A Brief Analysis of Technological Innovation in Urban Wastewater Treatment

Wen Wen [1, 2, 3]

[1] Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi’an Shaanxi, 710000, China

[2] Shaanxi Agricultural Development Group Co., Ltd., Xi’an Shaanxi, 710000, China

[3] Key Laboratory of Degraded and Unused Land Consolidation Engineering, Ministry of Natural Resources, Xi’an Shaanxi, 710000, China

Abstract

The accelerated pace of global urbanization has led to a dramatic increase in both the volume and complexity of urban wastewater, posing severe challenges to ecology, health, and climate. Traditional wastewater treatment models face multiple dilemmas, including high energy consumption and carbon emissions, resource wastage, high costs, difficulties in sludge disposal, and ineffective removal of emerging contaminants, necessitating fundamental reform. Future development directions should focus on unlocking resource recovery potential, pursuing technological innovations that are efficient, low-carbon, and smart, building digitalized and intelligent treatment plants, and establishing resilient systems capable of responding to risks and changes. Achieving this transformation requires synergistic drivers from policy, economics, and society. Despite challenges such as technological stability, economic viability, standardization, and massive investment, this systemic revolution, integrating technological innovation, management reform, and policy guidance, is destined to propel urban wastewater treatment towards a promising future characterized by resource cycling, energy self-sufficiency, environmental friendliness, and intelligent resilience, providing solid support for sustainable urban development.

Keywords

Wastewater Treatment; Technological Transformation; Resource Recovery.

1. Dilemmas of the Traditional Model and the Imperative for Change

With the accelerated advancement of global urbanization, cities, akin to vast living organisms, generate "blood" – urban wastewater – whose volume and complexity are growing at an unprecedented rate. United Nations data indicates that over 80% of global wastewater is discharged into the environment without adequate treatment, posing severe threats to aquatic ecosystems, human health, and even the climate system. [1-2]

For a long time, urban wastewater treatment plants (WWTPs) have functioned as "end-of-pipe purifiers," with the core objective of removing pollutants (especially COD, BOD, nitrogen, phosphorus) to meet discharge standards. While this model has played a crucial role in controlling point source pollution, its inherent defects are increasingly apparent:

1.1. High Energy Consumption and Carbon Emissions:

Processes like aeration and sludge treatment consume enormous amounts of energy, making WWTPs major urban energy consumers and indirectly generating significant greenhouse gases.

1.2. Resource Wastage:

Valuable resources contained in wastewater – water resources, nutrients (nitrogen, phosphorus), and the chemical energy embedded in organic matter – are often simply removed or converted and then discarded.

1.3. Process Complexity and High Costs:

To meet increasingly stringent discharge standards, treatment processes have become more complex, leading to continuously rising construction and operational costs.

1.4. Sludge Disposal Challenges:

The large quantities of residual sludge generated alongside the treatment process present a global challenge for safe, economical, and sustainable disposal.

1.5. Challenge of Emerging Contaminants:

Emerging pollutants such as pharmaceutical residues, endocrine disruptors, and microplastics are difficult to remove effectively with conventional processes, constituting potential ecological and health risks. [3-4]

However, challenges coexist with opportunities. These predicaments compel the industry to seek fundamental change. Driven powerfully by the concept of sustainable development and internationally recognized carbon neutrality goals ("Dual Carbon" targets in China), urban wastewater treatment is undergoing a profound technological revolution, moving towards a new era characterized by resource cycling, energy self-sufficiency, and environmental friendliness.

2. Development Directions

The core vision for future urban wastewater treatment plants is to become "resource cycling hubs" and "environmental enhancement nodes" within urban infrastructure. Its development prospects focus on the following aspects:

2.1. Unlocking Resource Recovery Potential

2.1.1. Water Resource Reuse:

High-quality reclaimed water will become the "second water source" for cities. Treatment technologies are evolving from traditional "tertiary treatment + disinfection" towards combined processes like "Ultrafiltration (UF) + Reverse Osmosis (RO) + Advanced Oxidation Processes (AOP)" to meet stringent water quality requirements for diverse uses such as industrial cooling, urban miscellaneous uses, landscape replenishment, groundwater recharge, and even potable reuse. Singapore's "NEWater" project is a global benchmark for reclaimed water utilization.

