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Circular economy approaches to promote sustainable wastewater treatment: A mini-review

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ABSTRACT

Circular economy (CE) has emerged as a sustainable policy framework adopted by many countries to reduce waste generation through the application of the 5R principles: reuse, recycle, recovery, reclamation, and reduce. This mini-review summarizes recent studies on the application of circular economy approaches in wastewater treatment, highlighting their potential contributions to sustainable development through resource conservation, waste minimization, and pollution reduction. CE-based wastewater treatment systems can also support climate change mitigation by improving energy efficiency and enabling energy recovery, while contributing to ecosystem protection through reduced pollutant discharge and the promotion of closed-loop material flows. This review discusses representative circular economy models for recovering water, valuable materials, and energy from wastewater, and outlines key strategies to address current limitations while strengthening opportunities for implementation. Overall, the integration of circular economy principles into wastewater treatment is emphasized as a promising pathway toward more sustainable and resilient water management systems.

Keywords: circular economy, sustainability, wastewater treatment, resource recovery.

INTRODUCTION

Water constitutes a critical resource underpinning a wide spectrum of human activities, including domestic consumption, agricultural irrigation, industrial manufacturing, and energy production. Despite these advancements, the world is facing an escalating water scarcity crisis. Estimates indicate that by 2025, nearly two-thirds of the global population will encounter water stress, and around 1.8 billion people will live under conditions of severe water scarcity (Boubakri, 2024). Exacerbating this issue, over 80% of wastewater is released into the environment without proper treatment, and in many developing regions, this figure rises to more than 95%. Untreated wastewater represents a significant source of environmental degradation, contributing to pollution, the spread of aquatic diseases, and an increase in emissions of greenhouse gas (Palanisami, 2024).

Water scarcity and pollution have emerged as critical global challenges, prompting governments, industries, and other stakeholders to adopt more sustainable approaches to water management. Consequently, the development of effective and sustainable water management practices has gained strategic importance worldwide, fostering innovation across multiple water-related sectors. These efforts are particularly relevant in wastewater management and treatment, where reducing the degradation of aquatic ecosystems and enhancing environmental sustainability are primary objectives. The

Sustainable Development Goals emphasize the need to ensure access to water and sanitation through integrated and effective water resource management, encompassing the entire hydrological cycle, from water conservation and efficient use to wastewater treatment and ecosystem protection. Within this broader framework, the CE has been increasingly recognized as a promising approach for addressing environmental challenges and supporting sustainable development. The core principles of the CE focus on redesigning systems and processes to eliminate waste and pollution, maintain materials and products in continuous use, and promote the regeneration of natural ecosystems.

Wastewater treatment plants (WWTPs) have considerable potential to support the transition toward a circular economy. In addition to providing an alternative source of water, these facilities can serve as hubs for the recovery of valuable resources, including energy and nutrients. For instance, nutrients contained in wastewater can be recovered and reused in agricultural applications, thereby reducing reliance on synthetic fertilizers. The circular economy offers a practical framework for redesigning systems and processes in line with sustainability principles. This paradigm represents a fundamental shift in resource management, moving away from the traditional take-make-dispose model toward more regenerative and sustainable systems. Within this context, wastewater recycling plays a crucial role in improving resource efficiency and unlocking the full potential of circular economy strategies in water and wastewater management.

Accordingly, this mini-review aims to synthesize and discuss the existing literature on the interconnections between the circular economy, wastewater treatment, and sustainability. Specifically, it explores the role of the circular economy as a strategic framework for enhancing sustainability in wastewater treatment and supporting progress toward the sustainable development goals (SDGs). Growing concerns related to sustainability and resource efficiency have intensified global interest in circular economy approaches within the wastewater sector. In this context, the review highlights representative circular economy models for resource management that focus on waste minimization, material recovery and recycling, process efficiency, and the creation of economic value in industrial and urban water systems.

CIRCULAR ECONOMY AS A PATH TO SUSTAINABLE DEVELOPMENT

The CE offers an alternative development paradigm aimed at minimizing waste generation while creating high-value products through a life-cycle perspective on goods and services (Bakır and Aral, 2025). Rather than focusing solely on end-of-life waste management, CE emphasizes systemic changes in production and consumption patterns to improve resource efficiency and environmental performance. Recent studies indicate that circular economy principles can be adapted across different regional and sectoral contexts. For example, in Central Asia, including Kazakhstan, circular business models have been proposed for integration into the construction value chain, supported by regulatory frameworks, infrastructure investment, collaborative platforms, and pilot initiatives.

Growing resource overconsumption and accelerating environmental degradation have prompted many countries, particularly in Europe, to transition from the traditional linear economy model toward circular economy approaches (Androniceanu et al., 2021; Bakır and Aral, 2025). This transition is widely recognized as a means to reduce environmental pressures, enhance raw material security, improve competitiveness, and stimulate innovation, economic growth, and employment. In addition, consumers are expected to benefit from increased access to more sustainable and innovative products, contributing to improved quality of life and long-term economic savings. Consequently, the circular economy is increasingly viewed as a strategic pathway toward sustainable development, supporting national well-being and raising overall societal living standards.

Sustainable development aims to balance social equity, environmental protection, and economic prosperity. These three interrelated pillars, including environmental sustainability, social inclusiveness, and economic viability, form the foundation of contemporary sustainability frameworks (Eelager et al., 2025). The United Nations Sustainable Development Goals (SDGs), illustrated in Figure 1, provide an integrated framework encompassing 17 interconnected goals that address multiple dimensions of sustainability. Many of these goals align closely with circular economy principles, particularly in relation to resource efficiency, waste reduction, and

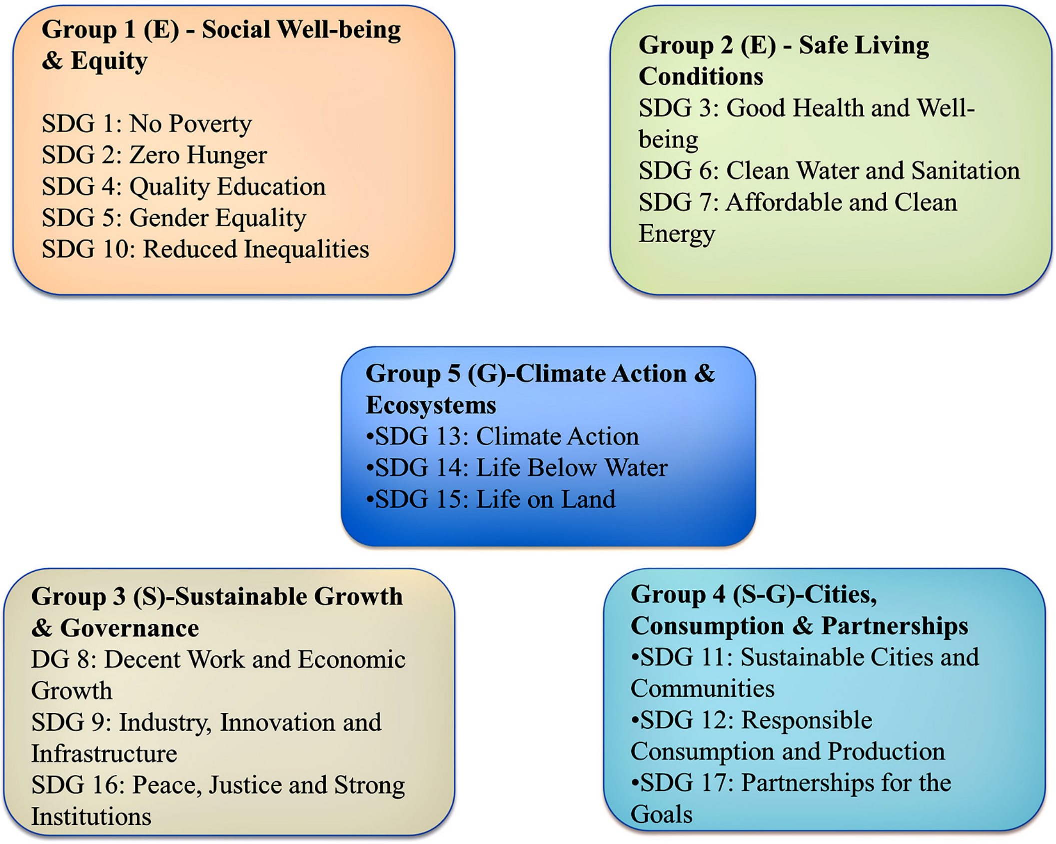

Figure 1. Integrated SDGs Framework for Sustainable Development (SDGs). Redrawn and modified by the authors

sustainable management practices, thereby reinforcing the role of the circular economy as a key enabler of sustainable development.

