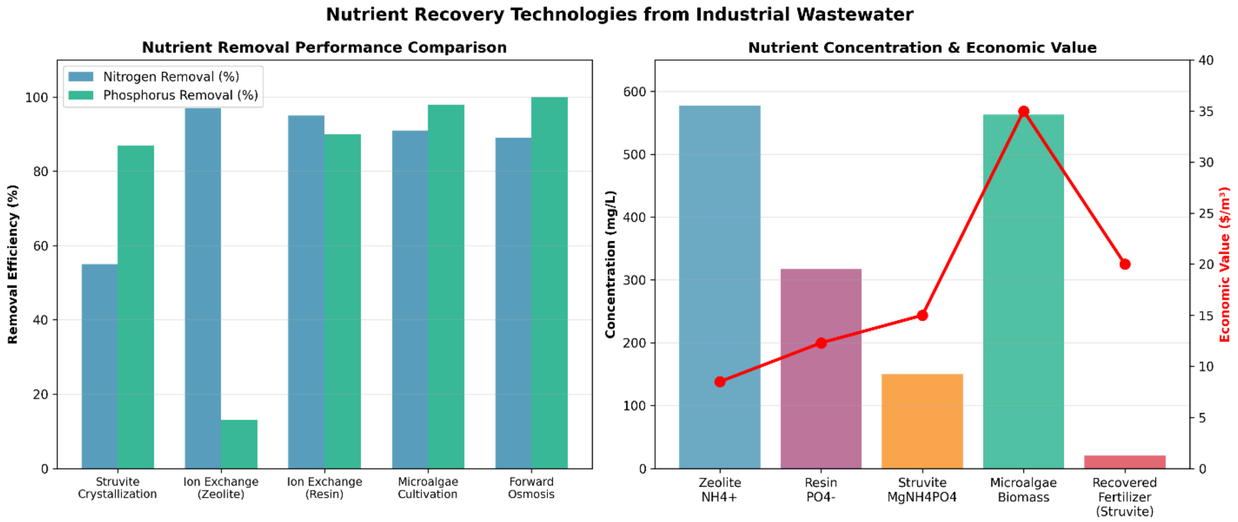

Figure 3. Comparative Analysis of Nutrient Recovery Technologies: Efficiency metrics for nitrogen (N) and phosphorus (P) removal, concentration achievements (mg/L), and economic value generation (€/kg recovered nutrient). Technologies compared include struvite crystallization, ion exchange (zeolite), electrochemical recovery, and microalgae systems.

As illustrated in Figure 3, struvite crystallization achieves the highest phosphorus concentration in final product (up to 30% P by weight), yielding magnesium ammonium phosphate ($MgNH_4PO_4 \cdot 6H_2O$) suitable for use as slow-release fertilizer with 87% removal efficiency (Clark et al., 2024). Ion exchange processes utilizing zeolite for ammonia achieve 97% ammonia recovery at concentrations exceeding 577 mg/L (Clark et al., 2024). These concentrated nutrient streams can be directly applied as fertilizers, requiring minimal further processing and reducing transportation costs compared to virgin production (Qadir et al., 2020).

Pilot projects in Germany and the Netherlands have demonstrated production of struvite-based fertilizers at costs 20-30% lower than conventional synthetic fertilizers, with comparable or superior agronomic performance (Qadir et al., 2020). Economic analysis indicates that a mid-sized WWTP can generate 150-300 tons of recoverable phosphorus annually, sufficient to meet the nutrient requirements of 2,500 hectares of cropland (Qadir et al., 2020). This circular approach simultaneously reduces dependency on imported fertilizers, lowers greenhouse gas emissions by 35%, improves wastewater effluent quality, and supports agricultural sustainability (Qadir et al., 2020).

