International Journal of Research Publications in Engineering, Technology and Management (IJRPETM)

|www.ijrpetm.com | ISSN: 2454-7875 | editor@ijrpetm.com |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 9, Issue 3, May-June 2026||

DOI:10.15662/IJRPETM.2026.0903004

Wastewater-Based Circular Economy: Water Reuse in Agriculture and Industry — A Comprehensive Review

Santunu Barua

MS in Environmental Engineering, Department of Civil and Environmental Engineering, Manhattan University, New York, USA

Email: sbarua03@manhattan.edu

Publication History: Received: 04.04.2026; Revised: 29.04.2026; Accepted: 03.05.2026; Published: 07.05.2026.

ABSTRACT: Escalating global freshwater demand driven by climate change, population growth, and industrialization necessitates transformative water management strategies. The shift from linear, end-of-pipe wastewater treatment to circular economy (CE) approaches offers significant opportunities for water security, environmental protection, and economic development. This review synthesizes two decades of research on wastewater-based circular economy (WBCE) systems, focusing on water reuse feasibility, nutrient recovery, and resource recovery potential across agricultural and industrial sectors. Globally, wastewater generation reaches 359.4 billion m³ annually, yet only 63% is collected and 52% is treated before discharge (Jones et al., 2021). This wastewater contains substantial recoverable nutrients—16.6 Tg nitrogen, 3.0 Tg phosphorus, and 6.3 Tg potassium annually—which could offset approximately 13–14% of global agricultural fertilizer demand (Qadir et al., 2020). Advanced treatment technologies such as membrane bioreactors (MBRs) and advanced oxidation processes (AOPs) achieve up to 95% BOD removal, 88% nitrogen removal, and 95% phosphorus removal, significantly outperforming conventional systems (Islam, 2025). Economic assessments indicate that integrated circular systems combining nutrient recovery, energy generation, and water reuse can achieve lower life-cycle costs than conventional treatment over 20 years, despite higher upfront capital investment (Barua, 2025). However, large-scale implementation remains constrained by regulatory fragmentation, financial limitations, technological gaps, and social acceptance barriers. Overall, this review identifies key technological innovations, policy frameworks, and institutional reforms required to scale WBCE systems. Integration of advanced treatment technologies with nature-based solutions and resource recovery strategies enables simultaneous progress toward water security, circular economy transition, climate resilience, and broader sustainable development goals.

KEYWORDS: wastewater reuse, circular economy, nutrient recovery, membrane bioreactors, advanced oxidation processes, agriculture, industrial water reuse, struvite crystallization, resource recovery, sustainable water management

I. INTRODUCTION: GLOBAL WATER CRISIS AND CIRCULAR ECONOMY IMPERATIVE

1.1 Global Water Scarcity, Wastewater Generation, and Resource Recovery Potential

The global water crisis has emerged as a critical challenge, with nearly 2 billion people experiencing high water stress and approximately 4 billion facing severe water scarcity for at least one month annually (Jain & Yadav, 2025). At the same time, global wastewater production has reached approximately 359.4 billion m³ per year—equivalent to nearly five times the annual flow of Niagara Falls—creating major implications for environmental quality and water security (Qadir et al., 2020). Of this volume, only 63% (225.6 billion m³) is collected through municipal systems, and just 52% (188.1 billion m³) undergoes treatment prior to discharge (Jones et al., 2021). Consequently, nearly 48% of global wastewater remains untreated, continuing to impose significant environmental and public health burdens despite improvements over earlier estimates suggesting ~80% untreated discharge (Jones et al., 2021).

The burden of untreated wastewater is concentrated primarily in South and Southeast Asia, where large volumes are discharged directly into natural water bodies, negatively affecting aquatic ecosystems, agricultural productivity, and public health (Jones et al., 2021). Strong geographic disparities also exist: although high-income countries account for only about 16% of the global population, they generate approximately 41% of global wastewater (Jones et al., 2021).

Wastewater collection coverage similarly varies widely, exceeding 95% in high-income countries but remaining below 50% in many low-income regions of sub-Saharan Africa and South Asia (Jones et al., 2021).

Wastewater also represents a significant untapped resource. Globally, wastewater contains an estimated 16.6 Tg of nitrogen, 3.0 Tg of phosphorus, and 6.3 Tg of potassium annually; full recovery of these nutrients could offset approximately 13.4% of global agricultural nutrient demand while simultaneously reducing eutrophication risks (Qadir et al., 2020). In addition, wastewater possesses considerable energy recovery potential, with biogas generated from treatment processes capable of supplying electricity to roughly 158 million households each year (Qadir et al., 2020). These resource recovery opportunities support the transition from viewing wastewater solely as a disposal challenge toward recognizing it as a valuable source of water, nutrients, energy, and organic matter within circular economy frameworks (Emeka & Chikwendu, 2025).

1.2 Circular Economy Framework: Principles, Definitions, and Water Sector Applications

The circular economy marks a systemic shift from the traditional linear model ("take–make–use–dispose") toward closed-loop resource systems that retain materials and energy within productive cycles while minimizing waste and environmental impact (Emeka & Chikwendu, 2025). In wastewater management, this paradigm reframes conventional treatment plants as Water Resource Recovery Facilities (WRRFs), which not only remove pollutants but also recover nutrients, generate energy from organic matter, and produce water suitable for reuse (Paliaga et al., 2025). The circular framework is commonly structured around the "6Rs" hierarchy: reduce (source minimization of wastewater generation), reuse (direct application of treated effluent), recycle (advanced treatment for potable reuse), reclaim (restoration of water quality through contaminant removal), recover (extraction of energy, nutrients, and valuable compounds), and restore (ecosystem rehabilitation) (Mbavarira & Grimm, 2021). Empirical assessments of integrated circular water systems show substantial environmental and resource efficiency gains. Compared to conventional treatment approaches, circular economy implementations can reduce freshwater consumption by 40–60%, energy demand by 50–70%, and nutrient discharges into the environment by 70–90% (Barua, 2025). These improvements result from synergistic mechanisms including water reuse reducing abstraction needs, biogas recovery offsetting electricity demand, nutrient recovery reducing fertilizer-related energy inputs, and revenue generation from recovered resources improving overall system economics (Barua, 2025).

Overall, transitioning to circular water management requires coordinated innovation across technology development, governance frameworks, economic instruments, and stakeholder engagement. This transformation is comparable in scale and complexity to decarbonization efforts in the energy sector, underscoring its significance for long-term sustainability and resource security (Emeka & Chikwendu, 2025).

1.3 Regulatory Frameworks Enabling Water Reuse: EU 2020/741 and Global Approaches

The European Union's Regulation (EU) 2020/741 on minimum requirements for water reuse, adopted in May 2020 and enforced from June 2023, represents one of the most comprehensive regulatory frameworks for reclaimed wastewater use (Szymański, 2024). It establishes harmonized minimum water quality and risk management requirements across EU member states while allowing flexibility for country-specific conditions related to water scarcity, agriculture, and local environmental contexts (Szymański, 2024). The regulation defines reuse classes (A, B, C) with strict microbial thresholds: Class A (<10 CFU/100 mL fecal coliforms and <1 CFU/100 mL fecal enterococci) for unrestricted agricultural and urban reuse, Class B (<100 CFU/100 mL fecal coliforms) for restricted crops, and Class C (<1,000 CFU/100 mL *E. coli*) for non-food applications such as forestry and ornamental irrigation (Szymański, 2024).

Implementation of EU 2020/741 highlights both regulatory strengths and practical constraints (Berbel et al., 2023). The framework introduces transparency requirements for public disclosure of water quality data, mandates HACCP-based risk management systems, and specifies monitoring protocols with defined sampling and analytical standards (Berbel et al., 2023). However, adoption remains voluntary at the national level, limiting uniform implementation across member states. Additional challenges include insufficient alignment of agricultural water pricing with true scarcity values and significant variability in public acceptance depending on regional water stress and cultural perceptions of reuse safety (Berbel et al., 2023).

Globally, regulatory frameworks for water reuse remain highly heterogeneous (Kanchanapiya & Tantisattayakul, 2022). Thailand has established operational reuse guidelines for agriculture, but faces challenges related to public confidence, limited monitoring capacity, and underdeveloped business models for reuse infrastructure (Kanchanapiya & Tantisattayakul, 2022). In the United States, regulatory authority is decentralized at the state level, resulting in uneven implementation; California has developed advanced non-potable and emerging potable reuse regulations, while other states maintain more restrictive policies (Kanchanapiya & Tantisattayakul, 2022). In many developing regions across Africa, South Asia, and Latin America, explicit regulatory frameworks for planned reuse are often absent, leading to widespread informal reuse practices alongside expanding wastewater treatment infrastructure (Singh et al., 2023).

This global regulatory heterogeneity creates significant barriers to technology transfer, international trade in recovered water and nutrient products, and consistent protection of public health and environmental quality standards (Berbel et al., 2023).

II. AGRICULTURAL WATER REUSE: TECHNOLOGY, QUALITY STANDARDS, AND AGRONOMIC PERFORMANCE

2.1 Water Quality Requirements for Agricultural Irrigation: Parameters, Standards, and Risk Management

Agricultural irrigation using reclaimed wastewater requires compliance with a broad set of quality parameters covering microbial safety, chemical composition, physical characteristics, and emerging contaminants (Chen et al., 2021). Key indicators include biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), pathogenic indicators such as *E. coli* and fecal coliforms, heavy metals (e.g., cadmium, chromium, copper, lead, mercury, nickel, zinc), and emerging contaminants such as pharmaceuticals, personal care products, pesticides, and industrial chemicals (Chen et al., 2021). Large-scale assessments have detected over 2,200 emerging contaminants in treated wastewater, with 104 compounds identified across nine chemical classes, often at higher diversity and concentrations than in groundwater sources (Koumaki et al., 2025).