Building on the role of the circular economy as a pathway to sustainable development, recent studies increasingly frame CE as a transformative paradigm for sustainable production and consumption. By prioritizing waste prevention and resource efficiency across the entire life cycle of products and services, CE contributes directly to environmental protection and broader sustainability objectives. Several conceptual frameworks have been proposed to operationalize circular economy principles in waste management systems. As illustrated in Figure 2 (Monfared et al., 2025), these frameworks commonly distinguish between strategies focused on intelligent production and use, product and component life extension, and material recovery. Together, these stages highlight how circular economy principles support the achievement of the Sustainable Development Goals through integrated resource management.

Complementary frameworks emphasize the application of the 5R principles, including reduce, reuse, recycle, recovery, and reclamation as key operational strategies for circular economy implementation (Aslan et al., 2025; Sharma et al., 2020), as shown in Figure 3. These principles illustrate pathways for transforming waste into valuable resources, including energy and materials. Figure 4 synthesizes the operational integration of circular economy principles within wastewater treatment systems. The figure illustrates wastewater treatment plants as central nodes in a closed-loop system, where wastewater generation and collection are followed by sequential treatment stages (primary, secondary, and advanced treatment), enabling the recovery of valuable resources such as reclaimed water, nutrients (nitrogen and phosphorus), and energy (biogas and heat). These recovered resources are subsequently reused across agricultural, industrial, and urban non-potable applications, thereby reducing dependence on virgin resources and minimizing environmental burdens. The feedback loop depicted in the figure emphasizes the role of reuse and recycling in decreasing residual waste generation and enhancing environmental protection, ultimately reinforcing the circularity of wastewater management systems. In this context, wastewater treatment shifts from

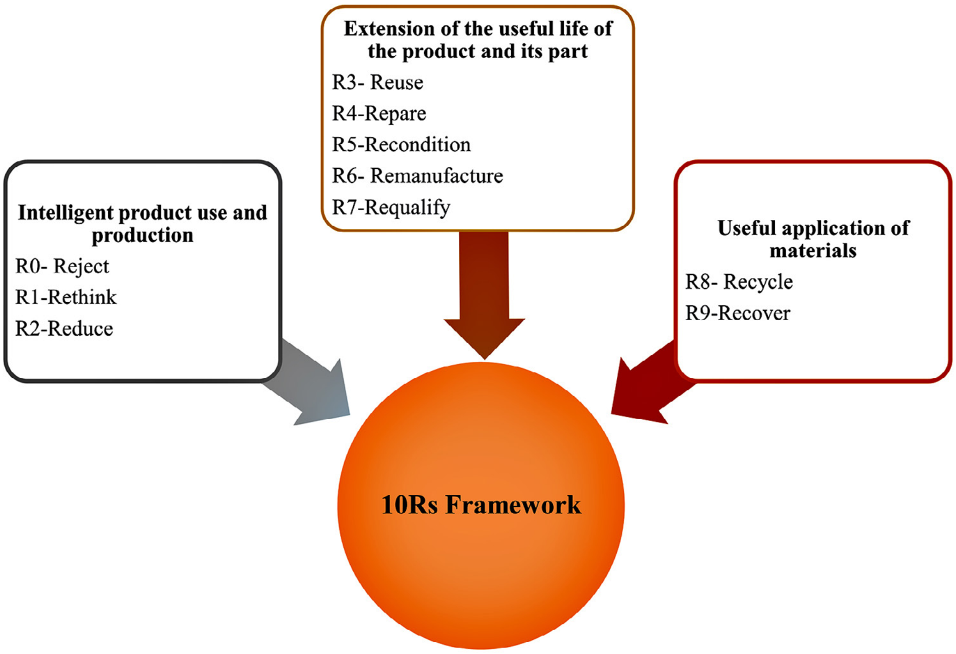

Figure 2. The circular economy approach following 10R

Figure 3. The circular economy approach following 5R

a pollution control function toward a resource-oriented and sustainability -driven system aligned with circular economy objectives.

Figure 5 provides a strategic perspective on the relationship between circular economy implementation and sustainability outcomes. While sustainability represents the overarching objective of long-term environmental, social, and economic balance, the circular economy functions as an enabling mechanism that operationalizes this objective through efficient resource management and system integration. The figure highlights the alignment between circular economy practices and the SDGs, emphasizing that progress toward these goals depends not only on technological solutions but also on