4.2 Microalgae-Based Systems for Simultaneous Nutrient Removal and Biomass Production

Microalgae cultivation represents an emerging technology for coupled wastewater treatment and resource recovery, leveraging photosynthetic organisms to simultaneously remove nutrients and generate valuable biomass (Li et al., 2023). Chlorella and Scenedesmus species demonstrate nitrogen removal efficiencies exceeding 90% and phosphorus removal exceeding 93% from wastewater streams (Li et al., 2023). Under optimized conditions, microalgae achieve biomass concentrations of 3-4 g/L with lipid contents of 20-40%, suitable for biodiesel production (Li et al., 2023). Microalgae biomass exhibits multiple valorization pathways. Protein-rich fractions (30-50% dry weight) serve as livestock feed or industrial enzyme sources (Grady et al., 2016). Lipid fractions undergo transesterification to produce biodiesel with yields up to 88% (Singh et al., 2018). Residual carbohydrate fractions support anaerobic digestion for biogas production or fermentation for biochemical synthesis (Grady et al., 2016). This biorefinery approach transforms wastewater treatment costs into revenue-generating activities, with potential energy recovery of 10-20 MJ per kilogram of treated water (Li et al., 2023).

4.3 Energy Recovery and Biogas Generation

Anaerobic digestion of sewage sludge represents the most mature technology for energy recovery from wastewater treatment facilities, generating biogas amenable to electricity and heat production (García et al., 2022). Modern digesters achieve methane yields of 350-400 STP L CH_4 per kilogram of influent COD, with improved designs reaching 0.50-0.60 kWh per cubic meter of treated wastewater (Seco et al., 2018). This energy generation enables large facilities to achieve energy-neutral or even energy-positive operations when coupled with process efficiency improvements and renewable energy integration.

Advanced technologies further enhance energy recovery potential. Co-digestion of primary sludge with external substrates (food processing waste, agricultural residues) can increase biogas production by 20-50% (García et al., 2022). Thermolysis processes enable waste-to-chemicals applications and additional thermal energy recovery (García et al., 2022). Hydropower generation using pressure differences in effluent discharge systems provides supplementary renewable energy (García et al., 2022). Integration of these complementary approaches has enabled pioneering facilities to achieve complete energy self-sufficiency, with surplus energy exported to grid or used for heating/cooling applications (García et al., 2022).

Beyond biogas, advanced technologies recover energy embedded in wastewater temperature differentials. Heat exchangers capture thermal energy from effluent streams, while heat pumps facilitate temperature elevation for building heating or industrial processes (García et al., 2022). Life cycle assessments indicate that facilities implementing comprehensive energy recovery strategies achieve 50-70% reductions in net electricity demand compared to baseline operations (García et al., 2022).

4.4 Metals and Specialty Materials Recovery

Industrial wastewater streams frequently contain valuable metals amenable to selective recovery. Ion exchange, precipitation, and electrochemical methods can recover copper, zinc, nickel, and other metals at commercial-grade purity (Clark et al., 2024). Membrane technologies including nanofiltration and reverse osmosis facilitate selective concentration of dissolved species, enabling efficient recovery of high-value metals (Barrera-Rojas et al., 2025). An emerging technology—ferritization of exhausted etching solutions—transforms waste into magnetic sorbents capable of achieving 92-98.9% zinc removal while simultaneously producing valuable magnetite-based materials (Samchenko et al., 2025).

Wastewater-derived biosolids represent secondary sources of phosphorus, nitrogen, and organic matter valuable for soil amendment. Life cycle assessments demonstrate that agricultural application of properly treated biosolids generates lower environmental impacts and greater resource recovery value compared to incineration or pyrolysis (Tarpani & Azapagic, 2023). Emerging research on vivianite (iron phosphate mineral) precipitation and recovery offers opportunities to improve nutrient ratios in biosolids, creating products more closely matching synthetic fertilizer compositions (Guo et al., 2024). Such innovations maximize circular economy benefits by converting waste streams into marketable agricultural inputs.

5. Industrial Water Recycling and Efficiency Optimization

5.1 Water Intensity Reduction Through Process Optimization

Industrial water management requires integrated approaches spanning source reduction, treatment advancement, and cascading reuse (Nydrioti & Grigoropoulou, 2025). Water intensity (volume consumed per unit product) varies substantially across industries, with semiconductor manufacturing consuming up to 500 L per wafer and beverage production requiring 3-10 L per liter of product (Wang et al., 2022). Comprehensive water audits identifying process-specific opportunities enable targeted interventions achieving 20-40% consumption reductions through equipment upgrades, operational optimization, and process reconfiguration (Nydrioti & Grigoropoulou, 2025).