EU Regulation 2020/741 establishes a tiered water reuse classification system aligned with exposure risk and crop type (Gomes et al., 2026). Class A allows unrestricted irrigation of edible crops consumed raw and requires strict microbial standards (≤10 CFU/100 mL fecal coliforms, ≤1 CFU/100 mL fecal enterococci), along with BOD <10 mg/L, TSS <10 mg/L, and turbidity <2 NTU. Class B permits irrigation of fodder and fiber crops with limited human contact, requiring ≤100 CFU/100 mL fecal coliforms and turbidity <5 NTU. Class C applies to non-food crops such as trees and ornamentals, with the least stringent microbial limit (≤1,000 CFU/100 mL *E. coli*) and higher allowable contaminant levels (Gomes et al., 2026). These standards are supported by probabilistic risk assessment frameworks that estimate human exposure, dose-response relationships, and acceptable infection risks (typically 10^{-6} per person per year) (Chen et al., 2021).

Soil protection parameters are also critical in reclaimed water irrigation, particularly sodium adsorption ratio (SAR) and electrical conductivity (EC), which influence long-term soil structure and productivity (Gomes et al., 2026). SAR values above 8 can cause sodium-induced clay dispersion and reduced soil permeability, while SAR values below 2 are generally considered safe for long-term irrigation. Similarly, treated wastewater with EC <700 µS/cm and SAR <2 can typically be applied without significant risk of soil degradation under most agricultural conditions (Gomes et al., 2026).

Overall, these integrated standards reflect extensive evidence that safe wastewater reuse requires simultaneous management of multiple contaminant classes and soil quality risks rather than isolated pollutant control strategies (Chen et al., 2021).

2.2 Membrane Bioreactor Technology: Performance, Advantages, and Operational Challenges

Membrane bioreactors (MBRs) represent an advanced wastewater treatment technology that integrates activated sludge processes with membrane filtration (typically ultrafiltration or microfiltration with 0.04–0.1 µm pore size) to simultaneously remove organic matter, suspended solids, and pathogens (Bermúdez et al., 2024). In these systems, mixed liquor is circulated through submerged or external membranes that retain biomass within the reactor, independent of settling characteristics (Bermúdez et al., 2022). This allows operation at higher mixed liquor suspended solids (6,000–10,000 mg/L) compared to conventional activated sludge systems (2,000–3,000 mg/L), resulting in higher treatment efficiency and reduced reactor footprint (Bermúdez et al., 2022).

A pilot-scale MBR system (50 m^3/day) operated under hydraulic retention times of 6–12 hours and MLSS levels of 2,429–6,696 mg/L achieved consistent compliance with EU agricultural reuse standards (Bermúdez et al., 2022). Performance results included 95–98% BOD removal, >99% total suspended solids removal, 75–90% ammonia nitrogen removal depending on retention time, and complete elimination of fecal coliforms below detection limits (<1 CFU/100 mL) (Bermúdez et al., 2022). Integration of anaerobic digestion for sludge treatment enabled biogas production that offset 40–50% of facility energy demand, while stabilized biosolids were suitable for agricultural application as nutrient-rich soil amendments (Bermúdez et al., 2024). These integrated systems reflect Water Resource Recovery Facility (WRRF) concepts by producing reusable water, energy, and biosolids while reducing environmental footprint (Bermúdez et al., 2024).

Despite these advantages, MBR systems face important operational constraints (Stankiewicz et al., 2024). Energy consumption for aeration and membrane operation typically ranges from 0.5–1.0 kWh/m^3, contributing significantly to operational costs and carbon emissions (Stankiewicz et al., 2024). Membrane fouling due to organic, colloidal, and microbial deposition reduces flux over time and necessitates chemical cleaning, increasing operational complexity and generating secondary waste (Stankiewicz et al., 2024). Another critical concern is the persistence of antibiotic-resistant bacteria and genes in MBR effluents, where 55–89% of detected *E. coli* exhibited resistance to multiple antibiotics including ampicillin, aztreonam, and cephalosporins (Stankiewicz et al., 2024). However, combining MBRs with tertiary treatments such as UV irradiation, granular activated carbon, or environmental retention systems (5–10 days storage) can reduce antibiotic-resistant bacteria by >99% and effectively eliminate detectable resistance genes, highlighting the necessity of multi-barrier treatment strategies for safe agricultural reuse (Stankiewicz et al., 2024).

2.3 Advanced Treatment for Emerging Contaminants: Pharmaceuticals, Pesticides, and Microplastics

Emerging contaminants—including pharmaceuticals, personal care products, pesticides, and microplastics—pose significant water quality challenges that conventional biological treatment systems cannot fully address (Masjoudi & Mohseni, 2023). Pharmaceuticals such as carbamazepine, diclofenac, and trimethoprim can persist through membrane bioreactor (MBR) treatment at concentrations of 10–100 μg/L, with potential accumulation in soils or transport to groundwater following reuse applications (Masjoudi & Mohseni, 2023). Advanced oxidation processes (AOPs), including ozonation, UV/H_2O_2, and electrochemical oxidation, mitigate these compounds through hydroxyl radical and reactive oxygen species–driven oxidation and mineralization pathways (Masjoudi & Mohseni, 2023).

Vacuum-UV (VUV) and VUV/chlorine AOP systems have shown strong performance for degrading persistent compounds such as 1,4-dioxane, although efficiency is influenced by water chemistry, particularly chloramine background levels (Masjoudi & Mohseni, 2023). Chloramines reduce VUV efficiency, whereas the presence of free chlorine enhances degradation via chlorine radical formation ($Cl_2^{\bullet -}$), with hydroxyl and chlorine radicals contributing 62.5% and 32.5% of overall degradation, respectively (Masjoudi & Mohseni, 2023). Chloride ions enhance degradation kinetics, while bicarbonate inhibits reactions through radical scavenging, providing important guidance for optimizing AOP design in potable reuse systems (Masjoudi & Mohseni, 2023).

Microplastic pollution in wastewater and irrigation systems is an emerging environmental concern with unresolved ecological and human health implications (Osman et al., 2023). Microplastics (<5 mm) originate from primary sources (manufactured microplastics), secondary fragmentation of larger plastics, synthetic textile fibers, and road wear particles (Osman et al., 2023). Global plastic production has reached approximately 359 million metric tons annually, with China contributing 17.5% of total output (Osman et al., 2023). Available removal technologies include coagulation, membrane bioreactors, sand filtration, adsorption, photocatalysis, electrocoagulation, and magnetic separation (Osman et al., 2023).

Microplastics induce cytotoxicity, oxidative stress, immune dysfunction, and genotoxic effects at concentrations around 10 μg/mL (Osman et al., 2023). In aquatic organisms, exposure disrupts gastrointestinal function, suppresses immune responses, alters gene expression, and reduces growth, with potential biomagnification through food webs raising concerns for human exposure (Osman et al., 2023). Control strategies include behavioral interventions, regulatory policies such as bans and taxation on plastic use, and substitution with biodegradable alternatives, achieving reductions in plastic consumption of 8–85% across different countries (Osman et al., 2023). Overall, microplastic management follows a hierarchical approach prioritizing prevention, followed by reduction, reuse, recycling, recovery, and disposal as the least preferred option (Osman et al., 2023).

2.4 Agronomic Performance of Reclaimed Water and Recovered Nutrients

Field trials on reclaimed wastewater irrigation demonstrate strong agronomic potential across diverse crops when supported by appropriate soil and water quality management strategies (Gomes et al., 2026). A pilot-scale study at Palermo University's water resource recovery facility (Depurazione Ambientale Palermo) assessed faba bean cultivation using treated wastewater and biosolid amendments (Paliaga et al., 2025). While irrigation with reclaimed wastewater alone increased soil electrical conductivity and initially reduced plant growth compared to freshwater irrigation, the application of biochar and zeolite effectively mitigated salinity impacts by improving soil structure and reducing salt accumulation (Paliaga et al., 2025). Microbiological assessments confirmed food safety, with no detection of pathogenic bacteria including fecal coliforms, *Salmonella*, *Listeria monocytogenes*, or *E. coli* in pods or seeds under properly managed conditions (Paliaga et al., 2025).

A systematic review of 85 field and pot studies (2010–2024) evaluated the agronomic performance of recovered nutrients from wastewater, including ammonium salts, struvite, ash, compost, digestate, biochar, hydrochar, and biostimulants (Shrivastava & Laasri, 2025). Ammonium sulfate and ammonium nitrate consistently achieved 95–105% yield equivalence to synthetic fertilizers due to high plant availability (Shrivastava & Laasri, 2025). Struvite and phosphorus-rich ash performed at 90–100% equivalence in soils with pH 6–7, but showed reduced effectiveness in alkaline soils due to phosphorus fixation; organo-mineral phosphate fertilizers achieved 85–95% equivalence depending on soil conditions (Shrivastava & Laasri, 2025). Potassium-rich recovered products showed 80–95% yield equivalence in soils with moderate cation exchange capacity, declining to 60–75% in sandy soils with low retention capacity (Shrivastava & Laasri, 2025).