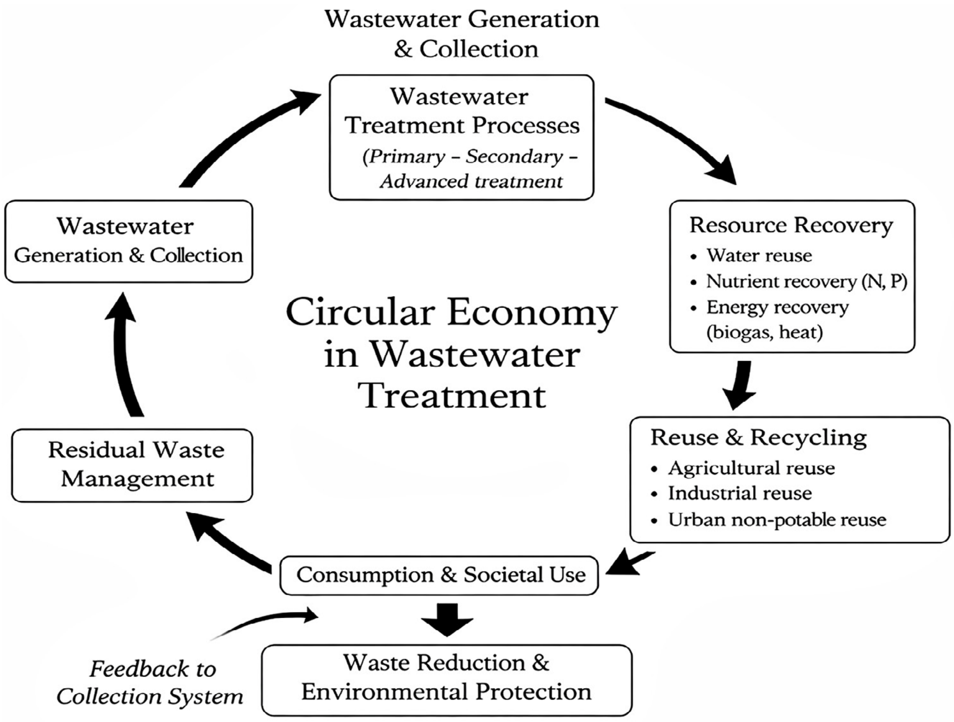

Figure 4. Framework of circular economy in wastewater treatment system

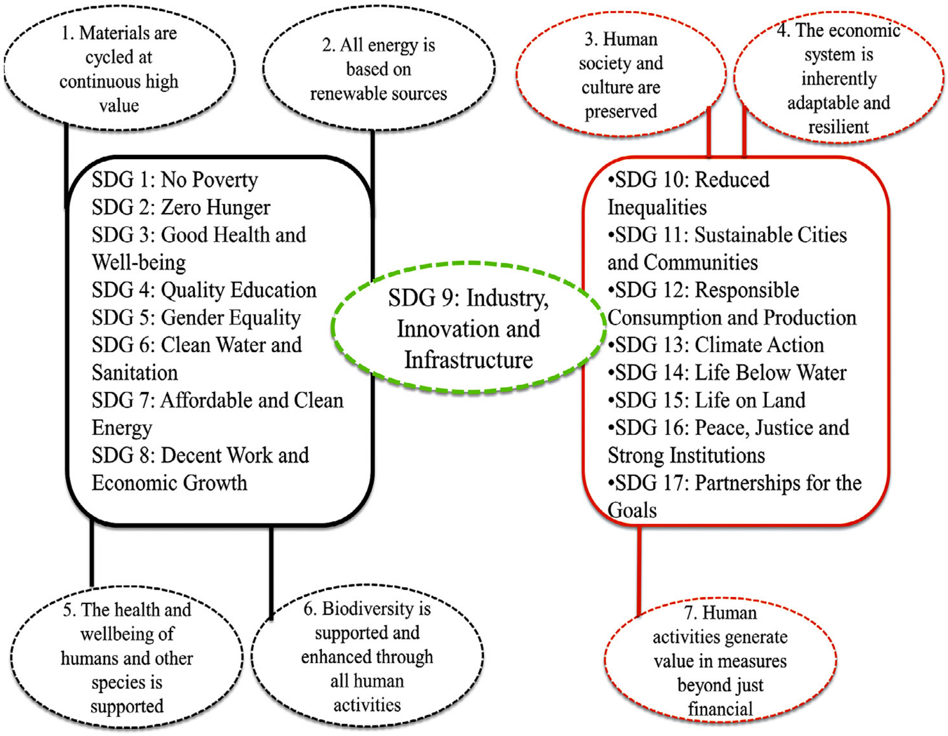

Figure 5. Synergizing between the 17 sustainable development goals (SDGs) of sustainability and the 7 pillars of the circular economy for a greener future

governance structures, policy frameworks, and multi-stakeholder engagement. In particular, SDG 17 underscores the importance of partnerships among governments, industries, and communities to scale up circular strategies and translate localized circular initiatives, such as circular wastewater management, into broader sustainability impacts (Eelager et al., 2025).

OVERVIEW OF THE APPLICATION OF CIRCULAR ECONOMY FOR THE WASTEWATER TREATMENT PLAN

Role of circular economy toward wastewater treatment plants to drive sustainable development

The CE is increasingly recognized as a suitable framework for transforming WWTPs from end-of-pipe facilities into resource recovery hubs that contribute to sustainable development. Within this context, wastewater treatment plays a strategic role by enabling the recovery of water, nutrients, and energy, thereby reducing environmental pressures and enhancing resource efficiency. By prioritizing resource reclamation, WWTPs can be better integrated into surrounding natural and socio-economic systems, supporting a transition toward more sustainable water management practices.

Decentralized wastewater treatment systems have attracted growing attention as a practical approach for implementing CE principles at the local scale. Compared with centralized infrastructure, decentralized systems located closer to wastewater generation points can reduce energy and water demands associated with transport while facilitating the reuse of treated effluent within communities. This localized integration supports the formation of closed water loops, decreases reliance on conventional freshwater sources, and enhances system resilience, particularly in water-scarce regions. Reclaimed wastewater thus represents a viable alternative water resource that can alleviate pressure on natural water bodies and contribute to their long-term protection (Bermejo-Campos and García-Avila, 2025).

From a circular economy perspective, WWTPs also serve as platforms for recovering valuable materials embedded in wastewater streams. Sewage sludge contains significant quantities of nitrogen, phosphorus, and organic matter, which can be transformed into fertilizers, soil conditioners, or energy carriers, thereby generating both environmental and economic benefits (Hernández-Chover et al., 2023). Water reclamation processes enable treated effluent to be reused for non-potable purposes such as irrigation, industrial operations, and urban applications, while nutrient recovery technologies facilitate the reintegration of essential elements into agricultural and industrial cycles. In parallel, the conversion of organic matter into biogas through anaerobic digestion contributes to renewable energy production and reduces reliance on fossil fuels.

Advances in treatment and recovery technologies have further strengthened the role of WWTPs within circular economy systems. Membrane-based processes, including reverse osmosis and nanofiltration, have expanded the potential for producing reclaimed water of suitable quality for diverse applications. At the same time, emerging nutrient recovery and energy recovery technologies continue to improve the efficiency and feasibility of resource extraction from wastewater. Collectively, these developments reduce dependence on finite resources and mitigate the environmental impacts associated with wastewater discharge.

Practical implementations reported in the literature demonstrate the feasibility of applying CE principles in wastewater management. For example, large-scale water reuse initiatives and energy recovery programs illustrate how WWTPs can simultaneously address water scarcity, energy demand, and environmental protection. Such examples highlight the broader applicability of circular strategies rather than serving as isolated case-specific solutions. For example, Practical studies offer concrete demonstrations of how wastewater treatment supports circular economy principles. Singapore's NEWater initiative is a notable example, showcasing effective resource recovery and the large-scale production of high-quality reclaimed water. By purifying wastewater to ultra-clean standards, the project provides recycled water for both industrial applications and drinking purposes. Similarly, the Netherlands' Energy Factory converts wastewater into biogas via anaerobic digestion, producing renewable energy that supplies the surrounding community.

Looking ahead, wastewater treatment is expected to play an increasingly important role in advancing circular economy objectives. Ongoing technological innovation, growing awareness of resource efficiency, and supportive regulatory frameworks are likely to accelerate the adoption of circular practices in wastewater management. As a result, WWTPs are poised to make a more substantial contribution to sustainable resource management and the broader goals of sustainable development. As conceptually summarized in Figure 6, the integration of circular economy principles into wastewater treatment generates multiple co-benefits across environmental,