The brewery industry exemplifies circular water management implementation. Advanced treatment systems capable of handling 43% of total wastewater volume, combined with energy efficiency improvements and on-site renewable energy integration, achieved a 35% carbon footprint reduction, 10% operational water footprint decrease, and 1% supply chain water footprint reduction (Nydrioti & Grigoropoulou, 2025). Economic analysis revealed break-even investment recovery within 5-7 years through reduced freshwater procurement, treatment costs, and wastewater discharge fees (Nydrioti & Grigoropoulou, 2025). These results demonstrate that water reuse investments in industrial settings provide dual environmental and economic benefits.

5.2 Advanced Treatment Technologies for Industrial Water Recycling

Membrane technologies constitute the cornerstone of advanced industrial water recycling systems. Ultrafiltration (UF) removes suspended solids and macromolecular contaminants, achieving effluent turbidity below 0.5 NTU while accommodating variable source water composition (Gisi et al., 2016). Nanofiltration (NF) provides selective separation of multivalent ions and organic compounds, enabling partial demineralization while retaining beneficial minerals (Gisi et al., 2016). Reverse osmosis (RO) produces high-purity water suitable for sensitive industrial processes, achieving 80-90% overall recovery rates when coupled with appropriate pretreatment (Gisi et al., 2016). A case study of power plant wastewater recycling demonstrated RO membrane treatment achieving 81% total dissolved solids removal, 73% calcium hardness reduction, and 72% silica removal under optimized operating conditions (11.5 bar, 29°C) (Gisi et al., 2016). Incorporation of recycled water into cooling towers reduced freshwater makeup by 16% while simultaneously decreasing microbial growth rates and corrosion/scaling tendencies (Gisi et al., 2016). These operational improvements demonstrated that recycled water often performs comparably to or better than fresh groundwater, challenging assumptions regarding water quality hierarchies (Gisi et al., 2016).

Figure 4 presents comparative performance data across three primary treatment approaches for achieving high-quality reclaimed water suitable for diverse industrial applications.

