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Circular Economy Approach in Wastewater Treatment: Recycling and Recovery

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Abstract

The demand for freshwater resources has been greatly raised by the exponential expansion of urbanization, industrialization, and population, therefore causing water scarcity in many different countries. Concerning the safe disposal of sewage to safeguard public health and the environment, traditional wastewater treatment methods have mostly concentrated. These linear solutions, however, sometimes ignore the possibilities of wastewater as a useful resource. Focused on resource recovery and recycling, the circular economy (CE) provides model directions toward sustainable wastewater treatment. Usually not sustainable, conventional wastewater treatment approaches largely help to deplete resources and cause environmental damage. Within the framework of wastewater treatment, a circular economy strategy stresses the recovery of valuable resources such water, energy, and nutrients from wastewater, therefore turning treatment plants into resource recovery facilities. Dealing with sustainable effect, case studies and technological breakthroughs, this paper addresses CE constitution applied to wastewater treatment. Important aspects are discussed: nutrient recovery, water reuse, biogas generation and enhancement of biosolids. The paper especially addresses policy implication, difficulties, and future possibilities for the strictly limited incorporation of CE concepts into sustainable wastewater treatment systems.

Keywords: Wastewater, circular economy, nutrient recovery, sustainable effect, environmental impact

INTRODUCTION

The premise of circular economy (CE) originated in 1989, when environmental economists David W. Pears and R. Kerry Turner proposed the circular economic system [1].

Other models closely associated with CE include Cradle-to-Cradle (2002) [2], Performance Economy (2006) [3] and Blue Economy (2010) [4]. The Ellen McArthur Foundation's work (2013) has recently been the most significant in revitalising the circular economy concept [5].

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The concept fundamentally relies on four principles:

1. waste elimination,
2. utilisation of renewable energy,
3. diversity strength, and
4. systems thinking.

In the current setting of escalating demand for raw materials and associated environmental concerns, Circular Economy (CE) is regarded as a viable solution to resource efficiency constraints.

Environmental pollution, depletion of natural resources, climate change and scarcity of water are critical global issues in present situation. To overcome these challenges traditional wastewater treatment methods, which many times give importance to pollutant removal aside from resource recovery are not sufficient to provide solution. On the contrary, a circular economy minimises waste by closing product and material loops within the industrial environment. It also alters economic logic by substituting 'production' with 'sufficiency' through reuse, refurbishment, remanufacturing, and recycling [6].

The rapid expansion of urban areas, coupled with industrial development and population growth, has markedly intensified the need for freshwater resources, resulting in water scarceness in many regions globally. Conventional approaches to wastewater management have primarily emphasized the secure disposal of sewage to safeguard public wellness and the environment. Nonetheless, these linear methodologies frequently fail to recognize the significant potential of wastewater as invaluable resource.

The idea of a circular economy presents a groundbreaking approach by observing wastewater as a valuable resource for water, essential nutrients like nitrogen and phosphorus, and energy. Instead of simply processing wastewater to comply with discharge regulations, the circular economy approach encourages the recycling and recovery of resources, effectively closing the loop in water systems.

The purpose of this review is to evaluate the potential of circular economy concept in wastewater treatment through examining existing technologies and techniques for implementation and offers approaches to increase circular economy adoption in this area.

CIRCULAR ECONOMY PRINCIPLES IN WASTEWATER TREATMENT

The circular economy is a production and consumption paradigm that promotes the reuse, repair, refurbishment, and recycling of existing resources and products for extended durations. Unlike the conventional linear economy; extract, produce, discard—the circular model seeks to maintain resource use, optimize value extraction, and reclaim materials and energy from trash. Implementing circular economy (CE) ideas in wastewater treatment is a novel and sustainable approach to tackle environmental issues, resource limitations, and economic inefficiencies.

Definition and Concepts

The CE emphasizes:

- *Design for sustainability:* Waste streams are viewed as potential resources.
- *Resource recovery:* Maximizing the extraction of valuable byproducts.
- *Reintegration:* Materials which are recovered will be reused within production system.