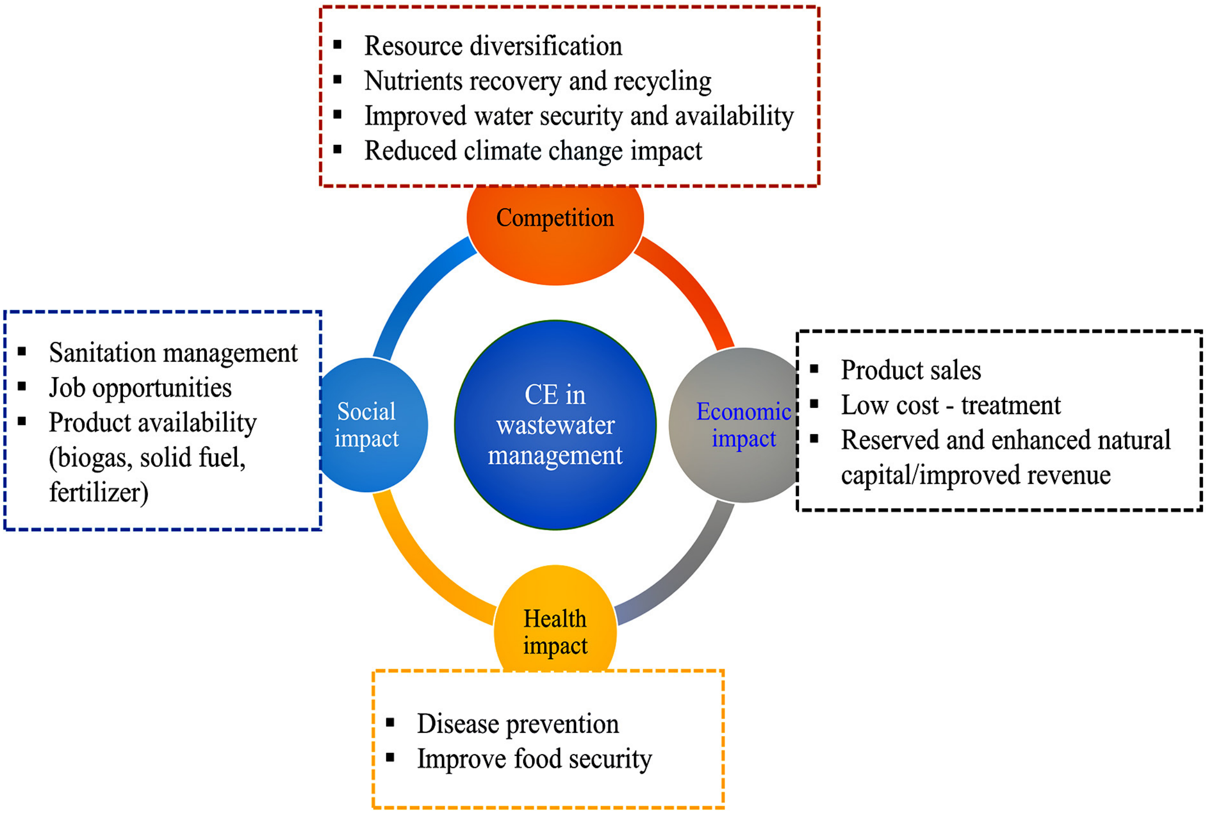

Figure 6. Drivers of the circular economy approach in wastewater management

social, health, and economic dimensions, reinforcing the strategic importance of wastewater management within circular and sustainable development pathways.

Opportunities and challenges of the circular economy in wastewater treatment

While previous section conceptualizes the circular economy as a key enabling framework for achieving sustainability and the SDGs, its practical realization ultimately depends on how circular principles are operationalized within specific sectors. Among these, wastewater treatment represents a particularly critical domain, where circular strategies can simultaneously address environmental protection, resource recovery, and system resilience. In this section, we examines the opportunities and challenges associated with implementing circular economy principles in wastewater treatment systems, with a focus on technological pathways, systemic limitations, and emerging research gaps.

Wastewater treatment constitutes a pivotal opportunity for advancing CE implementation, as it enables the recovery and reuse of valuable resources embedded within waste streams. Traditionally perceived primarily as a disposal challenge, wastewater systems have undergone a conceptual shift driven by technological advancements and innovative treatment processes. Increasingly, wastewater is recognized as a strategic reservoir of recoverable resources, including water, energy, nutrients, and other value-added compounds. Harnessing these resources supports sustainable development objectives, enhances resource efficiency, and contributes to the development of more resilient and adaptive environmental systems (Bermejo-Campos and García-Avila, 2025; Cairone et al., 2024).

Within this context, the circular economy-oriented resource recovery facility (RRF) concept, illustrated in Figure 7, represents a representative model for operationalizing CE principles in wastewater treatment. Beyond conventional contaminant removal from domestic, industrial, and agricultural effluents, RRFs emphasize the integrated recovery of clean water, energy, and nutrients, thereby transforming wastewater treatment plants into multifunctional hubs for resource generation (Bohra et al., 2022; Južnič-Zonta et al., 2022). Existing studies indicate that embedding CE principles into wastewater treatment systems can improve operational efficiency while simultaneously delivering environmental and economic benefits (Hernández-Chover et al., 2023).

Empirical evidence further demonstrates the feasibility of circular approaches in practice. For instance, reclaimed water currently supplies approximately 40% of Singapore's total water demand, with projections indicating continued growth in the future (Kog, 2020). Technological innovations, particularly the integrated application of membrane-based processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, have played a central role in enabling high-quality water reuse. By combining complementary treatment processes, these technologies help overcome the limitations of individual units, reduce energy consumption, and enhance overall treatment efficiency (Shehata et al., 2023). Such advances underscore the technical viability of CE-driven wastewater systems.

Despite these opportunities, significant challenges remain in translating circular economy concepts into system-wide and scalable wastewater management solutions. Figure 8 presents a bibliometric network analysis that reveals three major thematic clusters in CE-related wastewater research. The first cluster (yellow) focuses on pollution control, water resource management, and environmental-economic interactions, encompassing keywords such as adsorption, climate change, biomass, and water pollution. The second cluster (green) centers on treatment technologies and assessment tools, including anaerobic digestion, nutrient recovery, and life cycle assessment. The third cluster (blue) highlights core conceptual themes, including circular economy, sustainable development, and wastewater treatment, reflecting the theoretical grounding of CE principles within the field.

However, the network structure also exposes critical systemic gaps. A pronounced techno-centric bias is evident, as technological solutions such as adsorption and anaerobic digestion dominate the research landscape, while socio-institutional dimensions receive comparatively limited attention. Concepts related to governance, policy frameworks, business models, system integration, and stakeholder engagement are weakly represented, suggesting that technological investments have outpaced the development of enabling institutional and social mechanisms. Moreover, explicit linkages between CE practices and SDG implementation, particularly water-related goals such as SDG 6 and broader water security objectives, remain limited. The weak connectivity between sustainability-oriented concepts (blue cluster) and climate-change-related terms (yellow cluster) further indicates a fragmented approach to addressing interlinked sustainability challenges.

These gaps pose substantial barriers to the scalability and long-term effectiveness of circular economy-based wastewater solutions. While nutrient recovery and water resource management are frequently addressed, their integration with socioeconomic factors, rural contexts, and behavioral change dynamics remains insufficient. As summarized in Table 1, the application of CE principles in wastewater treatment offers considerable opportunities but is constrained by technical, economic, institutional, and governance-related challenges. Addressing these barriers is essential for accelerating adoption and enhancing the overall performance of circular wastewater systems (Bermejo-Campos and García-Avila, 2025; Jha and Dubey, 2024). Collaboration and active stakeholder participation, therefore, emerge as critical enablers for advancing CE implementation in wastewater treatment plants (Moshawih et al., 2025). Effective circular transitions require coordinated action among government agencies,

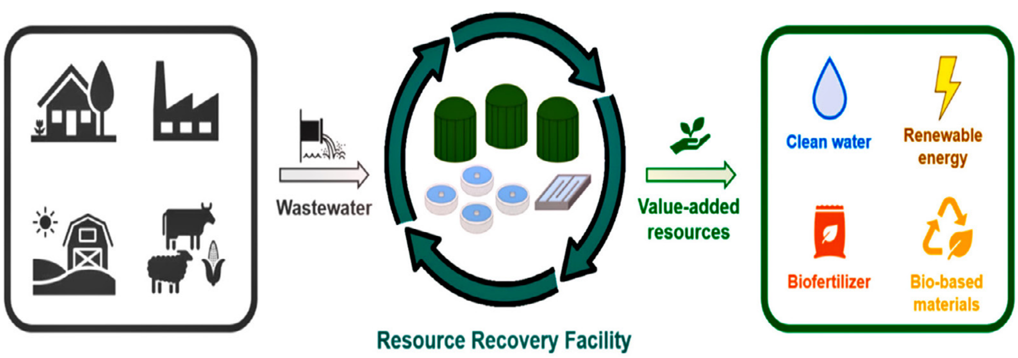

Figure 7. Concept towards sustainable resource recovery facility (Cairone et al., 2024), copyright permission from the publisher