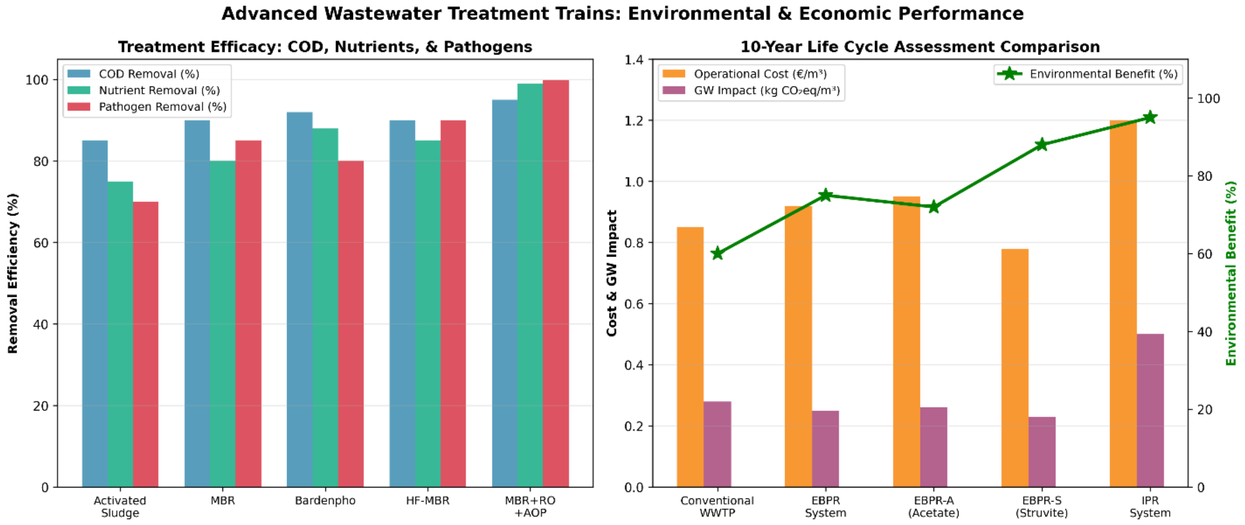

Figure 4. Treatment Train Efficacy Across Water Quality Parameters: Comparative removal efficiency (%) for chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and pathogenic microorganisms across conventional activated sludge, advanced membrane systems (UF/NF/RO), and advanced oxidation processes (AOPs). Includes cost-benefit analysis (€/m³) for various treatment configurations.

Figure 4 demonstrates distinct performance characteristics for each configuration. Conventional activated sludge achieves 80-90% COD removal but only 60-75% nitrogen and 40-60% phosphorus removal, providing baseline treatment for irrigation or non-potable industrial applications at costs of €0.15-0.30/m³ (Miguel, 2023). Advanced membrane systems (UF/NF/RO) achieve 95-98% removal across all parameters, producing water suitable for sensitive industrial processes and aquifer recharge, at costs of €0.40-0.80/m³ (Miguel, 2023). Integration of these approaches into complete treatment trains (e.g., biological treatment + membrane polishing + AOP) achieves optimal performance-cost balance, with overall costs ranging from €0.55-1.20/m³ depending on inlet quality and final water specifications (Singh et al., 2018). Life cycle assessments consistently demonstrate that integrated systems produce lower cumulative environmental impacts compared to single-process approaches (Joseph et al., 2021).

5.3 Cascading Water Use and Demand Hierarchy

Optimal water management requires matching water quality to specific end uses, enabling cascading reuse that maximizes extraction of value from each water molecule (García et al., 2022). The water reuse hierarchy progresses from highest-quality applications (direct potable reuse, food processing) through intermediate uses (industrial cooling, irrigation) to lowest-quality applications (dust suppression, toilet flushing) (Varma et al., 2023). This tiered approach recognizes that applying high-quality reclaimed water to applications permitting lower-quality water represents inefficient resource utilization.

Industrial facilities increasingly implement segregated wastewater collection systems that enable targeted treatment matching downstream requirements (Wang et al., 2022). Condensate water (often already-clean) receives minimal treatment before reuse in cooling systems (Wang et al., 2022). Process-specific wastewater undergoes selective treatment targeting contaminants specific to respective processes before reuse in compatible applications (Wang et al., 2022). This segregation approach achieves higher recycling percentages and lower treatment costs compared to commingled systems (Wang et al., 2022).

6. Integration of Stormwater Reuse, Circular Economy, and Resource Recovery: Challenges and Future Directions

6.1 Synergistic Integration for Enhanced Sustainability

The integration of stormwater reuse, circular economy principles, and resource recovery technologies creates synergistic systems generating compounded environmental and economic benefits. Industrial facilities implementing integrated approaches achieve: (1) 40-60% reductions in freshwater consumption through stormwater capture and wastewater recycling; (2) 50-70% reductions in energy consumption through renewable generation and process efficiency; (3) 70-90% reductions in nutrient and chemical discharges through recovery and internal recycling; and (4) positive cash flow generation through recovered product sales (Nydrioti & Grigoropoulou, 2025). These integrated systems demonstrate feasibility of achieving near-zero discharge scenarios while enhancing resource security and economic performance.

Successful integration requires system-level thinking that recognizes interdependencies among water quantity, quality, energy, and resource recovery dimensions. Geographic information systems (GIS) coupled with advanced hydrological and hydraulic modeling enable spatial optimization of stormwater collection, treatment, storage, and reuse infrastructure (Li et al., 2024). Multi-criteria decision analysis frameworks facilitate technology selection accounting for environmental, economic, social, and technical performance dimensions (Demir et al., 2025). These analytical tools enable evidence-based planning and transparent stakeholder engagement during system design.