CE in the Context of Wastewater Treatment

In waste water treatment, CE core principles are applied through:

- Recovery of nutrients such as nitrogen and phosphorus.
- Reuse of treated water for industrial or agricultural purposes.
- Conversion of organic waste into energy or value added products

Technologies for Resource Recovery in Wastewater Treatment

Nutrient Recovery

Nutrients like nitrogen and phosphorus are important for increasing agricultural productivity. Recovery process includes:

- *Struvite Precipitation:* It is technology to recover (phosphate to struvite) phosphorus from wastewater and used as a valuable fertilizer [7]. Struvite is a crystalline formation of magnesium ammonium phosphate ($MgNH_4PO_4•6H_2O$). Natural formation occurs in wastewater treatment plants when magnesium, ammonium, and phosphate concentrations reach saturation at optimal pH and temperature.

- *Ammonium Stripping:* A simple desorption process used to recover nitrogen as ammonium sulphate for use as fertilizer [8].

Ammonium stripping is a physical-chemical process used to remove ammonia nitrogen (NH_3-N) from wastewater. It involves converting ammonium ions (NH_4^+) in the water to gaseous ammonia (NH_3) by raising the pH and temperature, then stripping the gas from the water using air or steam.

Water Reuse

Treated wastewater can be recycled and reused for the purpose of agricultural, industrial by applying with advanced treatment technologies. This reduces freshwater extraction and promotes water sustainability.

- *Advance Treatment Technologies:* Membrane filtration technique which separates the particle in liquid solutions by semipermeable membrane, reverse osmosis is also a membrane treatment process which separates dissolved solutes from water, and ultraviolet disinfection which is chemical free water treatment for inactivation of microbes. These three methods improve water quality for reuse [9].
- *Applications:* The wastewater after treatment can be reused in municipal irrigation, industrial processes and in agricultural fields [10].

Energy Recovery

Wastewater contains significant chemical and thermal energy. Technologies are evolving to harness this energy effectively.

- *Biogas Production:* After wastewater treatment organic matter is separated. Organic matter produces biogas after anaerobic digestion, which can be used for generation of electricity [11].
- *Microbial Fuel Cells (MFCs):* Organic matter present in wastewater used as food for microbes. Generates electricity directly from wastewater [12].

Biosolid Valorization

Biosolids, the nutrient rich organic byproduct of wastewater treatment, can be processed into:

- *Compost:* Organic matter in wastewater is used in agricultural fields. The treated sludge from wastewater containing organic matter is used in agricultural fields [13].
- *Biochar:* A carbon rich product is having the application in soil conditioning and carbon sequestration [14].

CASE STUDIES AND SUCCESS STORIES

Nutrient Recovery in India

NEERI's Phosphorus Recovery from Sewage Sludge, Nagpur, Maharashtra

The CSIR-NEERI piloted a phosphorus crystallization nutrient recovery plant in Nagpur. The technique turned sewage sludge into slow-release fertilizer struvite ($MgNH_4PO_4{\bullet}6H_2O$). This project reduced effluent phosphorus and produced a valuable agricultural input. Local farmers applied recovered struvite to fields, closing the nutrient cycle [15].

Delhi Jal Board – Okhla Wastewater Treatment Plant, New Delhi

The Delhi Jal Board (DJB) used the anaerobic breakdown and struvite precipitation to recover phosphorus and nitrogen at the Okhla facility. Cleaning and reusing process biosolids as soil conditioners. This decreased sludge disposal expenses and produced organic fertilizers for Delhi's peri-urban farms [16].

Jalkund Nutrient Recycling Project – North East India

The Jalkund Project, run by ICAR and KVKs in northeastern states, recycled wastewater and organic matter to improve soil fertility in small farm ponds. The effort promoted vermiwash and composted fecal sludge, lowering farmers' synthetic input use and aiding tribal and marginal communities [17].

Tamil Nadu Urban Sanitation Support Programme (TNUSSP)

The TNUSSP, under the Indian Institute for Human Settlements (IIHS), has successfully promoted co-composting of faecal sludge and organic waste in cities like Trichy and Coimbatore. These efforts have led to the production of pathogen-free compost enriched with nitrogen, phosphorus, and potassium. This compost has been marketed to farmers through local cooperatives, showcasing a scalable urban-rural circular model [18].