Biochar and hydrochar derived from wastewater residuals provided additional agronomic benefits beyond nutrient supply, including 30–50% increases in soil water-holding capacity, improved microbial activity, and enhanced nutrient retention, resulting in 90–110% performance relative to synthetic fertilizers (Shrivastava & Laasri, 2025). Wastewater-derived biostimulants increased crop yields by 8–20% through phytohormonal effects, improved nutrient uptake, and enhanced stress tolerance (Shrivastava & Laasri, 2025). Long-term studies further show that reclaimed water irrigation leads to gradual accumulation of nitrogen and phosphorus in topsoil (0–30 cm) and increases soil organic matter by 0.5–2.0% annually over 5–10 years (Shrivastava & Laasri, 2025).

Overall, these findings indicate that recovered wastewater products function not only as substitutes for synthetic fertilizers but also as multifunctional soil amendments that enhance soil health, water retention, and productivity, provided they are integrated with appropriate management practices such as salinity control, pH optimization, and organic matter enhancement (Shrivastava & Laasri, 2025).

III. NUTRIENT RECOVERY TECHNOLOGIES: PATHWAYS FROM WASTEWATER TO FERTILIZER PRODUCTS

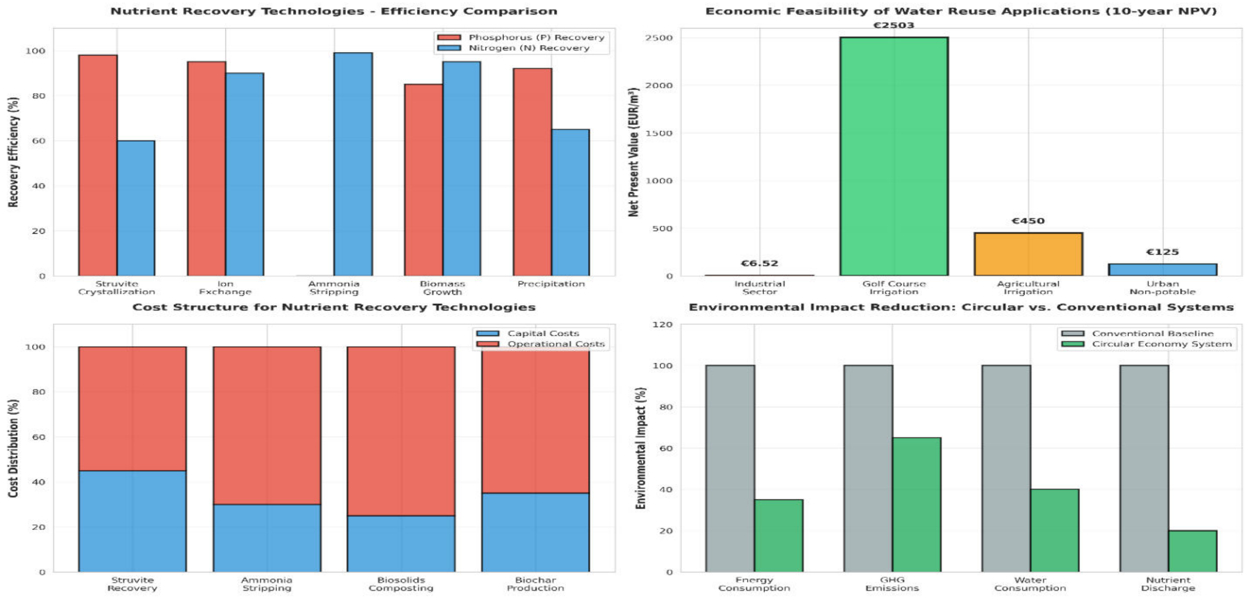

Figure 1: Comparative Analysis of Nutrient Recovery Technologies, Economic Viability, Cost Structures, and Environmental Impact Reduction Through Circular Economy Implementation

This four-panel economic and technical analysis in figure 1 synthesizes nutrient recovery technology performance, economic feasibility, cost distribution, and environmental benefits of circular economy approaches. **Panel A (Top-Left):** Nutrient recovery technology efficiency comparison demonstrates differential performance across five primary technologies: struvite crystallization achieves 98% phosphorus recovery but only 60% nitrogen recovery; ion exchange achieves 95% phosphorus and 90% nitrogen recovery; ammonia stripping achieves negligible phosphorus recovery but 99% nitrogen recovery; biomass growth achieves 85% phosphorus and 95% nitrogen recovery; and precipitation achieves 92% phosphorus and 65% nitrogen recovery (Hafiz et al., 2024). Technology selection requires matching chemical contaminant composition and treatment objectives to recovery pathway capabilities. **Panel B (Top-Right):** Net present value (NPV) analysis of wastewater reuse applications over 10-year facility lifespan demonstrates highly variable profitability by end-use: industrial water reuse achieves €6.52/m^3 profit, golf course irrigation €2,503/m^3 profit, unrestricted agricultural irrigation €450/m^3 profit (Vivas et al., 2023). These economic variations reflect end-use water quality requirements and alternative water cost baseline values determining water commodity valuation. **Panel C (Bottom-Left):** Cost structure analysis for nutrient recovery technologies reveals capital cost contributions of 25-45% (struvite recovery 45%, ammonia stripping 30%, biosolids composting 25%, biochar production 35%) with operational costs comprising 55-75% of total costs (Mayor et al., 2023), indicating energy and chemical intensity of recovery processes. **Panel D (Bottom-Right):** Environmental impact reduction from circular economy systems relative to conventional treatment baseline (set at 100%) demonstrates comprehensive improvements: energy consumption reduction of 65%, greenhouse gas emissions reduction of 35%, water consumption reduction of 60%, and nutrient discharge reduction of 80% (Barua, 2025). These environmental metrics establish the ecological case for circular approaches beyond economic considerations.

3.1 Struvite Crystallization: Phosphorus Recovery Mechanism, Technology Optimization, and Commercial Implementation

Struvite crystallization (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4\cdot 6H_2O$) is currently the most commercially mature phosphorus recovery technology, with more than 40 full-scale systems operating globally (Hafiz et al., 2024). Efficient crystallization requires controlled operating conditions, particularly pH values of 8.0–9.0 to promote struvite formation while minimizing competing iron- and calcium-phosphate precipitation, and temperatures between 20–60°C to optimize crystal nucleation and growth (Hafiz et al., 2024). Common reactor configurations include fluidized bed crystallizers, continuously stirred tanks, and airlift reactors designed to enhance particle suspension, mixing, and crystal growth (Hafiz et al., 2024).

The crystallization reaction requires a stoichiometric $Mg^{2+}:NH_4^{+}:PO_4^{3-}$ molar ratio of 1:1:1; however, municipal wastewater typically contains excess nitrogen relative to phosphorus, making phosphorus the limiting component (Hafiz et al., 2024). To optimize recovery, exogenous magnesium sources such as $MgCl_2$, MgOH, or $Mg(OH)_2$ are commonly added at 1.2–1.5 molar equivalents relative to phosphorus, while alkali addition (NaOH, KOH, or $Mg(OH)_2$) adjusts pH to favorable crystallization ranges (Hafiz et al., 2024). Recovery efficiency is further influenced by supersaturation control, mixing intensity, influent phosphorus concentration, and reactor contact time (Hafiz et al., 2024).

Alternative phosphorus recovery technologies, including ligand exchange adsorbents for phosphate and total ammonia nitrogen (TAN), provide enhanced ion selectivity, lower regeneration chemical demand, and production of concentrated nutrient products suitable for direct agricultural use (Clark et al., 2024). These systems utilize coordinate covalent bonding to selectively capture phosphate and ammonia while excluding competing ions, and regeneration is achieved through mild pH adjustment with reduced energy and chemical requirements (Clark et al., 2024). Comparative life cycle assessment indicated that chemical precipitation currently exhibits the lowest overall environmental impact due to its commercial maturity and energy recovery integration despite chemical consumption for pH and magnesium adjustment (Śniatała et al., 2024).

Enhanced nutrient recovery from anaerobically digested poultry wastewater combined organic acid pre-treatment with struvite precipitation in a bubble column electrolytic reactor, achieving high nutrient removal efficiencies (Aka et al., 2024). Oxalic acid pre-treatment at pH 2.5 enabled complete phosphorus solubilization, while subsequent crystallization achieved 88.9% phosphate and 90.1% ammonia-nitrogen removal (Aka et al., 2024). Seeding with 10 g/L struvite crystals increased removal efficiency by 11.5% and enlarged particle size from 75 to 149 µm (Aka et al., 2024). Analytical characterization confirmed the recovered product contained 94.7% struvite with negligible heavy metal concentrations (<0.1 mg/kg for zinc, lead, and cadmium), supporting its suitability for agricultural application (Aka et al., 2024).

3.2 Microalgae-Based Nutrient Recovery: Phototrophic Treatment and Biomass Valorization

Microalgae and cyanobacteria provide innovative approaches for simultaneous wastewater treatment and nutrient recovery through photosynthetic biomass production, generating feedstocks for biofuels, biofertilizers, nutraceuticals, pigments, and animal feed supplements (Janpum et al., 2022). Mixed microalgal-bacterial symbiotic systems utilize complementary metabolisms in which algae supply oxygen for aerobic bacterial degradation of organic matter, while bacteria provide CO_2 and nutrients supporting algal growth (Odibo et al., 2024). Co-immobilized cultures of *Chlorella vulgaris* and *Bacillus subtilis* achieved removal efficiencies of 86.7% for ammonium and 99.3% for phosphates while producing biomass suitable for biofertilizer applications (Odibo et al., 2024). These systems outperform monoculture systems due to enhanced microbial diversity and operational stability (Odibo et al., 2024).