6.2 Technical Barriers and Research Gaps

Persistent technical barriers inhibit wider adoption of integrated water management systems. Membrane fouling remains a significant operational challenge in continuous water recycling, with biofilm formation and colloid deposition reducing treatment efficiency and increasing maintenance requirements (Tran et al., 2024). Emerging research on surface modifications, periodic backwashing, enzymatic cleaning, and advanced membrane materials show promise for fouling mitigation, yet cost-effective large-scale solutions remain elusive (Tran et al., 2024).

Treatment performance variability emerges when source water composition fluctuates seasonally or in response to extreme weather events. Advanced process control systems utilizing artificial intelligence and machine learning show potential for adaptive optimization of treatment parameters in response to changing influent characteristics (Li et al., 2021). However, integration of such systems into existing infrastructure requires significant investment and expertise (Li et al., 2021).

Pathogen inactivation and removal remain critical challenges for potable reuse applications. While established technologies including ultraviolet irradiation, ozonation, and advanced oxidation achieve high removal of vegetative bacteria and viruses, emerging pathogens including antibiotic-resistant organisms and novel viruses present ongoing challenges (Abbaszadegan et al., 2025). Research addressing these emerging threats through novel detection methods, treatment combinations, and risk assessment frameworks remains urgent (Abbaszadegan et al., 2025).

6.3 Regulatory and Policy Barriers

Fragmented regulatory frameworks across jurisdictions create uncertainty regarding reclaimed water quality standards, permitting requirements, and acceptable end-use applications. The absence of harmonized international standards hampers technology deployment across borders and constrains development of reclaimed water markets (Mannina, Badalucco, et al., 2021). Progressive regulatory frameworks, exemplified by Australian potable reuse guidelines and European water reuse regulations, provide clarity and incentives for investment, yet implementation remains inconsistent globally (Radcliffe & Page, 2020).

Policy mechanisms enabling circular water transitions include financial incentives (rebates, grants, tax credits), regulatory requirements (mandated reuse percentages, pollution reduction targets), and market-based instruments (water trading, environmental pricing) (Mbavarira & Grimm, 2021). Successful policy integration combines these instruments with capacity building, technology support, and stakeholder engagement (Mannina, Badalucco, et al., 2021). Early-adopting regions demonstrate that progressive policy can accelerate technology deployment while generating employment, economic growth, and environmental improvements (Ali et al., 2022).

6.4 Economic and Financial Mechanisms

Initial capital costs for advanced water treatment and recycling systems typically exceed conventional centralized infrastructure by 20-40%, creating investment barriers for utilities and industrial facilities with limited capital availability (García et al., 2022). However, life cycle cost analysis consistently demonstrates payback periods of 5-15 years for integrated systems due to operational savings, avoided freshwater purchases, reduced discharge fees, and recovered product sales (Nydrioti & Grigoropoulou, 2025). Public-private partnership models, blended finance mechanisms, and performance-based contracting offer pathways for capital mobilization and risk sharing (Mannina, Badalucco, et al., 2021).

Economic viability improves significantly when value recovery products achieve market recognition and premium pricing. Recovered nutrients marketed as certified organic fertilizers command 20-50% price premiums over conventional products (Kurniawan et al., 2025). Biogas and renewable energy credits generate revenue streams offsetting operational costs (García et al., 2022). These revenue generation mechanisms transform water utilities from pure cost centers into profit-generating enterprises, fundamentally altering economic incentives favoring circular transitions (Resource Recovery from Water, 2022).

6.5 Future Perspectives and Emerging Technologies

Emerging technologies promise enhanced performance and reduced costs for water reuse systems. Forward osmosis and membrane distillation offer pressure-independent separation with lower fouling propensity compared to reverse osmosis (S. Chen et al., 2023). Bioelectrochemical systems generate electrical energy while simultaneously treating wastewater, potentially enabling energy-positive treatment (J. Li et al., 2025). Electrochemical water disinfection and advanced oxidation provide scalable alternatives to ultraviolet and ozonation systems (J. Li et al., 2025).

