

Circular Economy Approaches in Water Treatment

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ABSTRACT

Water treatment sector traditionally follows a linear model where water is extracted, treated, used and discharged as waste. This approach creates high energy demand, sludge generation and resource loss. Circular economy (CE) principles provide an alternative pathway by promoting water reuse, nutrient recovery, energy generation and material recycling within treatment systems. The concept integrates wastewater as a resource rather than waste, supporting sustainability and reducing environmental footprint. This paper reviews circular economy approaches in water treatment, including resource recovery technologies, decentralized reuse systems, energy-positive wastewater treatment plants, sludge valorization and industrial symbiosis. Emerging technologies such as membrane recovery, bio-electrochemical systems, and nature-based treatment solutions are discussed. Case examples demonstrate how CE can reduce operational costs and environmental impacts while enhancing water security. Challenges such as regulatory gaps, technological limitations and social acceptance are also highlighted. The review concludes that circular water treatment systems are essential for sustainable urban and industrial water management, though policy support and innovation scaling are needed for full implementation.

KEYWORDS: *Circular economy, water treatment, wastewater reuse, resource recovery, sludge valorization, sustainable water management*

INTRODUCTION

Water scarcity and pollution are becoming major global concerns due to population growth, industrialization and climate change. Conventional water treatment systems are mainly designed for contaminant removal and safe discharge, but they neglect recovery of valuable resources present in wastewater such as nutrients, energy and water itself. This linear model results in waste generation and inefficient resource utilization.

Circular economy (CE) concept aims to close resource loops by minimizing waste and maximizing reuse and recovery. In water sector, CE promotes transformation of wastewater treatment plants into resource recovery facilities. Instead of treating wastewater as a disposal problem, it is considered a source of water, energy and nutrients. This transition supports sustainability goals and reduces environmental pressures.

Adoption of circular economy in water treatment involves multiple strategies such as water recycling, sludge reuse, energy recovery and industrial water loops. Municipal wastewater contains organic matter, nitrogen, phosphorus and thermal energy, which can be converted into useful products like fertilizers, biogas and reclaimed water. Industrial effluents also contain recoverable chemicals and metals.

This paper presents a comprehensive review of circular economy approaches in water treatment systems. Technologies, applications, benefits, limitations and future perspectives are examined to provide a holistic understanding of circular water management.

CONCEPT OF CIRCULAR ECONOMY IN WATER TREATMENT

Circular economy (CE) in water treatment refers to a systemic approach where wastewater is not treated only for disposal, but considered as a valuable resource containing reusable water, nutrients and energy. Instead of the conventional “use and discharge” pattern, CE aims to close material and energy cycles within water infrastructure. This shift transforms wastewater treatment plants into **water resource recovery facilities (WRRFs)** that contribute to sustainable resource management.

The circular approach is based on three interlinked loops: water loop, nutrient loop and energy loop. These loops are connected because wastewater simultaneously contains water, organic

matter and dissolved nutrients. Effective circular systems try to recover all three, maximizing resource efficiency and minimizing environmental losses.

Traditional wastewater treatment mainly focuses on contaminant removal through physical, biological and chemical processes. Although these processes produce cleaner effluent, they also generate sludge that contains concentrated nutrients and organic matter. In linear systems this sludge is disposed in landfill or incinerated, resulting in resource loss and environmental burden. Circular systems instead recover these materials and reintroduce them into productive use cycles.

Water Loop – Reuse and Recycling of Treated Water

The water loop aims to retain water within the human use cycle for as long as possible before final discharge to the environment. Wastewater, after appropriate treatment and polishing, can serve as an alternative water source for various applications.

Water reuse may occur at different scales:

- **Direct reuse** – treated wastewater supplied directly for irrigation, cooling or industrial processes
- **Indirect reuse** – treated water discharged to rivers or aquifers and later abstracted
- **On-site reuse** – local recycling in buildings or communities

In circular systems, water quality is matched with end-use requirements. For example, irrigation or flushing does not require potable-quality water. This principle, called **fit-for-purpose treatment**, reduces energy and treatment cost.

Benefits of water loop include:

- Reduction of freshwater abstraction
- Decrease in wastewater discharge volume
- Improved water security in urban areas
- Climate resilience in water-scarce regions

Urban circular water systems often combine wastewater reuse with rainwater harvesting and stormwater capture to create integrated local water cycles.

Table: 1

Aspect	Linear Model	Circular Model
Water use	Single use	Multiple reuse cycles
Sludge	Waste disposal	Resource recovery
Energy	External consumption	Energy generation
Nutrients	Lost in sludge	Fertilizer recovery
Environmental impact	High	Reduced

Circular water treatment integrates treatment, recovery and reuse processes into a closed-loop system.