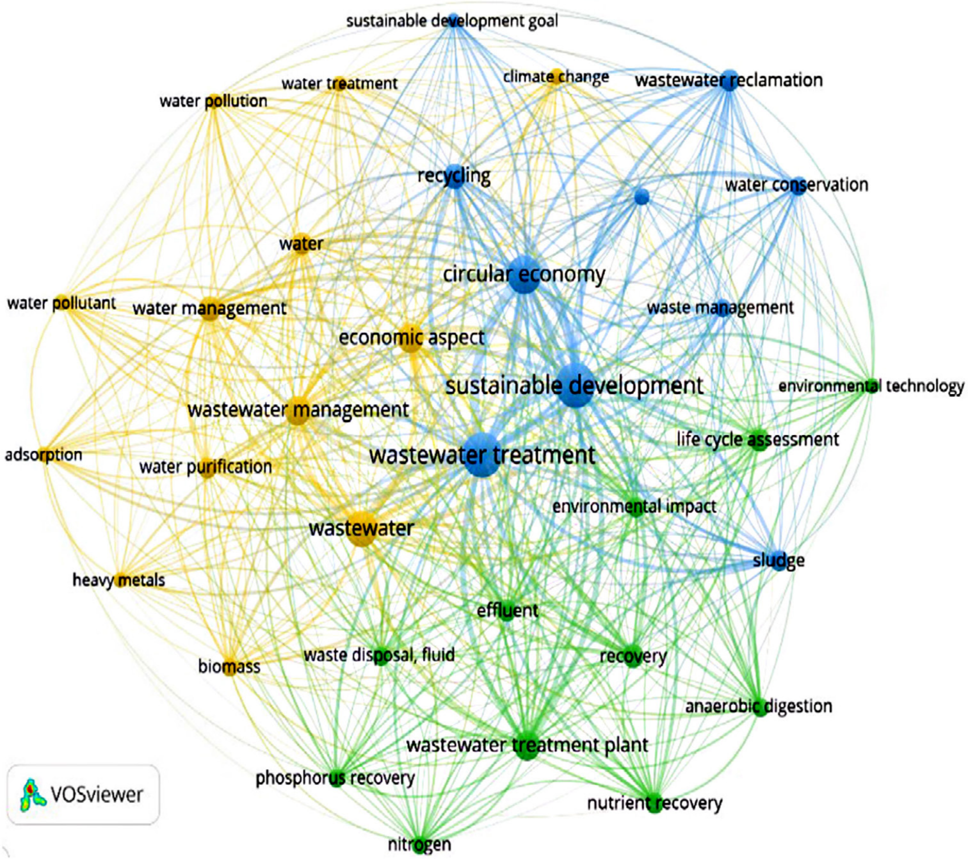

Figure 8. The system of main factors in circular economy research related to wastewater treatment (Bermejo-Campos and García-Avila, 2025), copyright permission from the publisher

industrial operators, and local communities to co-design sustainable management strategies. Such partnerships facilitate technological uptake, support the development of enabling policies, and strengthen monitoring and enforcement mechanisms. Nevertheless, divergent interests, limited financial resources, and institutional fragmentation continue to hinder collaboration, underscoring the need for integrated governance frameworks and aligned stakeholder objectives.

MODEL OF THE CIRCULAR ECONOMY APPLIED IN WASTEWATER TREATMENT PLANT

The model of the circular economy in a wastewater treatment plant in Vietnam

In Vietnam, wastewater reuse remains underdeveloped despite its significant potential as a secondary resource within a circular economy framework. Limited regulatory guidance, insufficient monitoring mechanisms, and the absence of wastewater reuse considerations during project planning and appraisal have constrained broader implementation (Hoang Thi Thu Hương*, 2023). Nevertheless, several pioneering initiatives illustrate how circular economy principles can be practically embedded in wastewater treatment systems.

One representative example is the wastewater reuse model implemented at a cassava starch production facility in Tay Ninh Province, Vietnam, as illustrated in Figure 9. This model demonstrates how industrial wastewater can be reintegrated into agricultural production systems through controlled reuse pathways. Compared with a baseline scenario, the adoption of wastewater reuse resulted in an estimated 40% reduction in groundwater abstraction, highlighting its potential contribution to local water security. Treated effluent is stored in biological ponds and subsequently reused for agricultural irrigation after dilution to ensure compatibility with crop requirements. In this context, reclaimed wastewater functions not only as an alternative water source but also as a carrier of nutrients, thereby

Table 1. Opportunities and challenges associated with resource recovery processes within wastewater treatment systems

Process	Input stream	Main product	Opportunities	Challenges	References
Conventional activated Sludge process	Wastewater	Treated water	Effective removal of organics; Can treat varieties of wastewater	Excess sludge generation; Sensitive to the influent flow rate	(Brucculeri et al., 2005)
Sequencing batch reactors	Wastewater	Treated water; Bio-gas (if anaerobic)	Effective for decentralized wastewater treatment; Ability to handle extremely high organic and hydraulic shock loads	Excess sludge generation; Complex Operation and Control	(Bermejo-Campos and García-Avila, 2025)
Membrane bioreactors	Wastewater	High-quality treated water	Reduced sludge generation; Effective for decentralized wastewater treatment	Membrane fouling; High capital cost of installation	(Bermejo-Campos and García-Avila, 2025)
Anaerobic digestion	Wastewater, Microalgae, Sewage sludge	Treated water, Biogas, Digestate	Renewable energy production; Reduced sludge generation	Process control; Sensitivity to toxic substances; Nutrient imbalance	(Uddin and Wright, 2023)
Constructed wetlands	Wastewater	Treated water; Biomass	Low energy requirements; Cost-effective decentralized wastewater treatment	Efficiency varies with the climate conditions and seasonal changes	(Parde et al., 2021)
Algal-mediated wastewater treatment	Wastewater	Treated water; Microalgae	Carbon sequestration; Renewable energy production	Harvesting and dewatering of algal biomass; Sensitive to certain contaminants	(Bhatt et al., 2022)
Bioelectrochemical systems	Wastewater	Treated water; Bioenergy; Biochemicals	Carbon sequestration; Renewable energy production; Environment friendly	Scaling-up; Low power density	(Ghangrekar et al., 2022)
Advanced oxidation process	Wastewater	Treated water	Effective removal of recalcitrant pollutants; Minimization of harmful byproducts; Versatility i.e. non-selective oxidation	Safety considerations; High energy consumption; Scaling-up	(Saúco et al., 2021)
Hybrid wastewater treatment	Wastewater	Treated water	Comprehensive treatment; Resource recovery; Improved treatment efficiency	Complexity; Maintenance; Site-specific consideration	(Djandja et al., 2023)
Hydrothermal carbonization	Algae; Sewage sludge	Biochar	Carbon sequestration; Biofuel; Waste valorisation	Economic viability; Scaling-up; Environmental impact assessment	(Djandja et al., 2023)
Transesterification	Algal lipids	Biodiesel	Renewable energy	Economic viability	(Mandari and Devarai, 2022)

reducing dependence on synthetic fertilizers and supporting resource circularity (Nguyen Thanh Nam, 2020). Beyond industrial settings, treated urban domestic wastewater can also be reused for a range of non-potable applications, including irrigation, street cleaning, toilet flushing, fire-fighting water storage, and the rehabilitation of urban rivers and lakes, as conceptually illustrated in Figure 10. In addition, managed aquifer recharge using appropriately treated wastewater represents a strategic option to mitigate groundwater depletion, land subsidence, and saltwater intrusion in urban areas. However, despite these technical possibilities, the large-scale adoption of wastewater reuse remains constrained by socio-economic and institutional barriers. Public acceptance is limited due to concerns regarding health risks and environmental safety, while technical complexity and cost considerations further hinder implementation (Tran Duc Ha, 2023). These challenges underscore the need for supportive regulatory frameworks, risk communication strategies,