Immobilized microalgae-bacterial biofilms encapsulated in calcium alginate beads demonstrated high treatment efficiency for pig farm wastewater (Thi & Bui, 2025). Ammonium concentrations decreased from 157.5 to 9.71 mg/L (93.8% removal), while total nitrogen, phosphate, and total phosphorus removals reached 85.9%, 77.7%, and 66%, respectively, exceeding Vietnam's national discharge standards (Thi & Bui, 2025). The recovered biomass also functioned as a biofertilizer product, reducing operational costs and generating additional economic value (Thi & Bui, 2025). Studies further demonstrated that pharmaceutical contaminants did not significantly reduce biomass productivity or nutrient recovery performance; over 97% of six priority pharmaceuticals were degraded in the mixed liquor rather than accumulated within biomass (Morillas-España et al., 2025). Seasonal variations affected removal efficiency, averaging 90% during summer and 74% during winter due to changes in photosynthetic activity and wastewater composition (Morillas-España et al., 2025). The resulting biomass exhibited plant biostimulant properties through phytohormone production and improved nutrient availability, supporting agricultural reuse potential (Morillas-España et al., 2025).

Norwegian microalgae strains including *Tetradesmus wisconsinensis*, *Lobochlamys segnis*, and *Klebsormidium flaccidum* demonstrated complete nitrogen and phosphorus removal in synthetic municipal wastewater experiments (Umetani et al., 2023). *L. segnis* achieved the fastest ammonium and phosphate removal, while *T. wisconsinensis* exhibited the highest carbohydrate content (40%) and favorable fatty acid profiles for biorefinery applications (Umetani et al., 2023). *L. segnis* accumulated the highest fatty acid concentration (193 ± 12 mg/g dry cells), whereas *K. flaccidum* produced the highest polyunsaturated fatty acid fraction (82%) and protein content (53%) (Umetani et al., 2023). These systems illustrate the transition from conventional single-output wastewater treatment toward integrated multi-output resource recovery facilities producing treated water, nutrients, and valuable biochemical products (Umetani et al., 2023).

3.3 Ammonia Recovery and Nitrogen Cycling: Ion Exchange, Stripping, and Biological Assimilation

Ammonia recovery from wastewater represents the second-largest nutrient recovery opportunity after phosphorus, with 60–90% nitrogen recovery achievable through ammonia stripping, ion exchange, and microbial assimilation (Kurniawan et al., 2025). Ammonia stripping coupled with gas-permeable membrane absorption enables near-complete nitrogen removal without external chemical dosing, with recovered ammonia convertible into ammonium nitrate for agricultural use (Kurniawan et al., 2025). Denitrifying phosphorus removal combined with ammonium assimilation can eliminate over 80% of influent nitrogen while recovering more than 60% through biomass accumulation in activated sludge systems (G. Zhang et al., 2024).

Halophilic ammonium-assimilating microorganisms provide an emerging solution for nitrogen recovery in saline wastewater, where conventional nitrification–denitrification is inhibited (M. Zhang et al., 2021). An engineered microbiome using *Psychrobacter aquimaris* A4N01 achieved >80% removal of ammonium, total nitrogen, and phosphorus, along with >98% COD removal and zero gaseous nitrogen emissions, avoiding greenhouse gas formation associated with conventional nitrogen removal pathways (M. Zhang et al., 2021). By converting nitrogen directly into microbial biomass, this assimilation pathway enables nutrient recovery in forms suitable for soil amendment, feed, or biorefinery applications while maintaining effectiveness in high-salinity conditions where traditional systems fail (M. Zhang et al., 2021).

Recovered nitrogen products exhibit agronomic performance comparable to synthetic fertilizers when properly managed, with effectiveness dependent on soil conditions and application strategies (Shrivastava & Laasri, 2025). Economic analyses indicate break-even thresholds of approximately €0.58/kg for struvite and €0.68/kg for ammonium nitrate, while current market prices (€0.30–0.40/kg) suggest that profitability depends on either price increases or policy-driven internalization of environmental costs (Mayor et al., 2023). Although nutrient recovery systems increase treatment costs by 5–15%, they deliver net environmental benefits by reducing synthetic fertilizer production impacts (Mayor et al., 2023). These findings highlight the need for supportive policy mechanisms such as tax incentives, subsidies, and payment-for-ecosystem-services schemes to align environmental value with economic viability (Barua, 2025).

3.4 Biochar and Hydrochar Production: Co-Benefits Beyond Nutrient Content

Biochar and hydrochar amendments derived from wastewater treatment residuals (dewatered sludges from biological treatment or thermal residues) provide agronomic benefits extending substantially beyond nutrient supply (Shrivastava & Laasri, 2025). Biochar (produced through pyrolysis at 300-700°C in oxygen-limited conditions) and hydrochar (produced through hydrothermal carbonization at 180-250°C under hydrostatic pressure) both enhance soil properties through: improved water retention (30-50% increase in plant-available water capacity), enhanced soil structure through aggregate stabilization, increased microbial habitat provision through extensive porosity, and increased cation exchange capacity enabling nutrient retention (Shrivastava & Laasri, 2025). These mechanisms produce agronomic yields of 90-110% of synthetic fertilizer performance, with additional benefits including reduced nutrient leaching losses (5-20% reduction compared to soluble synthetic phosphates) and enhanced drought tolerance (Shrivastava & Laasri, 2025).

Biochar's sorptive properties enable additional environmental remediation functions: the extensive surface area (>300 m^2/g for activated biochar) enables sorption of heavy metals, persistent organic pollutants, and emerging contaminants, potentially attenuating contaminant leaching to groundwater (Shrivastava & Laasri, 2025). Application of biochar to soils receiving reclaimed wastewater irrigation specifically mitigated salt accumulation effects observed with treated water irrigation alone (Paliaga et al., 2025). Life cycle assessment of biochar from wastewater sludge demonstrated net carbon sequestration when biochar remains soil-applied for >10 years, with climate benefits from avoided synthetic fertilizer manufacturing emissions amplified by carbon sequestration in stable soil organic matter (Shrivastava & Laasri, 2025). These multiple co-benefits establish biochar and hydrochar as valuable components of integrated wastewater-based circular economy systems rather than single-function nutrient sources (Shrivastava & Laasri, 2025).

IV. INDUSTRIAL WATER REUSE: TECHNOLOGIES, CASE STUDIES, AND CIRCULAR ECONOMY IMPLEMENTATION

4.1 Industrial Sector Water Consumption, Wastewater Characterization, and Reuse Potential

Industrial water consumption represents a critical global challenge, accounting for approximately 19% of freshwater withdrawals while generating substantial wastewater volumes laden with recoverable resources (Barua, 2025). The beverage, semiconductor, textile, and food processing industries consume the most water per unit production and generate effluents with high concentrations of recoverable nutrients, salts, organic matter, and valuable chemical compounds (Barua, 2025). Industrial wastewater treatment plants transformation into Water Resource Recovery Facilities (WRRFs) demonstrates technical and economic feasibility across these diverse sectors through integrated systems: demonstrated implementations achieve 40-60% reductions in freshwater consumption, 50-70% reductions in energy demand, and 70-90% reductions in nutrient environmental discharges (Barua, 2025).

Stormwater retention systems with forecast-based real-time control represent emerging technology for industrial water reuse, enabling 50% reduction in overflow volumes while meeting 95% of irrigation demand through integrated stormwater-wastewater management (Barua, 2025). Combined with advanced treatment trains using biological, membrane, and advanced oxidation processes, such systems produce high-quality reclaimed water suitable for industrial cooling, toilet flushing, and landscape irrigation applications (Barua, 2025). Water Resource Recovery Facilities exemplify the circular economy principle of waste elimination: industrial wastewater, conventionally viewed as a problematic byproduct requiring expensive disposal, transforms into recovered feedwater, nutrient sources, and energy products (Barua, 2025).

4.2 Automotive Industry Case Study: Paint Rinsing Wastewater Treatment and Water Recycling

The paint manufacturing sector exemplifies complex industrial wastewater challenges and circular economy solutions through detailed technical and economic analysis (Mazik et al., 2025). Paint production wastewater is characterized by high chemical oxygen demand (500-2,000 mg/L), elevated turbidity (100-500 NTU), and presence of organic materials, suspended particles, and heavy metals requiring treatment before environmental discharge or reuse (Mazik et al., 2025). A comprehensive wastewater management study examined 190 samples from paint rinsing machines and containers across multiple manufacturing facilities, employing probabilistic methods including Monte Carlo simulations and distribution fitting to characterize wastewater quality variability and treatment requirements (Mazik et al., 2025).

Implementation of water treatment and recycling systems enabled paint manufacturers to reduce reliance on freshwater resources by 35-45%, lower wastewater disposal costs by 25-40%, and mitigate environmental impact through resource recovery (Mazik et al., 2025). The optimal treatment strategy encompassed: collection system design emphasizing source reduction strategies (minimizing pollutants generated through process optimization), combined with advanced treatment technologies enabling reuse of rinse wastewater (Mazik et al., 2025). This case demonstrates that effective industrial circular economy implementation requires integration of three complementary approaches: source reduction (minimizing pollutants at generation point), treatment technology selection (matching treatment intensity to specific wastewater characteristics), and end-use design (matching treated water quality to application requirements) (Mazik et al., 2025).