RESOURCE RECOVERY FROM WASTEWATER

Wastewater is not only a polluted stream that needs treatment before discharge, but it also contains large amount of recoverable resources including water, nutrients, organic matter and thermal energy. In traditional wastewater management these resources are mostly lost during treatment and sludge disposal. Circular economy approaches instead aim to extract and reuse them, converting wastewater treatment plants into resource recovery hubs.

Municipal and industrial wastewater together represent a continuous and renewable source of water, nitrogen, phosphorus, carbon and energy. Recovering these resources reduces pressure on natural reserves such as freshwater bodies, fossil fuels and mined fertilizer minerals. At the same time it improves economic viability of treatment plants by creating valuable outputs.

Resource recovery from wastewater generally focuses on three main streams: reclaimed water, nutrient products and bioenergy. Each of these recovery pathways requires suitable treatment technologies and quality control measures to ensure safe reuse.

Water Reuse and Recycling

Water reuse is the most direct and widely adopted form of wastewater resource recovery. After proper treatment, wastewater can serve as an alternative water supply for non-potable and sometimes potable uses. Reclaimed water helps reduce freshwater withdrawal from rivers, lakes and groundwater aquifers, which is especially important in water-scarce regions.

The level of treatment required depends on intended reuse purpose. Primary and secondary treated effluent may be sufficient for some irrigation applications, while high-quality reuse such as industrial process water or indirect potable reuse requires advanced polishing steps.

Common advanced treatment technologies for water reuse include:

- Membrane filtration (microfiltration, ultrafiltration, reverse osmosis)
- Activated carbon adsorption
- UV or ozone disinfection
- Advanced oxidation processes

These technologies remove pathogens, suspended solids, dissolved salts and trace contaminants, producing safe reclaimed water.

Water reuse can be categorized into different scales:

Agricultural reuse:

Treated wastewater used for crop irrigation is one of the oldest reuse practices. Nutrients remaining in reclaimed water also reduce fertilizer demand.

Industrial reuse:

Industries require large volumes of water for cooling, washing and processing. Reclaimed water can substitute freshwater in these operations after appropriate treatment.

Urban non-potable reuse:

Cities increasingly reuse treated wastewater for toilet flushing, street cleaning, parks irrigation and landscaping. Dual plumbing systems are sometimes installed to supply reclaimed water separately.

Groundwater recharge:

Highly treated wastewater can be infiltrated into aquifers to replenish groundwater resources. This method also provides natural filtration through soil layers.

Water reuse creates a local circular water loop, where water remains within urban or industrial systems for multiple cycles before eventual environmental discharge. This approach enhances water security and reduces dependence on distant water sources.

Nutrient Recovery

Municipal wastewater contains significant quantities of nitrogen and phosphorus originating from human excreta, food residues and cleaning products. These nutrients are essential for agricultural productivity but are conventionally removed in treatment plants to prevent eutrophication of receiving waters. However, conventional removal transfers nutrients into sludge, where they are often wasted during disposal.

Circular economy promotes recovery of nutrients in concentrated and usable forms, converting wastewater into a renewable fertilizer source. Nutrient recovery is particularly important for phosphorus because global phosphate rock reserves are finite and unevenly distributed geographically. Recovering phosphorus from wastewater can contribute to long-term food security.

Several technologies are used for nutrient recovery:

Struvite precipitation:

Magnesium, ammonium and phosphate ions react to form struvite crystals (magnesium ammonium phosphate). These crystals can be harvested and used as slow-release fertilizer. Struvite recovery also prevents scaling problems in pipelines and digesters.

Ammonia stripping and absorption:

Ammonia is removed from wastewater or sludge liquor by raising pH and temperature, converting ammonium to gaseous ammonia. The gas is captured in acid solution to produce ammonium salts suitable as fertilizers.

Ion exchange:

Selective resins or natural zeolites capture ammonium or phosphate ions from wastewater. The nutrients are later recovered by regeneration of the media.

Membrane nutrient concentration:

Processes such as nanofiltration or membrane distillation concentrate nutrients into smaller volumes, enabling fertilizer production.

Biological nutrient recovery:

Algae cultivation or microbial biomass production incorporates nutrients into organic biomass

that can be used as soil amendment or biofertilizer.

Nutrient recovery closes the urban-agricultural nutrient loop. Nutrients consumed in cities through food return to agricultural land instead of being lost in water bodies or landfills. This reduces dependency on synthetic fertilizers and decreases environmental pollution.