Ecosan Toilets and Urine Diversion – Auroville, Tamil Nadu

In Auroville, ecological sanitation systems (EcoSan) have been deployed to recover nutrients directly from human excreta. The use of urine-diverting dry toilets enables the collection of urine as liquid fertilizer, rich in nitrogen, while fecal matter is composted for soil enhancement. These practices promote decentralized nutrient recovery and sustainable agriculture.

JSW Steel Ltd. – Bellary, Karnataka

Industrial giant JSW Steel installed a zero-liquid discharge (ZLD) technology at its Bellary factory. Greenbelt development and cooling and processing employed treated industrial effluents with organic and inorganic fertilizers. Afforestation operations used nutrient-rich treatment biosolids [19].

Water Reuse in India

Nagpur, Maharashtra: Reuse of Treated Sewage for Power Generation:

Nagpur is a pioneering city in India where treated sewage is reused in thermal power plants. The Nagpur Municipal Corporation partnered with Mahagenco to set up a 200 MLD sewage treatment plant under a PPP model. Treated water from this plant is supplied to the Koradi and Khaparkheda power plants for cooling purposes.

- *Impact:* Saves freshwater for municipal use, reduces energy consumption for water extraction, and ensures long-term water security.
- *Circular Economy Link:* Closed-loop reuse system reduces dependency on natural water bodies [20].

Surat, Gujarat: Municipal Wastewater for Industrial Use

Surat Municipal Corporation (SMC) has implemented a large-scale wastewater reuse model by supplying tertiary-treated wastewater to industries in Pandesara and Sachin GIDC. The reuse capacity exceeds 40 MLD, and the model has proven financially sustainable.

- *Impact:* Reduces freshwater demand from the Tapi River and supports industrial growth.
- *Circular Economy Link:* Converts wastewater into an industrial resource, creating economic and environmental value [21].

Chennai, Tamil Nadu: TTRO Plants for Industrial Use

The Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB) developed two 45 MLD Tertiary Treatment Reverse Osmosis (TTRO) plants in Koyambedu and Kodungaiyur. Treated water is supplied to industrial users in SIPCOT.

- *Impact:* Reduces groundwater stress in Chennai's industrial belts.
- *Circular Economy Link:* Encourages reuse of treated sewage, promoting industrial symbiosis [22].

Aluva, Kerala: Decentralized Wastewater for Agriculture

Decentralized systems, such as DEWATS and artificial wetlands, are utilized by the Aluva Municipality in Kerala for the purpose of treating greywater. This treated water is subsequently utilized for the cultivation of bananas and vegetables.

- *Impact:* Promotes community-level water management and food security.
- *Circular Economy Link:* Integrates water reuse with local agricultural systems [23].

Along with the above examples of water reuse in various regions like, Bengaluru, Karnataka: Treated Water for Non-Potable Use [24], Tiruppur, Tamil Nadu: Textile Sector Achieving Zero Liquid Discharge [25], Delhi: Reuse of Treated Sewage for Irrigation and Horticulture [26].

- In Singapore NEWater initiative treats wastewater to a quality wise safe to drink by using advanced dual-membrane and ultraviolet technologies significantly reduces dependence on freshwater imports [27].
- *Biogas Production in Germany:* Germany has administered anaerobic digestion in many wastewater treatment plans, generating biogas to power plant operations and then supply it to local grids [28].

ENERGY RECOVERY IN INDIA

Okhla Waste-to-Energy Plant, New Delhi

The Okhla WTE plant is one of India's first large-scale waste-to-energy projects located in New Delhi. Operated by the Jindal ITF Urban Infrastructure Ltd, it processes over 2000 tonnes of municipal solid waste (MSW) daily and generates about 16 MW of electricity.

Success Indicators

- Reduces landfill burden.
- Supplies electricity to the grid.
- Demonstrated viability of large-scale MSW to energy conversion in India [29].