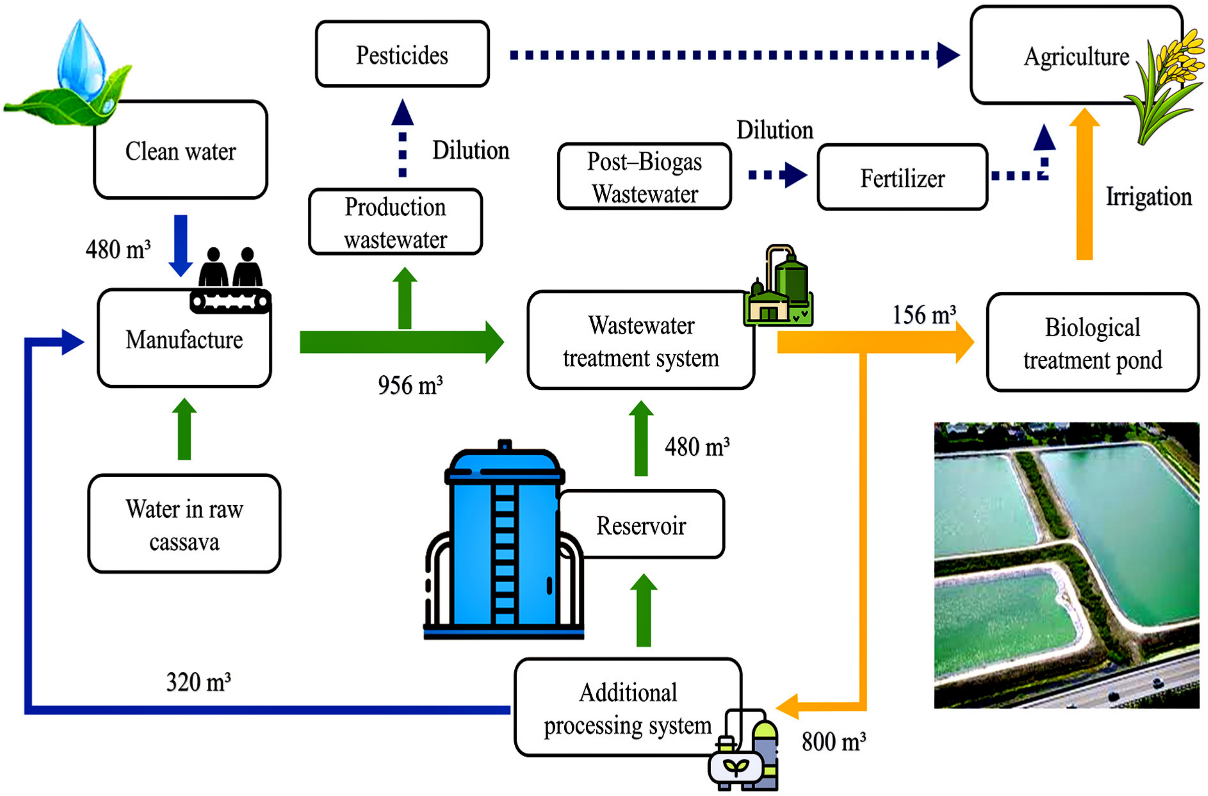

Figure 9. Wastewater reuse of Xuan Hong cassava starch production factory

and integrated planning approaches to enable the broader application of circular economy models in wastewater management.

The circular economy model in wastewater treatment in the world

Globally, CE models in wastewater treatment have evolved from disposal-oriented systems toward integrated frameworks that emphasize water reuse, resource recovery, and value creation. Rather than representing isolated national practices, these models reflect transferable approaches that combine technological innovation, regulatory support, and risk management to enhance water security and sustainability under increasing pressures from population growth and climate change.

One dominant circular economy pathway at the global scale is the implementation of water reuse-driven wastewater management models. Countries such as the United States and Singapore have progressively developed advanced treatment technologies and regulatory frameworks that enable the safe reuse of treated wastewater for non-potable and, in some cases, potable applications. These approaches demonstrate how wastewater can be repositioned as a strategic water resource, provided that stringent quality control and monitoring mechanisms are in place to safeguard public health and environmental integrity (Bermejo-Campos and García-Avila, 2025).

The wastewater management model in the United States, illustrated in Figure 11, exemplifies a large-scale, decentralized-to-centralized reuse framework in which treated municipal wastewater is reused for urban activities, agricultural irrigation, and environmental enhancement. Recent regulatory developments, particularly in water-stressed regions such as California, further highlight the transition toward potable water reuse as a climate adaptation strategy. By integrating advanced treatment and regulatory oversight, this model reduces reliance on conventional freshwater sources and strengthens long-term water resilience under drought conditions (Nga, 2023).

Singapore represents a highly centralized and technologically advanced circular economy model for wastewater reuse, as shown in Figure 12. Facing severe water scarcity, the country has invested extensively in research and development to establish an integrated water management system in which reclaimed wastewater, known as NEWater, plays a critical role. Advanced membrane filtration and disinfection processes enable the production of