Economic analysis of paint industry water recycling systems demonstrated payback periods under one year, indicating rapid return on investment; annual operating costs achieved €0.05-0.12/m³ for treatment, substantially lower than freshwater costs of €1.50-3.00/m³ in most industrial locations (Mazik et al., 2025). These economics exemplify the fundamental circular economy principle: resource recovery investments exhibit high financial returns through eliminated consumption of virgin resources plus potential recovered product revenues (Mazik et al., 2025).

4.3 Membrane-Based Treatment for Industrial Cooling Water and Degreasing Effluent

The automotive industry exemplifies successful industrial water reuse implementation through membrane-based treatment systems optimized for specific wastewater streams (Carvalho et al., 2025). Automotive painting processes generate two primary wastewater streams requiring distinct treatment: degreasing washing water with high alkalinity (pH >11) and high surfactant concentration (500-1,000 mg/L), and cooling tower water containing salts, biocides, and corrosion inhibitors (Carvalho et al., 2025). Treatment of degreasing washing water employed cation exchange on weak-acid-based resin combined with microfiltration (0.1-1 μm pore size) achieving 88% recovery efficiency, enabling recirculation of treated water within degreasing processes (Carvalho et al., 2025). Capital cost for degreasing treatment reached €245 thousand for a facility treating 50 m³/day; treatment of cooling tower water applied subsequent ultrafiltration and reverse osmosis steps, recovering approximately 68% of available water at capital cost of €582 thousand (Carvalho et al., 2025).

Estimated annual water income after treatment implementation reached €0.07 per manufactured vehicle for the washing stage and €0.13 per vehicle for cooling towers, with water cost savings substantially exceeding treatment costs within 3-year payback periods (Carvalho et al., 2025). This financial performance demonstrates the economic viability of industrial water reuse when wastewater volumes are substantial and freshwater costs are significant (Carvalho et al., 2025). The integration of membrane technologies with advanced oxidation processes enables treatment of complex industrial effluents containing recalcitrant organic compounds; however, hybrid system selection requires careful sideration of feed water characteristics, treatment objectives, and economic constraints (Ni et al., 2024). A comprehensive review of advanced oxidation processes coupled with membrane filtration identified electrochemical oxidation, photocatalysis, Fenton reactions, and ozonation as effective antifouling strategies that simultaneously degrade pollutants while maintaining membrane permeability (Ni et al., 2024). These hybrid approaches are particularly valuable for industrial applications where membrane fouling prevention directly impacts economic viability through sustained treatment efficiency (Ni et al., 2024).

4.4 Resource Recovery and Nutrient Cycling in Industrial Systems

Industrial wastewater contains diverse recoverable resources including phosphorus, nitrogen, sulfur, and carbon with substantial economic value when coupled with market-ready end-products (Mayor et al., 2023). Recovered struvite sells at €500-800 per ton, recovered biogas at €0.08-0.15 per kWh equivalent energy, and biosolids compost at €30-60 per ton, establishing economic incentives for resource recovery implementation (Mayor et al., 2023). A pilot-scale nutrient recovery system implementing struvite crystallization and ion exchange with gas permeable membrane contactors achieved recovery of ammonium nitrate and struvite for agricultural application while demonstrating environmental superiority in most life cycle assessment impact categories (Mayor et al., 2023). However, economic viability depends critically on recovered product values and treatment costs; life cycle assessment indicated environmental benefits but negative net present values under current market conditions (Mayor et al., 2023). Implementation could become economically favorable if ammonium nitrate and struvite prices increase to €0.68 and €0.58 per kilogram, respectively, or if external costs of nutrient pollution (eutrophication damages valued at €500-1,000 per ton of excess nutrient) are internalized through regulatory mechanisms (Mayor et al., 2023).

V. ADVANCED WASTEWATER TREATMENT TECHNOLOGIES FOR RESOURCE RECOVERY

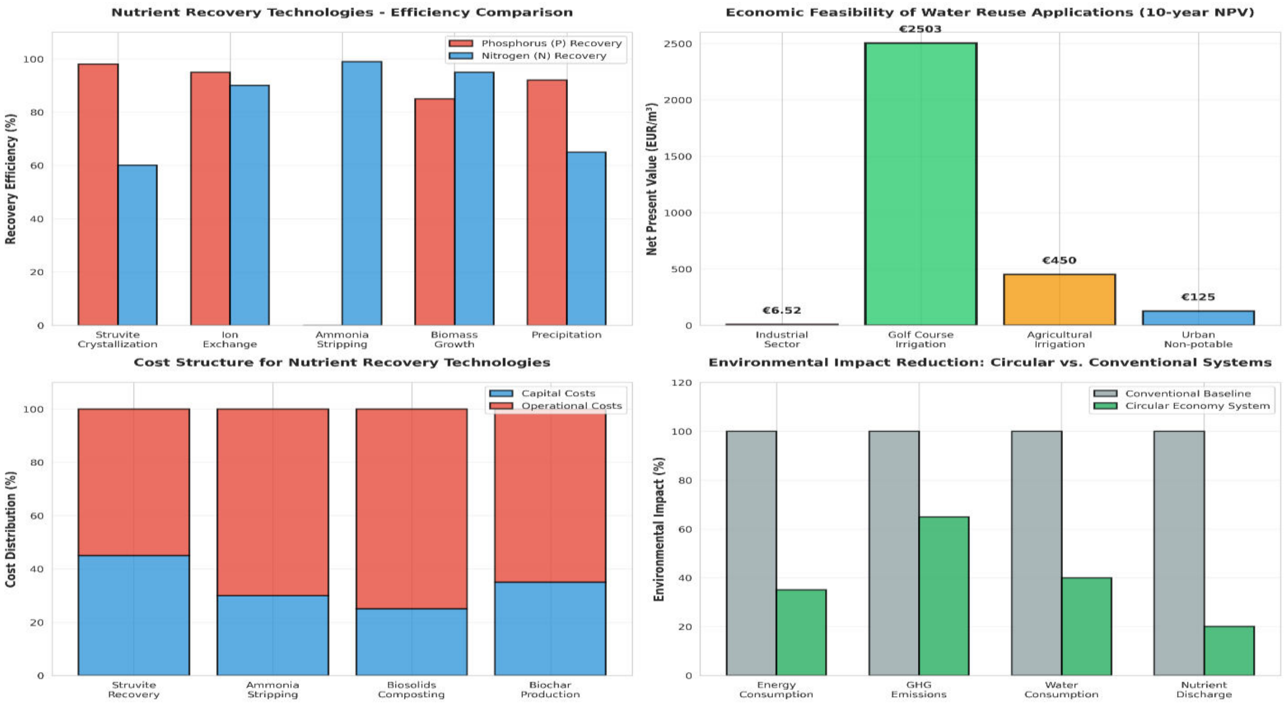

Figure 2: Global Wastewater Production, Collection, Treatment, and Reuse Statistics Demonstrating Treatment Gaps and Resource Recovery Opportunities

This comprehensive four-panel visualization in figure 2 illustrates the global wastewater production cascade and international variations in water reuse implementation. **Panel A (Top-Left):** Global wastewater production trajectory shows 359.4 billion m³ annual production, declining to 225.6 billion m³ collected through municipal systems (63%), 188.1 billion m³ treated (52%), and 40.7 billion m³ intentionally reused (11.3% of production), demonstrating substantial treatment gaps and underutilized reuse potential (Jones et al., 2021). **Panel B (Top-Right):** Nutrient recovery potential analysis reveals global wastewater contains 16.6 Tg nitrogen, 3.0 Tg phosphorus, and 6.3 Tg potassium annually—quantities capable of offsetting 13.4% of global agricultural nutrient demand (Qadir et al., 2020). The comparative analysis demonstrates that available nutrient quantities substantially exceed agricultural nutrient offsetting capacity, establishing economic and environmental incentives for nutrient recovery implementation. **Panel C (Bottom-Left):** Treatment effectiveness comparison between conventional wastewater treatment (achieving 75% BOD removal, 65% nitrogen removal, 70% phosphorus removal, 80% pathogen inactivation) versus advanced treatment systems incorporating membrane bioreactors and advanced oxidation processes (achieving 95% BOD removal, 88% nitrogen removal, 95% phosphorus removal, 98% pathogen removal) (Islam, 2025). **Panel D (Bottom-Right):** Geographic variation in treated wastewater reuse rates reveals Middle East and North Africa leading adoption at 15% reuse, Western Europe at 16%, with substantially lower rates in Asia (8%), North America (6%), and Australia (12%), reflecting geographic water scarcity variations and treatment infrastructure development stages (Jones et al., 2021). These regional disparities highlight both implementation success in water-scarce regions and adoption barriers in water-abundant areas.