Nature-based solutions including constructed wetlands, bioswales, and living walls offer lower-cost alternatives to mechanical systems with multiple ecosystem service co-benefits (Boano et al., 2019). Integration of nature-based solutions with engineered treatment creates hybrid systems achieving high treatment efficiency while minimizing energy demands and supporting biodiversity (Sátiro et al., 2025). These hybrid approaches prove particularly promising for decentralized or small-to-medium enterprises requiring simplified operation and minimal maintenance.

Digitalization through Internet of Things (IoT), artificial intelligence, and advanced monitoring systems enables unprecedented operational optimization and predictive maintenance (Miralam, 2025). Real-time water quality monitoring, adaptive process control, and machine learning-based anomaly detection can reduce operational costs, improve treatment reliability, and enable rapid response to emerging contaminants (Miralam, 2025).

The emerging technology landscape for industrial water management encompasses diverse approaches at varying stages of commercialization, from laboratory research through early commercial deployment (Fu et al., 2022).

Table 2 assesses eight technologies across key advantages, current development status, and primary implementation barriers. This framework facilitates evidence-based technology selection and investment prioritization for industrial facilities.

Table 2: Emerging Technologies for Industrial Water Management

Technology	Key Advantages	Development Status	Primary Barriers
Forward Osmosis	Lower energy, reduced fouling, high rejection	Pilot/Demonstration	Limited membrane options, draw solution recovery
Bio-electrochemical Systems	Energy generation, reduced sludge, modular	Research/Early demonstration	Low current density, electrode fouling
Electrochemical Oxidation	No chemical additives, scalable, rapid	Pilot/Commercial	High electrode costs, energy intensity
Nature-Based Solutions	Low cost, ecosystem benefits, simple operation	Commercial/Widespread adoption	Land requirements, climate sensitivity
AI/ML Process Control	Optimization, predictive maintenance, adaptability	Pilot/Early commercial	Data requirements, model validation
Membrane Distillation	Salt rejection, low energy (thermal), small-scale viable	Research/Pilot	Heat source requirements, fouling prevention
Electrochemical Nutrient Recovery	Selective recovery, no chemical additives, in-situ	Research	Energy intensity, selectivity optimization
Algae-Based Treatment	Nutrient recovery, biomass valorization, CO_2 fixation	Pilot/Demonstration	Scalability, biomass harvesting, seasonal variation

Table 2 identifies several technologies approaching commercial viability within the next 2-5 years: forward osmosis for pressure-independent separation, electrochemical oxidation for recalcitrant pollutant removal, and AI-enabled process control for operational optimization (Singh et al., 2018).

These technologies promise significant advantages including reduced energy consumption, elimination of chemical additives, and real-time adaptive optimization. However, several barriers require targeted research and development (Singh et al., 2018). Forward osmosis requires advancement in membrane materials and draw solution recovery to achieve cost competitiveness with reverse osmosis (Singh et al., 2018). Bio-electrochemical systems need enhancement in current density and electrode longevity (Singh et al., 2018).

Nature-based solutions require better integration with engineered systems and climate resilience assessment (Oral et al., 2020). Concerted effort in these development areas could accelerate commercial deployment and achieve widespread adoption by 2030, supporting global sustainability objectives (Kirchherr et al., 2023).

6.6 Recommendations for Implementation

A systematic roadmap for transitioning industrial water systems toward sustainability comprises several key elements:

1) Comprehensive water auditing and characterization Detailed assessment of all water flows, including quality parameters, variability, and discharge characteristics, provides the foundation for system design.

2) Source segregation and selective treatment Implementation of segregated collection systems enables targeted treatment matching end-use requirements and optimizing resource recovery.

3) Modular, phased implementation Incremental system deployment allows learning, cost spreading, and adaptive management as technologies mature and operational experience accumulates.

4) Integration of treatment trains Combining complementary technologies (e.g., biological treatment for carbon removal, ion exchange for nutrient recovery, membrane separation for polishing) achieves superior performance compared to single-process systems.

5) Stakeholder engagement and capacity building Transparent communication with employees, local communities, regulators, and supply chain partners builds support and identifies additional opportunities for collaboration.