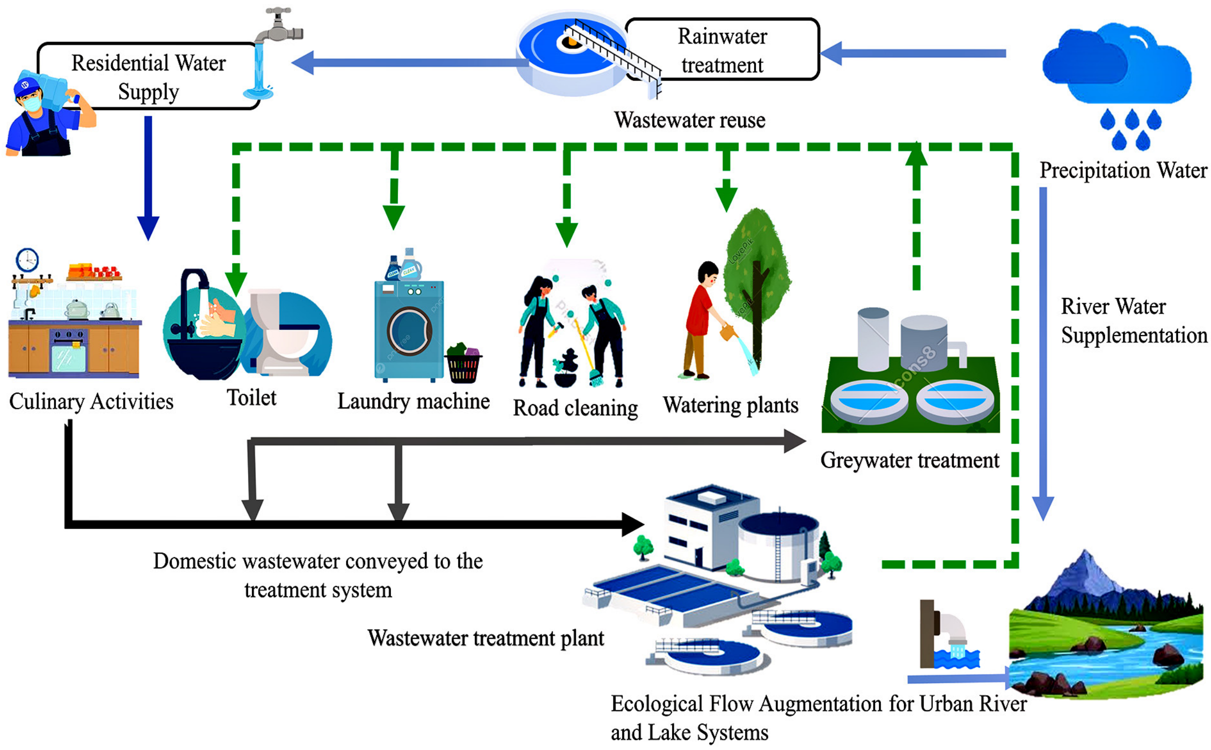

Figure 10. Integrated model for sustainable urban water management

high-quality reclaimed water that is primarily supplied to industrial users and strategically blended into potable water reservoirs. This model demonstrates how strong governance, public communication, and technological reliability can collectively support the acceptance and scalability of potable water reuse. Reclaimed water currently meets 40% of Singapore's water demand and is expected to increase to 55% by 2060, according to the national water agency. While most reclaimed water is used for industrial purposes, a portion is blended into the potable water supply through the country's reservoirs, serving its population of 5.7 million. The final product, known as NEWater, is primarily supplied to industrial facilities and is also conveyed to artificial reservoirs to augment the potable water supply during dry seasons. The reclaimed water undergoes an additional round of treatment before being distributed to households (Phuong, 2023).

Beyond water reuse, another important global circular economy pathway in wastewater treatment focuses on the valorization of sewage sludge and wastewater-derived microalgae as bioresources. As illustrated in Figure 13, these biomass streams can be processed through biorefinery-based approaches to generate a wide range of value-added products, including bioenergy carriers, biopolymers, enzymes, and soil conditioners. Sewage sludge, in particular, contains recoverable resources such as biochar, methane, bio-oil, and biohydrogen, which contribute to renewable energy production, carbon sequestration, and improved soil quality (Capodaglio, 2023). Anaerobic digestion further enables the generation of polyhydroxyalkanoates (PHAs) and volatile fatty acids, supporting the production of environmentally sustainable bioplastics (Semaha et al., 2023). Converting sludge into construction materials further supports circular economy goals, providing a sustainable outlet for sludge management while ensuring compliance with safety standards. Recovering valuable resources from wastewater, sewage sludge, and microalgae provides an integrated framework for generating renewable materials while simultaneously delivering significant environmental benefits (Gherghel et al., 2019).

In addition to bioenergy and bioproduct recovery, wastewater-derived materials can be incorporated into construction materials, adsorbents, and functional components for wastewater treatment systems, as illustrated in Figure 14. Biochar produced from sludge and other waste streams has gained increasing attention for its application as an adsorbent, membrane material, and electrode component in advanced treatment technologies (Leong et al., 2021). Furthermore,