5.1 Advanced Oxidation Processes: Mechanisms, Applications, and Performance

Advanced oxidation processes (AOPs) generate hydroxyl radicals (•OH) and other reactive oxygen species (ROS) that non-selectively oxidize organic pollutants into CO_2, water, and inorganic ions (Satyam & Patra, 2025). Homogeneous AOPs such as Fenton’s process (Fe^{2+}/H_2O_2) achieve high degradation efficiency but are limited by narrow pH control (2.5–3.5), catalyst recovery issues, sludge generation, and high energy demand (Satyam & Patra, 2025). Heterogeneous AOPs using catalysts such as TiO_2, Fe_3O_4 composites, and other transition metals overcome these limitations by offering broader pH applicability, improved light activation, and catalyst reusability (Satyam & Patra, 2025). Recent developments include UV-LED-based AOP systems that reduce energy consumption by 20–40% compared to mercury lamps, plasma-assisted oxidation producing reactive species via non-thermal plasma, and AI-enabled reactors for real-time process optimization (Satyam & Patra, 2025). Biochar-based catalysts are emerging as low-cost, sustainable alternatives due to high surface area, porosity, and active sites, although large-scale application remains limited (Aziz et al., 2025). Their performance depends strongly on feedstock type and pyrolysis conditions, and hybrid AOP configurations further enhance treatment efficiency (Aziz et al., 2025). Graphene oxide quantum dots-based membranes (GQDs-Ms) integrate oxidation and membrane filtration into a hybrid system (Tshangana & Muleja, 2023). Incorporation of graphene oxide quantum dots improves hydrophilicity, pore structure, flux, and antimicrobial properties in polymeric membranes (Tshangana & Muleja, 2023). Multi-AOP systems combining GQDs and peracetic acid achieved removal efficiencies of 83.45% for turbidity, 64.12% for total dissolved solids, 40.76% for organic carbon, and 70.36% for electrical conductivity, demonstrating performance approaching commercial membrane technologies and significantly enhancing reuse potential (Tshangana & Muleja, 2023).

5.2 Constructed Wetlands and Nature-Based Treatment Solutions

Constructed wetlands and other nature-based solutions offer low-energy, cost-effective alternatives to conventional wastewater treatment while enabling resource recovery through phytoremediation and microbial processes (Gomes et al., 2026). Horizontal subsurface flow constructed wetlands using macrophytes such as *Phragmites australis* and *Typha* spp. achieve >97% removal of chemical oxygen demand and total suspended solids, along with 50–70% nitrogen and 40–60% phosphorus removal through combined microbial degradation, plant uptake, and filtration (Gomes et al., 2026). Effluent quality consistently meets European and national irrigation standards (Gomes et al., 2026). Integrated systems combining floating treatment wetlands (FTWs), subsurface flow constructed wetlands (SSF-CWs), and sand filtration have demonstrated effective performance in industrial applications, including vehicle-washing facilities in Pakistan, achieving compliance with discharge standards while reducing treatment costs to €0.0163/m³ and payback periods below one year (Afzal et al., 2024). These systems are particularly suitable for decentralized and rural contexts due to low energy requirements, though their land demand (2–5 m² per capita) limits scalability in dense urban areas (Afzal et al., 2024). Rotating algal biofilm (RAB) systems further enhance nutrient recovery through synergistic light–dark biofilm interactions (W. Liu et al., 2024). Under optimized conditions (5-day harvest cycle, 12-hour hydraulic retention time), RAB systems achieved 3.3 $g\ m^{-2}\ d^{-1}$ biomass productivity and 82.3% ammonium nitrogen removal (W. Liu et al., 2024). Functional partitioning within the system improved overall performance, with light biofilms enhancing carbon fixation and nutrient uptake, while dark biofilms supported denitrification and phosphorus removal. Key microbial and algal taxa, including *Haliangium*, *Methyloversatilis*, Comamonadaceae, and *Chlorella*, played central roles in nutrient cycling (W. Liu et al., 2024).

5.3 Membrane Filtration Technologies and Water Quality Enhancement

Membrane filtration technologies include microfiltration (0.1–10 µm), ultrafiltration (0.01–0.1 µm), nanofiltration (0.001–0.01 µm), and reverse osmosis (<0.001 µm), enabling progressive control of effluent quality (C. Zhang et al., 2024). Reverse osmosis removes ~99% of dissolved salts, producing effluent conductivity below 500 µS/cm suitable for sensitive irrigation uses (C. Zhang et al., 2024). Nanofiltration selectively removes divalent ions and larger organic molecules while allowing monovalent ions to pass, offering lower energy demand than reverse osmosis with intermediate treatment performance (C. Zhang et al., 2024). Ceramic (inorganic) membranes provide higher thermal and chemical stability than polymeric membranes, enabling integration with advanced oxidation processes without material degradation (C. Zhang et al., 2024). Membrane fouling remains a key operational limitation, driven by accumulation of organic matter, colloids, and biofilms that reduce permeate flux over time (C. Zhang et al., 2024). Combining advanced oxidation processes with membrane filtration can reduce fouling by degrading organic foulants, while catalytic membranes enable in-situ oxidation for continuous fouling control (C. Zhang et al., 2024). Emerging materials such as metal-organic frameworks (MOFs), including ZIF-8 and F300, enhance pharmaceutical removal efficiency in membrane systems (Polak et al., 2025). ZIF-8 achieved adsorption capacities of 442.2 mg/g for tetracycline and 219.3 mg/g for sulfadiazine, improving removal efficiency by 187% and 224%, respectively, compared to unmodified membranes (Polak et al., 2025). Hybrid treatment systems such as ozone/biologically active filtration (O_3/BAF) followed by UV/AOP achieve high removal of emerging contaminants, with >95% efficiency for most compounds and reduced formation of disinfection byproducts within regulatory limits (B. Liu et al., 2025). This combination also improves UV transmittance, enhancing the efficiency of downstream advanced oxidation processes (B. Liu et al., 2025).

VI. REGULATORY FRAMEWORKS, ECONOMIC FEASIBILITY, AND IMPLEMENTATION BARRIERS

6.1 Economic Analysis of Water Reuse and Nutrient Recovery Systems

The economic viability of water reuse and resource recovery systems varies significantly with application type, location, infrastructure, and market conditions (Vivas et al., 2023). A technical-economic assessment of El Salitre WWTP (Bogotá) showed strong variation in reuse profitability: industrial reuse (€6.52/m³), golf course irrigation (€2,503/m³), and agricultural irrigation (€450/m³) (Vivas et al., 2023). Technology choice also strongly affects feasibility; membrane systems require €245,000–582,000 in capital costs with operating costs of €0.05–0.15/m³, yielding payback periods of 3–5 years under typical pricing conditions (Carvalho et al., 2025). Nutrient recovery increases treatment costs by 5–15% but generates revenue through product recovery, with estimated costs of €500–800/ton for phosphorus and €200–400/ton for nitrogen products (Mayor et al., 2023). Despite higher upfront investment, 20-year life cycle analyses show that integrated systems combining water reuse, energy recovery, and nutrient recovery achieve lower overall unit costs than conventional treatment (Mayor et al., 2023). However, economic viability is sensitive to market prices; profitability becomes favorable only when recovered product prices rise by 50–100% above current levels (Mayor et al., 2023). Externality pricing mechanisms—such as carbon pricing (€100–150/ton CO_2e), nutrient pollution fees (€500–1,000/ton), and water scarcity pricing—could substantially improve the economic competitiveness of circular wastewater systems (Barua, 2025).

6.2 Barriers to Implementation and Policy Recommendations

The transition toward circular water management is constrained by barriers that extend beyond technology (Mannina et al., 2022). Regulatory fragmentation remains a key challenge: although EU Regulation 2020/741 sets minimum reuse standards, member states can impose stricter requirements, leading to inconsistent implementation and limiting cross-border exchange of reclaimed water and recovered products (Berbel et al., 2023). Financial constraints further restrict adoption, particularly for small operators, with global water infrastructure investment needs estimated at $300–450 billion annually versus current investments of about $100 billion (Mannina et al., 2022). Institutional inefficiencies also persist due to weak coordination among water utilities, agriculture, and industrial sectors (Mannina et al., 2022). Public acceptance varies significantly by region, with higher acceptance in water-scarce areas and over 70% concern in water-abundant regions despite scientific evidence supporting safety (Berbel et al., 2023). Successful regulatory models in Estonia, Denmark, and parts of Australia demonstrate that clear quality standards, fit-for-purpose reuse requirements, defined risk and liability frameworks, and strong monitoring systems are critical for enabling adoption (Kostakis et al., 2025). Complementing these frameworks, circular economy indicators—based on reduction, reclamation, reuse, recycling, recovery, and rethinking—provide standardized tools to measure and track progress in circular water systems (Smol et al., 2024).

VII. COMPREHENSIVE SYNTHESIS AND FUTURE PERSPECTIVES

7.1 Integrated Framework for Wastewater-Based Circular Economy Implementation

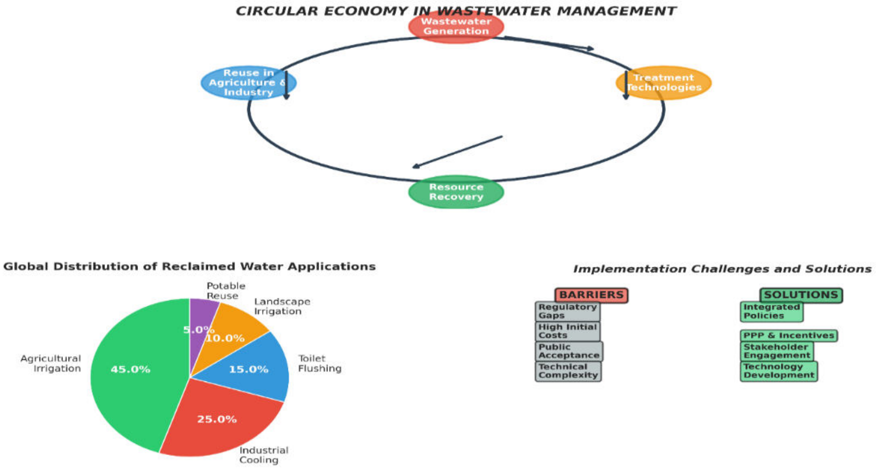

Figure 3: Integrated Circular Economy Framework for Wastewater Management: Process Flows, Reuse Applications, and Implementation Barriers with Solutions

Figure 3 presents a comprehensive framework of the wastewater-based circular economy system, integrating treatment technologies, resource recovery pathways, reuse applications, and implementation challenges.