2.1.2. Nutrient (N, P) Recovery:

Phosphorus is a non-renewable resource facing global depletion risks. Technologies for recovering phosphorus (e.g., struvite crystallization, calcium phosphate precipitation) and nitrogen (e.g., ammonia stripping and absorption, membrane contactor ammonia recovery) from wastewater are maturing and becoming commercialized. For instance, the Netherlands' "P-Recovery" plant successfully extracts high-purity phosphate fertilizer from sludge incineration ash.

2.1.3. Organic Matter-to-Energy Conversion:

The organic matter in wastewater contains substantial chemical energy. Through efficient anaerobic digestion technologies (e.g., thermophilic digestion, co-digestion), sludge and some influent organic matter can be converted into biogas (primarily methane), which, after purification, can be used as vehicle fuel (Bio-CNG) or fed into natural gas grids. Denmark's Aarhus Marselisborg WWTP, through process optimization, achieves an energy self-sufficiency rate exceeding 150%, serving as a model "energy factory." Furthermore, sludge can be converted into higher-value products like biochar and syngas via pyrolysis, gasification, etc. [5]

2.2. Pursuing Efficient, Low-Carbon, and Smart Technological Innovations

2.2.1. Mainstream Anammox (Anaerobic Ammonium Oxidation):

This revolutionary technology utilizes specific bacterial consortia to convert ammonium directly to nitrogen gas under anaerobic conditions without requiring organic carbon sources. Compared to traditional nitrification-denitrification, it can save approximately 60% of aeration energy and 100% of external organic carbon source (e.g., methanol) addition, while also significantly reducing sludge production. Practical engineering applications exist in places like the Netherlands and China, representing the future direction of nitrogen removal technology. [6]

2.2.2. Aerobic Granular Sludge (AGS):

AGS technology cultivates densely structured granular sludge with excellent settling properties, enabling efficient organic matter removal, nitrogen, and phosphorus removal within a single reactor. It offers significant advantages such as reduced footprint (saving ~75%), lower energy consumption (saving ~30%), and less sludge production, transitioning from the laboratory to large-scale engineering applications.

2.2.3. Continuous Evolution of Membrane Technology:

Membrane Bioreactors (MBR) provide stable, high-quality effluent, with the core focus being on improving membrane material fouling resistance, flux, and cost reduction. Emerging Anaerobic Membrane Bioreactors (AnMBR) combine anaerobic digestion with membrane separation, ensuring effluent quality while achieving organic matter removal and energy recovery. Novel membrane technologies like Forward Osmosis (FO) and Membrane Distillation (MD) show promise in specific areas (e.g., high-salinity wastewater, advanced reclaimed water treatment).

2.2.4. Low-Carbon/Carbon-Neutral Processes:

Develop and apply processes with low energy consumption, low chemical usage, and low sludge production; explore deploying renewable energy sources like photovoltaics (PV) and small wind turbines on plant grounds or surrounding facilities; research and apply Carbon Capture, Utilization, and Storage (CCUS) technologies to treat CO2 in digester gas; optimize operational strategies to minimize emissions of potent greenhouse gases like N2O.

2.3. Building Digitalized and Intelligent Treatment Plants

The deep integration of technologies like the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Digital Twins will fundamentally transform the operational management model of WWTPs:

2.3.1. Precise Sensing and Prediction:

Utilize widely deployed online sensors to monitor key parameters such as water quality, flow rate, equipment status, and energy consumption in real-time. Combine with AI models to predict influent load variations, process performance, and equipment failure risks.

2.3.2. Intelligent Decision-Making and Optimized Control:

AI algorithms, based on real-time data and predictive models, automatically optimize key operational parameters like aeration volume, chemical dosing, and recirculation ratios. This achieves minimized energy and chemical consumption and maximized resource recovery while ensuring compliance.

2.3.3. Predictive Maintenance:

Analyze equipment operational data to predict failures in advance and schedule maintenance, significantly reducing unplanned downtime.

2.3.4. Smart Operation and Management Platform:

Integrate all data and functions to enable remote monitoring, centralized dispatching, intelligent reporting, and assisted decision-making, enhancing management efficiency.