Energy Recovery

Wastewater contains chemical energy stored in biodegradable organic compounds. Conventional aerobic treatment oxidizes this organic matter using aeration, which consumes large electricity input. Circular energy recovery instead captures this energy through anaerobic or bioelectrochemical processes before it is lost as heat or CO₂.

Anaerobic digestion is the most widely applied energy recovery technology. In this biological process, microorganisms break down organic matter in absence of oxygen, producing biogas composed mainly of methane and carbon dioxide. Methane is a renewable fuel that can replace fossil energy.

Anaerobic digestion is applied to:

- Primary sludge
- Waste activated sludge
- High-strength industrial wastewater
- Organic co-substrates such as food waste

Biogas produced can be used in several ways:

- Electricity generation via gas engines or turbines
- Heat production for digester and plant operations
- Combined heat and power (CHP) systems
- Upgrading to biomethane for vehicle fuel or grid injection

With improved digestion efficiency and energy recovery systems, many wastewater treatment plants are approaching energy neutrality, meaning they generate as much energy as they consume. Some advanced facilities even export surplus electricity.

Additional emerging energy recovery technologies include:

Microbial fuel cells (MFC):

Electroactive bacteria convert organic matter directly into electricity while treating wastewater.

Microbial electrolysis cells (MEC):

These systems produce hydrogen gas from wastewater organics using small external voltage.

Thermal energy recovery:

Wastewater leaving buildings often carries heat. Heat exchangers installed in sewer networks or treatment plants can capture this thermal energy for space heating.

Energy recovery not only reduces operational costs but also lowers greenhouse gas emissions by replacing fossil fuels. It transforms wastewater treatment from an energy-intensive service into a renewable energy generator.

SLUDGE VALORIZATION APPROACHES

Sewage sludge is often considered waste but contains organic carbon and nutrients. Circular economy promotes sludge valorization instead of disposal.

Compost and Fertilizer Production

Stabilized sludge can be converted into compost or soil conditioner. Nutrients improve soil fertility and structure.

Benefits:

- Reduces landfill disposal
- Returns nutrients to soil
- Improves agriculture productivity

Biochar Production

Thermal treatment of sludge produces biochar, a carbon-rich material used for soil amendment and pollutant adsorption.

Biochar benefits include:

- Carbon sequestration

- Soil moisture retention
- Heavy metal immobilization

Construction Material Recovery

Sludge ash can be used in:

- Bricks
- Cement
- Aggregates

This reduces raw material extraction and supports circular construction.

ENERGY-POSITIVE WASTEWATER TREATMENT PLANTS

Conventional wastewater treatment consumes large energy for aeration and pumping. Circular systems aim to generate more energy than consumed.

Anaerobic Treatment Systems

Anaerobic reactors treat wastewater while producing methane. Compared to aerobic systems, they require less energy and generate biogas.

Common technologies:

- Upflow Anaerobic Sludge Blanket (UASB)
- Anaerobic Membrane Bioreactor (AnMBR)
- Anaerobic Lagoons

Bio-Electrochemical Systems

Microbial fuel cells (MFC) and microbial electrolysis cells (MEC) convert organic matter directly into electricity or hydrogen.

Advantages:

- Simultaneous treatment and energy generation
- Low sludge production
- Potential for decentralized treatment

DECENTRALIZED AND NATURE-BASED CIRCULAR SYSTEMS

Centralized treatment systems require large infrastructure and energy. Decentralized and nature-based solutions support circular water reuse locally.

Constructed Wetlands

Wetlands mimic natural purification processes using plants, microbes and soil. Treated water can be reused locally.

Benefits:

- Low energy demand
- Habitat creation
- Nutrient recovery in biomass

Greywater Recycling Systems

Household greywater from sinks and showers can be treated onsite and reused for flushing or irrigation.

This reduces freshwater demand and wastewater load on centralized plants.

Urban Water Loop Systems

Circular cities integrate rainwater harvesting, wastewater reuse and stormwater management into closed loops.

Urban circular water cycle:

Freshwater → Use → Wastewater → Treatment → Reuse → Reduced Discharge

INDUSTRIAL CIRCULAR WATER SYSTEMS

Industries consume large water volumes and produce contaminated effluents. Circular approaches include water reuse and material recovery.

Industrial Water Reuse

Treated effluent can be reused for:

- Cooling
- Process water

- Cleaning operations

This reduces freshwater withdrawal and discharge fees.

Chemical and Metal Recovery

Industrial wastewater may contain recoverable substances such as:

- Heavy metals
- Salts
- Organic solvents

Recovery technologies:

- Membrane separation
- Electrochemical recovery
- Crystallization

Industrial symbiosis occurs when waste from one industry becomes resource for another.