The top panel illustrates a circular process flow comprising four stages: (1) wastewater generation from residential, commercial, and industrial sources (~359.4 billion m³ annually); (2) treatment using membrane bioreactors, advanced oxidation processes, and constructed wetlands achieving up to 95% BOD removal and 88–95% nutrient removal; (3) resource recovery via struvite crystallization, biogas production, and biochar generation with phosphorus recovery up to 98%; and (4) reuse in agriculture and industry, mainly irrigation (45%), industrial cooling (25%), and other uses, completing the resource loop (Barua, 2025). The bottom-left panel shows global reuse distribution: agricultural irrigation (45%), industrial cooling (25%), building toilet flushing (15%), landscape irrigation (10%), and potable reuse (5%), reflecting current adoption trends and technological maturity (Barua, 2025). The bottom-right panel highlights key barriers and solutions. Barriers include fragmented regulations (Berbel et al., 2023), high capital costs (€245,000–582,000) (Carvalho et al., 2025), uneven public acceptance linked to water scarcity perception (Berbel et al., 2023), and technical complexity in selecting appropriate treatment systems. Corresponding solutions include harmonized regulatory frameworks such as EU Regulation 2020/741 (Szymański, 2024), public–private partnerships and financial incentives (Barua, 2025), stakeholder engagement and participatory planning (Jain & Yadav, 2025), and continued innovation in advanced materials and hybrid treatment systems (Satyam & Patra, 2025). Overall, the framework emphasizes that successful circular economy implementation requires integrated progress across technical, regulatory, economic, and social dimensions rather than isolated technological improvements (Barua, 2025).

7.2 Emerging Technologies and Future Research Directions

Future development of wastewater-based circular economy systems requires targeted research across multiple domains, including scaling advanced oxidation processes to industrial applications while reducing energy demand, developing low-cost adsorbents and nanomaterials for emerging contaminant removal, improving microalgae-based systems under variable climatic conditions, integrating artificial intelligence and machine learning for real-time process optimization, advancing biochar and hydrochar applications for soil remediation and nutrient recovery, and strengthening regulatory frameworks to ensure safety and quality of recovered products (Satyam & Patra, 2025). In parallel, integrating life cycle assessment into technology selection and process optimization provides a robust scientific basis for minimizing environmental impacts and improving overall system sustainability (Feijoó et al., 2026). Public–private partnership models with clear performance incentives, risk-sharing mechanisms, and structured dispute resolution can further accelerate deployment and improve investment viability (Barua, 2025). At the global level, aligning wastewater circular economy strategies with the Sustainable Development Goals—particularly SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)—provides a unified framework for managing the water–energy–food nexus (Kurniawan et al., 2025). Achieving net-zero emissions will depend on integrating wastewater treatment with renewable energy systems, enhancing carbon sequestration through biochar soil application, and reducing emissions associated with synthetic fertilizer production (Yang et al., 2022). Overall, the transition to a wastewater-based circular economy represents not only a technological advancement but also a fundamental paradigm shift: from viewing wastewater as a waste stream to recognizing it as a valuable resource, from treatment plants as disposal systems to multi-output resource recovery facilities, and from fragmented water management to integrated systems supporting climate resilience, food security, and environmental restoration (Barua, 2025).

VIII. CONCLUSION

The evidence synthesized in this review demonstrates that wastewater-based circular economy (WBCE) approaches are both an environmental necessity and a significant economic opportunity, enabling concurrent progress toward water security, environmental protection, and sustainable development goals. Global wastewater streams contain substantial recoverable nutrients, energy, and water, representing a largely untapped resource base. However, realizing this potential requires coordinated advancement across technology development, regulatory reform, economic instruments, and stakeholder engagement. While advanced treatment systems, nutrient recovery technologies, and integrated resource recovery processes are technically feasible, their large-scale deployment depends on economic viability shaped by policy mechanisms that internalize environmental externalities and incentivize investment in circular infrastructure. Effective implementation must also be context-specific, adapted to local geographic, economic, and institutional conditions, while aligning with the broader objective of universal access to safely managed water and sanitation services. Overall, the transition to a wastewater-based circular economy provides a strategic pathway toward a water-secure, climate-resilient, and food-secure future, supporting multiple Sustainable Development Goals through integrated and science-driven water resource management.

REFERENCES

1. Afzal, M., Arslan, M., Younus, S., Müller, J. A., Usman, M., Yasin, M., Mehmood, M. A., Mehdi, T., Islam, E., Tauseef, M., & Iqbal, S. (2024). A nature-based closed-loop wastewater treatment system at vehicle-washing facilities: From linear to circular economy. iScience. https://doi.org/10.1016/j.isci.2024.109361
2. Aka, R. J. N., Hossain, Md. M., Nasir, A., Zhan, Y., Zhang, X., Zhu, J., Wang, Z.-W., & Wu, S. (2024). Enhanced nutrient recovery from anaerobically digested poultry wastewater through struvite precipitation by organic acid pre-treatment and seeding in a bubble column electrolytic reactor. Water Research. https://doi.org/10.1016/j.watres.2024.121239
3. Aziz, K. H. H., Mustafa, F. S., Karim, M. A. H., & Hama, S. (2025). Biochar-based catalysts: An efficient and sustainable approach for water remediation from organic pollutants via advanced oxidation processes. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2025.126245
4. Barua, S. (2025). Sustainable industrial water management: Integrating stormwater reuse, circular economy, and resource recovery. British Journal of Environmental Studies. https://doi.org/10.32996/bjes.2025.5.3.2
5. Berbel, J., Mesa-Pérez, E., & Simón, P. (2023). Challenges for circular economy under the EU 2020/741 wastewater reuse regulation. Global Challenges. https://doi.org/10.1002/gch2.202200232
6. Bermúdez, L. A., Díaz, J. C. L., Martín-Pascual, J., Mar Muñío, M. del, & Poyatos, J. M. (2022). Study of the potential for agricultural reuse of urban wastewater with membrane bioreactor technology in the circular economy framework. Agronomy. https://doi.org/https://doi.org/10.3390/agronomy12081877
7. Bermúdez, L. A., Mendoza, V. D., Díaz, J. C. O., Pascual, J. M., Mar Muñio Martínez, M. del, & Capilla, J. M. P. (2024). Investigation of the agricultural reuse potential of urban wastewater and other resources derived by using membrane bioreactor technology within the circular economy framework. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2024.177011
8. Carvalho, S., Eusébio, M., & Velizarov, S. (2025). Techno-economic and feasibility assessment of membrane-based wastewater treatment and reuse in the automotive industry. Separations. https://doi.org/10.3390/separations12020030
9. Chen, C.-Y., Wang, S.-W., Kim, H., Pan, S., Fan, C., & Lin, Y. J. (2021). Non-conventional water reuse in agriculture: A circular water economy. Water Research. https://doi.org/10.1016/j.watres.2021.117193
10. Clark, B., Sharma, N., Apraku, E., Dong, H., & Tarpeh, W. A. (2024). Ligand exchange adsorbents for selective phosphate and total ammonia nitrogen recovery from wastewaters. Accounts of Materials Research. https://doi.org/https://doi.org/10.1021/accountsmr.3c00290
11. Emeka, U. C., & Chikwendu, O. C. (2025). Circular economy in wastewater management: Water reuse and resource recovery strategies. International Journal of Latest Technology in Engineering Management &Amp; Applied Science. https://doi.org/10.51583/ijltemas.2025.140300016
12. Feijoó, H., Estévez, S., González-García, S., & Moreira, M. T. (2026). Insights into the environmental performance of nature-based wastewater technologies towards water and carbon neutrality. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2026.128657
13. Gomes, P., Pinheiro, M., Martins, J., Castro, J., Valente, T., Ribeiro, V., & Mendes, M. (2026). Circular economy: Water quality assessment for irrigation purposes in a constructed-wetland scenario. Scientific Reports. https://doi.org/10.1038/s41598-025-34161-6
14. Hafiz, N. F. H., Rahman, M., Othman, M., Jaafar, J., & Abas, K. (2024). Review on phosphorus recovery as struvite from wastewater. Key Engineering Materials. https://doi.org/10.4028/p-wipB9R
15. Islam, F. A. S. (2025). Advanced wastewater treatment technologies in addressing future water scarcity through resource recovery and reuse. Journal of Engineering Research and Reports. https://doi.org/https://doi.org/10.9734/jerr/2025/v27i51513
16. Jain, L., & Yadav, S. (2025). Circular economy in water and waste management: Sustainable strategies for conservation. Journal of Research in Environmental and Earth Sciences. https://doi.org/10.35629/2532-11041016
17. Janpum, C., Pombubpa, N., Monshupanee, T., Incharoensakdi, A., & In-na, P. (2022). Advancement on mixed microalgal-bacterial cultivation systems for nitrogen and phosphorus recoveries from wastewater to promote sustainable bioeconomy. Journal of Biotechnology. https://doi.org/10.1016/j.jbiotec.2022.11.008
18. Jones, E. R., Vliet, M. T. H. van, Qadir, M., & Bierkens, M. F. P. (2021). Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data. https://doi.org/https://doi.org/10.5194/essd-13-237-2021