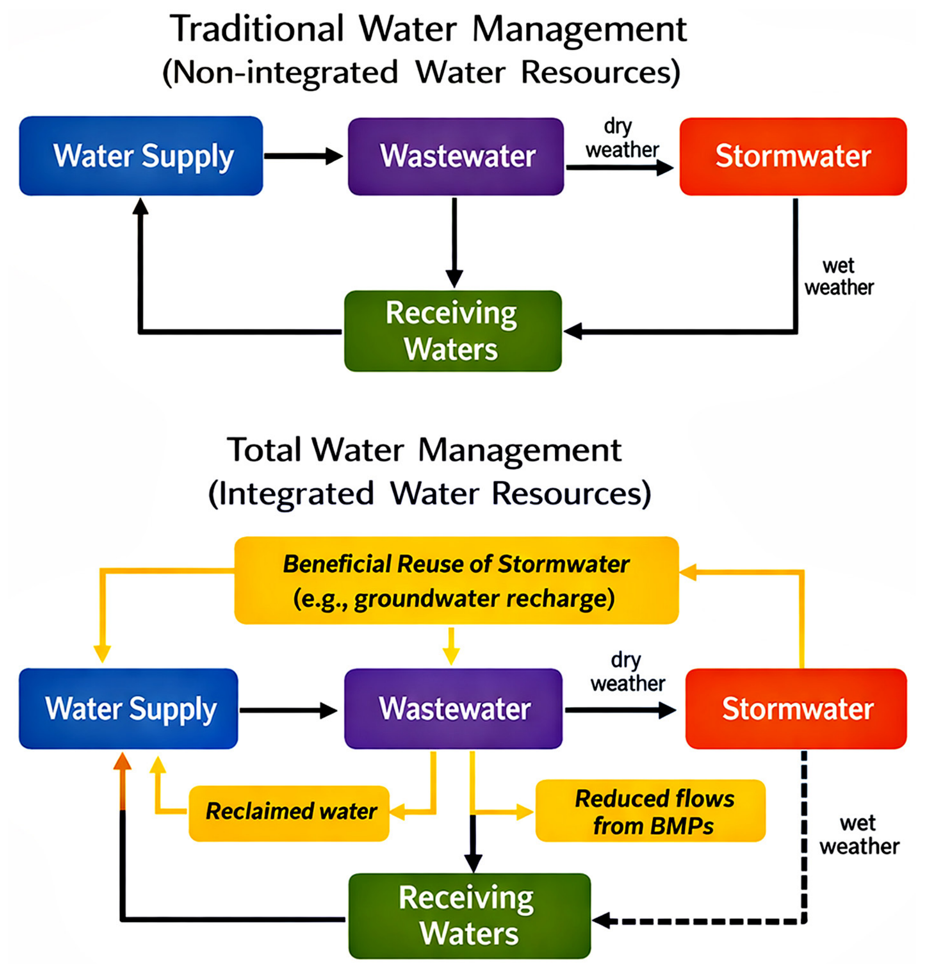

Figure 11. Wastewater management model in the United States

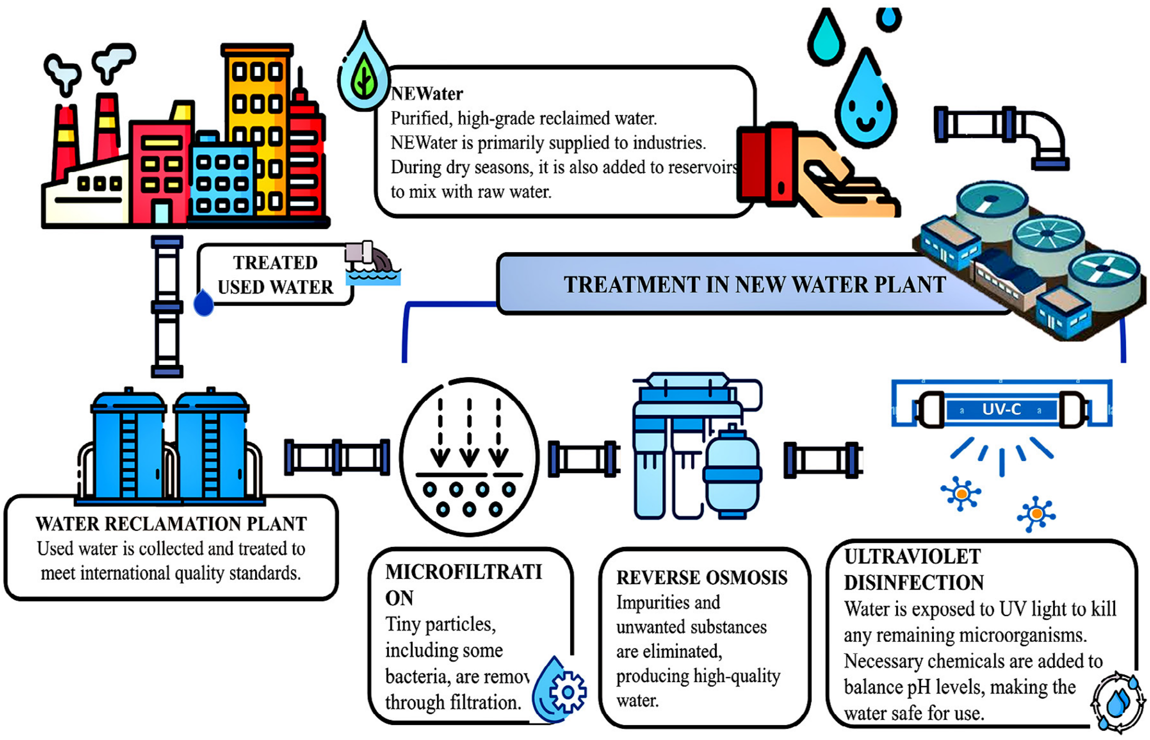

Figure 12. Wastewater management model in Singapore

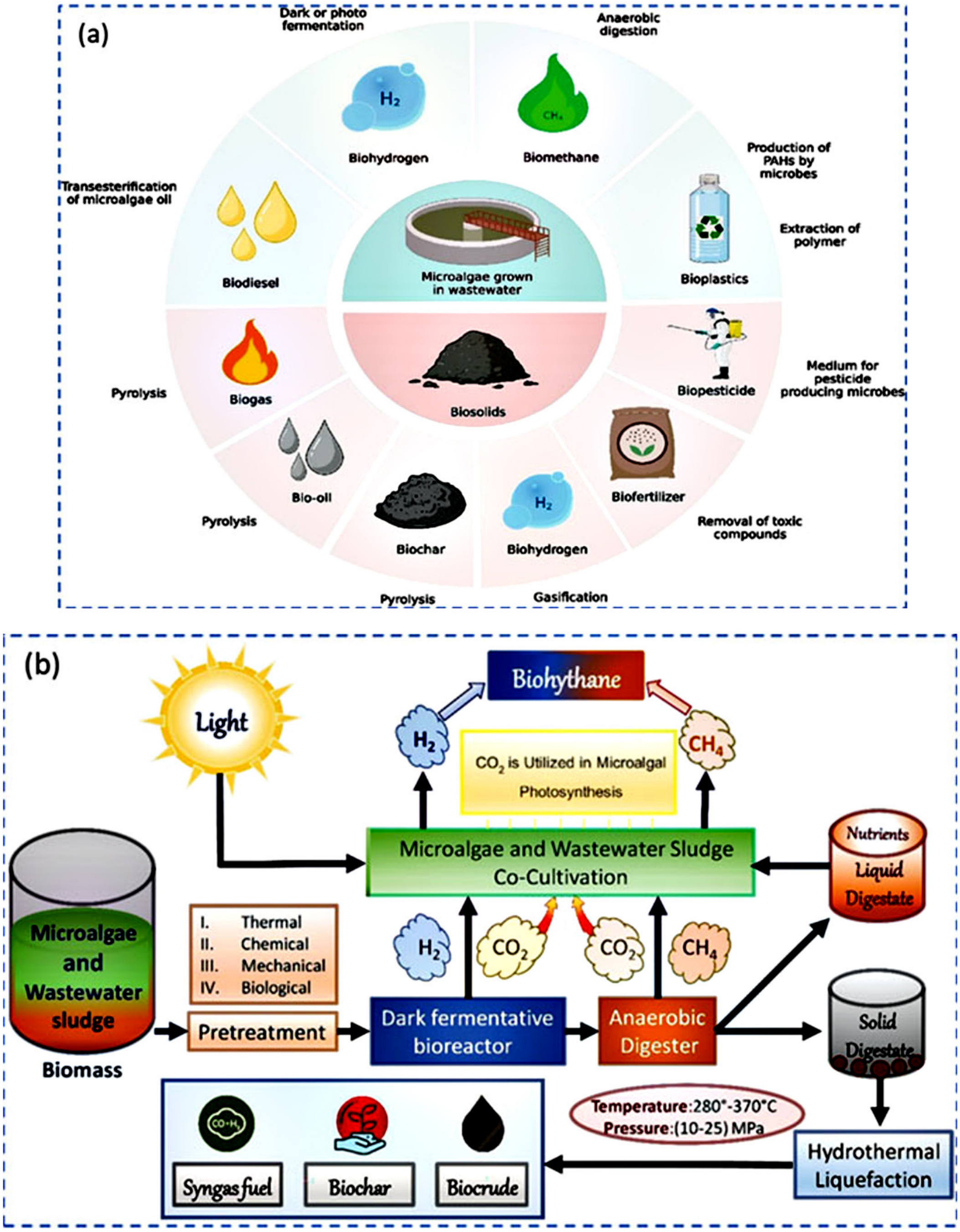

Figure 13. Opportunities of resource recovery from microalgae and sewage sludge: (a) potential energy products and valuable products; (b) biorefinery demonstrations (Kabir et al., 2022; Waikar and Sadgir, 2023), copyright permission from the publisher

the reuse of dried sludge-derived materials in biological treatment processes has shown potential for enhancing system performance during start-up phases (Sellamuthu et al., 2021). However, the large-scale implementation of material valorization pathways requires a comprehensive assessment of treatment efficiency, contaminant accumulation, economic feasibility, and environmental impacts to ensure safe and sustainable reuse (Baskar et al., 2022; Maged et al., 2023). Overall, these global circular economy models demonstrate that wastewater treatment can function as a multifunctional platform for water reuse, bioresource recovery, and material valorization. Despite differences in scale, technological maturity, and regulatory contexts, successful implementation consistently depends on the integration of advanced treatment technologies with supportive

Figure 14. Production process of valuable materials from wastewater treatment plant (Hossain et al., 2020), copyright permission from the publisher

governance frameworks, economic viability, and public acceptance. These shared characteristics provide valuable insights for the broader adoption of circular economy principles in wastewater management and inform the concluding discussion on key enablers, remaining challenges, and future research directions.

CONCLUSIONS

A systematic assessment conducted in this study demonstrates that adopting a circular economy (CE) framework in wastewater treatment plants has strong potential to reshape conventional wastewater management practices. Wastewater can be regarded as a valuable source of water, energy, and recoverable materials that may be reintegrated into multiple sectors. In particular, the recovery of nitrogen and phosphorus not only provides essential inputs for agricultural fertilizers but also mitigates the unsustainable extraction of finite natural resources. The analysis reveals notable gaps related to governance, public policy, social engagement, and business model development, while technological solutions continue to receive disproportionate attention. This imbalance highlights the necessity of interdisciplinary collaboration to address the complex technical, social, and environmental dimensions of wastewater treatment systems. Integrative circular economy approaches can generate environmental benefits through pollution mitigation and resource recovery, economic value through the production of value-added by-products, and social benefits by supporting sustainable practices and enhancing community well-being. Overall, this review provides consolidated insights for infrastructure managers and policymakers, emphasizing the importance of rethinking wastewater treatment systems through a circular economy perspective. With existing technological capabilities, wastewater treatment plants can achieve higher-quality effluent while increasing resource recovery, thereby supporting the sustainability of urban water cycles and contributing to broader societal well-being.

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