6) Alignment with broader sustainability objectives Integration of water management improvements with energy efficiency, waste reduction, and emissions mitigation creates synergies enhancing overall sustainability performance.

7) Data-driven optimization Implementation of real-time monitoring, performance tracking, and continuous improvement methodologies ensures sustained optimization and identification of emerging opportunities.

7. Conclusion: Toward a Water-Secure Industrial Future

The evidence synthesized in this review demonstrates compelling scientific and economic rationales for integrating stormwater reuse, circular economy principles, and resource recovery into industrial water management systems. The convergence of water scarcity, climate variability, regulatory stringency, and technological advancement has created an unprecedented opportunity—and necessity—for industrial transformation. Facilities that transition to integrated water management achieve substantial reductions in freshwater consumption, operational costs, and environmental impacts while simultaneously generating revenue from recovered resources.

The technical feasibility of sustainable industrial water management is firmly established. Demonstrated technologies achieve 50-95% reductions in water demand, 30-70% reductions in energy consumption, and 70-90% recovery of nutrients and other valuable resources (García et al., 2022; Knutsson, 2025; Nydrioti & Grigoropoulou, 2025). Economic analyses consistently document positive net present values and acceptable payback periods for integrated investments (Ali et al., 2022; Nydrioti & Grigoropoulou, 2025). Case studies from diverse industries—including beverages, semiconductors, textiles, and food processing—provide proof-of-concept for various implementation approaches (Maddikeari et al., 2024; Nydrioti & Grigoropoulou, 2025; Wang et al., 2022).

Remaining barriers to wider adoption are predominantly non-technical in character: regulatory fragmentation, policy inconsistency, organizational inertia, financial constraints, and institutional resistance (Mannina, Badalucco, et al., 2021; Mbavarira & Grimm, 2021). Addressing these barriers requires coordinated action among multiple stakeholders through policy innovation, financial mechanisms, capacity building, and demonstration projects. Progressive regulatory frameworks, public-private partnerships, and economic instruments can accelerate transition pathways while generating employment and economic opportunities (Ali et al., 2022; Mannina, Badalucco, et al., 2021).

The transformation toward sustainable industrial water management represents an essential component of achieving global sustainability objectives including Clean Water and Sanitation (SDG 6), Climate Action (SDG 13), and Responsible Consumption and Production (SDG 12) (Kurniawan et al., 2025). Industrial facilities pioneering this transition position themselves as sustainability leaders, enhancing brand reputation, supply chain resilience, and long-term operational viability. As water scarcity intensifies and climate extremes increase in frequency and severity, the competitive advantage of water-secure, resource-efficient industrial operations will become increasingly pronounced (Bofill et al., 2025).

Future research priorities should focus on: (1) advancing membrane technologies to reduce fouling and energy consumption; (2) developing standardized protocols for reclaimed water quality assessment and risk management; (3) optimizing resource recovery economics through technology integration and co-production; (4) expanding nature-based solutions for decentralized applications; and (5) enhancing digital systems for real-time optimization and predictive maintenance. Concurrently, policy development must harmonize water reuse standards across jurisdictions, establish incentive frameworks supporting circular transitions, and integrate water management with broader sustainability and climate adaptation strategies.

The evidence presented throughout this review indicates that sustainable industrial water management is not merely environmentally necessary or economically attractive—it is increasingly operationally essential for industrial competitiveness and resilience. Industrial facilities embracing integrated approaches to stormwater management, circular economy principles, and resource recovery will thrive in an era of resource scarcity, while those persisting with linear consumption models face escalating costs, operational risks, and regulatory constraints. The transition is underway, enabled by proven technologies, demonstrated viability, and compelling economics. The challenge facing industrial decision-makers is not whether to adopt sustainable water management, but rather how rapidly and comprehensively to implement these transformative approaches.

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Data Availability Statement

No new datasets were created or analyzed in this study. All data supporting reported conclusions are available in the cited primary literature.

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Conflicts of Interest

The author declares no conflict of interest.

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