EMERGING CIRCULAR TECHNOLOGIES IN WATER TREATMENT

Technological innovation is driving circular economy adoption.

Membrane Resource Recovery

Membrane filtration allows selective recovery of water and solutes.

Examples:

- Forward osmosis
- Nanofiltration
- Membrane distillation

These enable high-quality water reuse and nutrient concentration.

Algae-Based Treatment Systems

Microalgae absorb nutrients and CO₂ from wastewater.

Biomass can be used for:

- Biofuel
- Animal feed
- Fertilizer

This closes nutrient and carbon cycles.

Thermal Energy Recovery

Wastewater carries heat from domestic and industrial use. Heat exchangers recover thermal energy for buildings.

Benefits:

- Reduces heating energy demand
- Improves plant energy efficiency

BENEFITS OF CIRCULAR ECONOMY IN WATER TREATMENT

Circular water treatment offers environmental, economic and social benefits.

Environmental Benefits

- Reduced water extraction
- Lower pollution discharge
- Nutrient recycling
- Energy generation
- Reduced greenhouse gas emissions

Economic Benefits

- Lower operational costs
- Resource recovery revenue
- Reduced sludge disposal cost
- Energy savings

Social Benefits

- Improved water security

- Sustainable agriculture
- Job creation in resource recovery sector

CHALLENGES IN IMPLEMENTATION

Despite advantages, circular water treatment faces several challenges.

Technical Challenges

- High capital cost of advanced recovery technologies
- Membrane fouling and maintenance
- Variable wastewater composition

Regulatory Barriers

- Lack of reuse standards in many regions
- Restrictions on sludge reuse
- Limited incentives for resource recovery

Social Acceptance

Public perception of wastewater reuse (especially potable reuse) can be negative. Education and awareness are essential.

CASE EXAMPLES OF CIRCULAR WATER TREATMENT

Case 1: Energy-Neutral Wastewater Plant

Municipal plant integrated anaerobic digestion and biogas recovery, producing electricity exceeding plant demand.

Case 2: Industrial Water Loop

Textile industry reused treated effluent for dyeing processes, reducing freshwater consumption by 60%.

Case 3: Nutrient Recovery Facility

Struvite precipitation system recovered phosphorus fertilizer from municipal wastewater sludge.

FUTURE PERSPECTIVES

Circular economy in water treatment is expected to expand due to water scarcity and sustainability goals.

Future directions include:

- Integration of digital monitoring and AI optimization
- Decentralized modular treatment units
- Zero-liquid-discharge industrial systems
- Carbon-neutral wastewater plants
- Resource recovery markets

Transition from wastewater treatment plants to **water resource recovery facilities** will define future water management.

CONCLUSION

Circular economy approaches in water treatment represent a paradigm shift from waste disposal to resource recovery. Wastewater contains valuable water, nutrients, energy and materials that can be reused within closed loops. Technologies such as anaerobic digestion, nutrient recovery, membrane filtration and nature-based treatment enable circular water systems. These approaches reduce environmental impacts, conserve resources and improve sustainability of water infrastructure. However, implementation barriers including cost, regulation and social perception must be addressed. Policy support, technological innovation and stakeholder awareness are necessary for large-scale adoption. Circular water treatment systems will play a critical role in achieving sustainable water management and climate resilience in the future.

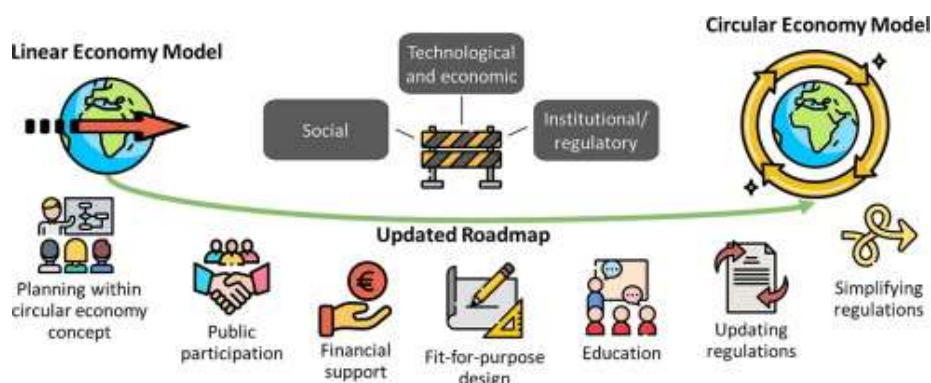


Figure 1: Circular Economy Framework in Water Treatment



Figure 2: Resource Recovery from Wastewater

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