Surat Municipal Corporation – Biogas Energy Recovery from Sewage

The Surat Municipal Corporation (SMC) has implemented a successful biogas energy recovery project from sewage treatment plants (STPs), particularly from the Dindoli and Bamroli STPs. It uses anaerobic digesters to generate **biogas**, which is converted to electricity.

Success Indicators

- Generates **approx. 2.5 MW of electricity** from biogas.
- Reduces operational costs of STPs.
- Cuts greenhouse gas emissions [30].

Nagpur: Sludge-to-Energy Plant at Bhandewadi STP

Nagpur has implemented a sludge-to-energy project under a PPP model, supported by the National Mission for Clean Ganga. It utilizes **sewage sludge** to generate **methane**, which is used for energy and heat generation.

Success Indicators

- Utilizes 200 TPD (tons per day) of sludge.
- Provides **heat and power** for treatment plant operation [31].

CHALLENGES IN ADOPTING CIRCULAR ECONOMY APPROACHES IN WASTEWATER TREATMENT

The transformation from a linear economy to a circular economy (CE) in wastewater treatment offers a viable approach for sustainable resource management. This transition presents multiple interconnected challenges that impede its broad adoption. The challenges can be classified into five main categories: technological, economic, governing, institutional, and social elements.

Technological Barriers

A significant obstacle to the adoption of circular economy principles in wastewater treatment is the complexity of technology linked to resource recovery. Processes like nutrient recovery (e.g., phosphorus and nitrogen), reusing water, and energy generation from sludge necessitate advanced and integrated technologies, many of which remain in developmental or pilot phases [32]. Furthermore, guaranteeing the security and quality of obtained products, particularly in the context of water reuse, necessitates rigorous monitoring and treatment protocols. The conventional activated sludge process coupled with membrane filtration or ultrafiltration is complex, having high initial cost for implementing advance recovery technologies [33]. Some processes for low concentration waste streams have limited efficiency.

Economic and Financial Constraints

Numerous wastewater treatment facilities (WWTPs), especially in developing nations, function with constrained financial resources. The substantial capital and operational expenses associated with circular technologies dissuade investment, especially if the return on investment (ROI) is ambiguous or protracted [34]. Moreover, markets for recovered resources, such as struvite fertilizers or biogas, remain underdeveloped, so constraining their economic appeal.

Regulatory and Policy Challenges

The absence of standardized regulations for the reuse of waste and recovered materials present a major challenges. Without clear, consistent guideline, there's a lot of ambiguity and variability in how water and materials can be safely and effectively reused [35]. There are also insufficient incentives for adopting CE practices.

Public Perception

Study suggested that people show resistance to using recycled water due to health and safety concern [36]. The benefits of CE in wastewater treatment have limited awareness.

POLICY AND ECONOMIC IMPLICATIONS

Policy Recommendations

- Clear regulations should be created for the reuse and recovery of wastewater resources.
- Governing bodies must give financial incentives for industries which adopt CE technologies.
- Encourage public –private partnership to fund innovative solutions.

Economic Viability

- The expenses needed for water treatment plant can cover by onsite energy generation; nutrient recycling and water reuse [37].
- Fertilizers and biogas monetization of can improve economic sustainability.

Future Directions

- *Technological Innovations:* Hybrid systems are developed by combing multiple resource recovery technologies. The novel material. Like Nano composite material are used to enhance the recovery efficiency [38].
- *Integration with Smart System:* For real time monitoring and optimization of wastewater treatment process the artificial intelligence (AI) and Internet of Things (IoT) are used.
- *Scaling Up:* For scaling up wastewater treatment process pilot project should be launched. The projects that which are attain success are used as models. The collaboration between the industries, academia and government are needed to share knowledge and resources.

CONCLUSION

After a sustainable road to solve problems such as water scarcity, minimize environmental pollution, and recover valuable resources, circular economy methods in wastewater treatment followed after a sustainable pathway. The system for wastewater treatment can make the transition from a linear model to a resource-efficient, closed loop system by incorporating cutting-edge technologies, resolving challenges related to public perception and policy, and addressing the challenges of public perception. In the future, efforts should focus interdisciplinary collaborations, public awareness, and investment in advanced technology in order to fully exploit the promise of CE in wastewater management.

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