2.4. Establishing Resilient Systems Capable of Responding to Risks and Changes

Climate change (extreme rainfall/drought), unexpected events (e.g., pandemics), and fluctuations in water quality and quantity pose severe challenges to wastewater treatment systems. Building resilient systems is crucial:

2.4.1. Source Control and Network Optimization:

Promote separate stormwater and sewage systems to reduce Combined Sewer Overflows (CSOs) during wet weather; strengthen pipeline leak detection and repair; explore decentralized treatment to alleviate load on centralized plants. [7]

2.4.2. Integrated Plant-Network-Receiving Water Body Dispatching:

Utilize smart platforms to achieve coordinated, optimized operation of wastewater treatment plants, drainage networks, and receiving water bodies (or reclaimed water networks), coping with peak flows and safeguarding ecological base flows.

2.4.3. Modular Design and Emergency Treatment Capacity:

Adopt modular design to facilitate expansion and upgrades; reserve emergency treatment units (e.g., AOP, activated carbon adsorption) to respond to sudden pollution incidents or emerging contaminants.

2.4.4. Safe Resource Recovery Pathways for Sludge:

Establish secure and sustainable pathways for sludge stabilization (anaerobic digestion, aerobic composting), harmless treatment (thermal drying, incineration), and resource utilization (land application, building material utilization, phosphorus recovery), eliminating secondary pollution risks. [8]

3. Engines Driving Change

The realization of the technological vision relies on the joint drive of policy, economics, and society: Establish stricter and scientifically sound water quality discharge standards (especially for emerging contaminants); introduce mandatory requirements and incentive policies (subsidies, tax incentives, green electricity tariffs) to encourage reclaimed water use, resource recovery (e.g., phosphorus recovery quotas), energy self-sufficiency, and low-carbon operation; integrate resource recovery and energy generation in WWTPs into urban circular economy development plans and carbon neutrality roadmaps. Simultaneously, strengthen public awareness campaigns on water scarcity, the importance of the circular economy, and the safety of wastewater resource recovery to eliminate "psychological barriers" (e.g., acceptance of reclaimed water); encourage public participation in water conservation and source control of pollution (e.g., reducing food waste disposal into sewers, rational medication use). [9]

4. Future Vision and Challenges

However, technological innovation also faces significant challenges. The stability and economic viability of some advanced technologies at large scale still need improvement; removal technologies for emerging contaminants require breakthroughs. Quality standards, application norms, and safety regulatory systems for products like reclaimed water, recovered nutrients, and biochar need refinement. Constructing resource-recovering, smart, and low-carbon future treatment plants requires massive initial investment. Breaking down departmental silos between water, environmental protection, energy, agriculture, and urban construction for cross-departmental and cross-regional collaborative management is paramount.

The future of urban wastewater treatment is no longer merely a technological upgrade, but a systemic revolution involving technological innovation, management reform, and policy guidance. It is an essential path to address the challenges of water resource crises, environmental pollution, and climate change. Despite numerous challenges, propelled by technological innovation, policy drivers, and societal consensus, urban wastewater treatment is destined to embrace a bright future characterized by highly efficient resource cycling, green energy self-sufficiency, ecologically friendly environments, and intelligently resilient systems, providing solid support for sustainable urban development and the improvement of human settlements.

References

[1] McCarty, P. L., Bae, J., & Kim, J. (2011). Domestic wastewater treatment as a net energy producer–can this be achieved? Environmental Science & Technology, 45(17), 7100–7106.

[2] van Loosdrecht, M. C. M., et al. (2013). Making wastewater treatment plants viable by using mainstream anammox. Water 21, 15(4), 40–41.

[3] de Kreuk, M. K., et al. (2010). Aerobic granular sludge technology: State of the art. Water Science and Technology, 61(11), 2733–2740.

[4] Guest, J. S., et al. (2009). A new planning and design paradigm to achieve sustainable resource recovery from wastewater. Environmental Science & Technology, 43(16), 6126–6130.

[5] Shizas, I., & Bagley, D. M. (2004). Experimental determination of energy content of unknown organics in municipal wastewater streams. Journal of Energy Engineering, 130(2), 45–53.

[6] Hao, X., et al. (2021). Digital twin for wastewater treatment process: A review. Water Research, 201, 117343.

[7] UN-Water. (2021). The United Nations World Water Development Report 2021: Valuing Water. UNESCO.

[8] World Bank. (2020). Wastewater: From Waste to Resource – The Case of the Mediterranean Region.

[9] IWA. (2018). Water Utility Pathways in a Circular Economy. International Water Association.