19. Kanchanapiya, P., & Tantisattayakul, T. (2022). Wastewater reclamation trends in thailand. Water Science & Technology. https://doi.org/https://doi.org/10.2166/wst.2022.375

20. Kostakis, I., Papadas, D., Smol, M., & Tsagarakis, K. P. (2025). Circular economy policies for water and wastewater. Water Policy. https://doi.org/10.2166/wp.2025.077

21. Koumaki, E., Konomi, A., Gkotsis, G., Nika, M., Seintos, T., Statiris, E., Maragou, N. C., Thomaidis, N., Kouris, N., Mamais, D., Stasinakis, A., Malamis, S., Katsou, E., & Noutsopoulos, C. (2025). Circular water management in agriculture: Screening of contaminants of emerging concern in a real-world water-soil-crop system and human health risk assessment. Journal of Hazardous Materials. https://doi.org/10.1016/j.jhazmat.2025.138167

22. Kurniawan, T. A., Bustos-Terrones, Y., Loaiza, J. G., Dissanayake, K., Onn, C. W., Abass, K. S., Jumaniyozov, K., Oktriono, K., Wong, W. K., Kusworo, T., Zhang, D., & Kusuma, H. S. (2025). Applying nutrient recovery from unused wastewater to overcome fertilizer shortage for global food security. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2025.127543

23. Liu, B., Knopf, A., Watts, M. J., Payne, E. M., & Linden, K. G. (2025). Improving water quality for inland potable reuse via O3/biologically active filtration followed by UV/advanced oxidation. Water Reuse. https://doi.org/10.2166/wrd.2025.023

24. Liu, W., Qian, J., Ding, H., Li, J., Liu, J., & Zhou, W. (2024). Synergistic interactions of light and dark biofilms in rotating algal biofilm system for enhanced aquaculture wastewater treatment. Bioresource Technology. https://doi.org/10.1016/j.biortech.2024.130654

25. Mannina, G., Gulhan, H., & Ni, B. (2022). Water reuse from wastewater treatment: The transition towards circular economy in the water sector. Bioresource Technology. https://doi.org/10.1016/j.biortech.2022.127951

26. Masjoudi, M., & Mohseni, M. (2023). Photolysis of chloramines in vacuum-UV and vacuum-UV/chlorine advanced oxidation processes for removal of 1,4-dioxane: Effect of water matrix, kinetic modeling, and implications for potable reuse. Journal of Hazardous Materials. https://doi.org/10.1016/j.jhazmat.2023.131454

27. Mayor, Á., Vinardell, S., Ganesan, K., Bacardí, C., Cortina, J., & Valderrama, C. (2023). Life-cycle assessment and techno-economic evaluation of the value chain in nutrient recovery from wastewater treatment plants for agricultural application. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2023.164452

28. Mazik, A., Stanek, P., Malczewska, B., & Lochyński, P. (2025). Towards circular economy solutions: Managing wastewater from paint production. Sustainability. https://doi.org/10.3390/su172310515

29. Mbavarira, T., & Grimm, C. (2021). A systemic view on circular economy in the water industry: Learnings from a belgian and dutch case. Sustainability. https://doi.org/https://doi.org/10.3390/su13063313

30. Morillas-España, A., López-Serna, R., Chikri, L. Y. R., Jiménez, J. J., Lafarga, T., Uggetti, E., Acién, G., & González-López, C. (2025). Microalgae wastewater treatment: Pharmaceutical removal and biomass valorization. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2025.124942

31. Ni, L., Wang, P., Westerhoff, P., Luo, J., Wang, K., & Wang, Y. (2024). Mechanisms and strategies of advanced oxidation processes for membrane fouling control in MBRs: Membrane-foulant removal versus mixed-liquor improvement. Environmental Science and Technology. https://doi.org/10.1021/acs.est.4c02659

32. Odibo, A., Janpum, C., Pombubpa, N., Monshupanee, T., Incharoensakdi, A., Rehman, Z. ur, & In-na, P. (2024). Microalgal-bacterial immobilized co-culture as living biofilters for nutrient recovery from synthetic wastewater and their potential as biofertilizer. Bioresource Technology. https://doi.org/10.1016/j.biortech.2024.130509

33. Osman, A. I., Hosny, M., Eltaweil, A. S., Omar, S., Elgarahy, A. M., Farghali, M., Yap, P., Wu, Y. S., Nagandran, S., Batumalaie, K., Gopinath, S. C. B., John, O. D., Sekar, M., Saikia, T., Karunanithi, P., Hatta, M. H. M., & Akinyede, K. A. (2023). Microplastic sources, formation, toxicity and remediation: A review. Environmental Chemistry Letters. https://doi.org/https://doi.org/10.1007/s10311-023-01593-3

34. Paliaga, S., Muscarella, S., Alduina, R., Badalucco, L., Fischer, P. T. B., Leto, Y. D., Gallo, G., Gaglio, R., Mineo, A., Laudicina, V. A., & Mannina, G. (2025). Resource recovery from wastewater treatment: Effects of water reuse and slow-release fertilizers on faba bean within palermo university (italy) case study. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2024.123839

35. Polak, D. W., Kamocki, S., & Szwast, M. (2025). Evaluation of the potential of metal–organic compounds ZIF-8 and F300 in a membrane filtration–adsorption process for the removal of antibiotics from water. Antibiotics. https://doi.org/10.3390/antibiotics14060619

36. Qadir, M., Drechsel, P., Jiménez, B., Kim, Y., Pramanik, A., Mehta, P., & Olaniyan, O. (2020). Global and regional potential of wastewater as a water, nutrient and energy source. Natural Resources Forum. https://doi.org/https://doi.org/10.1111/1477-8947.12187

37. Satyam, S., & Patra, S. (2025). The evolving landscape of advanced oxidation processes in wastewater treatment: Challenges and recent innovations. Processes. https://doi.org/10.3390/pr13040987

38. Shrivastava, V., & Laasri, I. (2025). Nutrient recovery strategies and agronomic performance in circular farming: A comprehensive review. Nitrogen. https://doi.org/10.3390/nitrogen6030080

39. Singh, B. J., Chakraborty, A., & Sehgal, R. (2023). A systematic review of industrial wastewater management: Evaluating challenges and enablers. Journal of Environmental Management. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.119230

40. Smol, M., Mejía, A., Gastaldi, M., & D'Adamo, I. (2024). Environmental indicators for assessment of circular economy (CE) implementation in the water and wastewater sector. Business Strategy and the Environment. https://doi.org/10.1002/bse.4090

41. Śniatała, B., Al-Hazmi, H., Sobotka, D., Zhai, J., & Mąkinia, J. (2024). Advancing sustainable wastewater management: A comprehensive review of nutrient recovery products and their applications. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2024.173446

42. Stankiewicz, K., Boroń, P., Prajsnar, J., Żelazny, M., Heliasz, M., Hunter, W., & Lenart-Boroń, A. (2024). Second life of water and wastewater in the context of circular economy - do the membrane bioreactor technology and storage reservoirs make the recycled water safe for further use? Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2024.170995

43. Szymański, K. (2024). Reuse of treated municipal wastewater for the production of water for agriculture. Rocznik Ochrona Srodowiska. https://doi.org/10.54740/ros.2024.059

44. Thi, M. P., & Bui, X. D. (2025). Selection enhanced nutrient removal from pig farm wastewater using co-immobilized chlorella vulgaris and azospirillum brasilense Azo09 in alginate beads. European Journal of Biology and Biotechnology. https://doi.org/10.24018/ejbio.2025.6.2.541

45. Tshangana, C., & Muleja, A. A. (2023). Graphene oxide quantum dots membrane: A hybrid filtration-advanced technology system to enhance process of wastewater reclamation. Chemical Papers. https://doi.org/https://doi.org/10.1007/s11696-023-03187-3

46. Umetani, I., Sposób, M., & Tiron, O. (2023). Indigenous green microalgae for wastewater treatment: Nutrient removal and resource recovery for biofuels and bioproducts. Bioenergy Research. https://doi.org/10.1007/s12155-023-10611-9

47. Vivas, M. A. U., Seguí-Amórtegui, L., Pérez, C. T., & Rojas, H. G.-G. (2023). Technical–economic evaluation of water reuse at the WWTP el salitre (bogotá, colombia): Example of circular economy. Water. https://doi.org/10.3390/w15193374

48. Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. (2022). Circular economy strategies for combating climate change and other environmental issues. Environmental Chemistry Letters. https://doi.org/https://doi.org/10.1007/s10311-022-01499-6

49. Zhang, C., Yuan, R., Chen, H., Zhou, B., Cui, Z., & Zhu, B. (2024). Advancements in inorganic membrane filtration coupled with advanced oxidation processes for wastewater treatment. Molecules. https://doi.org/10.3390/molecules29174267

50. Zhang, G., Li, W., Li, D., Wang, S., & Lv, L. (2024). Integration of ammonium assimilation with denitrifying phosphorus removal for efficient nutrient management in wastewater treatment. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2024.120116

51. Zhang, M., Han, F., Li, Y., Liu, Z., Chen, H., Li, Z., Li, Q., & Zhou, W. (2021). Nitrogen recovery by a halophilic ammonium-assimilating microbiome: A new strategy for saline wastewater treatment. Water Research. https://doi.org/10.1016/j.watres.2021.117832