

From carbon emitters to carbon managers: Data-driven pathways to carbon neutrality for wastewater treatment plants

Zhenhan Li,¹ Renke Wei,^{1,2,*} Hongwei Yu,^{1,2,*} Zhenao Gu,^{1,2} Jing Qi,^{1,2} and Chengzhi Hu^{1,2}

¹Key Laboratory of Environmental Aquatic Chemistry, State Key Laboratory of Regional Environment and Sustainability, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

²University of Chinese Academy of Sciences, Beijing 100049, China

*Correspondence: hwyu@rcees.ac.cn

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Pollution control and carbon reduction have become central to sustainable water management. Wastewater treatment plants (WWTPs), while vital for water purification, have become a non-negligible source of carbon emissions. From this perspective, a systematic review of the composition, drivers, and mitigation potential of carbon emissions from wastewater treatment is provided, highlighting key research breakthroughs, including the application of data-driven models for accurate carbon footprint assessment and the identification of previously overlooked carbon sources from sludge treatment units. A paradigm shift toward carbon neutrality is proposed: WWTPs can achieve carbon neutrality by transitioning from passive reduction to proactive management through intelligent process upgrades, enhanced energy and resource recovery, and life-cycle carbon management.

Amid accelerating global climate change, the wastewater treatment sector faces unprecedented pressure to pursue rapid decarbonization. Although ensuring water purification, wastewater treatment plants (WWTPs) have become a significant source of greenhouse gas (GHG) emissions. Globally, CH₄ and N₂O emissions from wastewater treatment contribute approximately 6.9% and 8.1%, respectively, to total anthropogenic emissions.¹ Carbon emissions from wastewater treatment arise from dispersed sources, exhibit high variability, and depend significantly on treatment processes and influent quality. Variations in treatment technologies, operating conditions, and seasonal factors can cause order-of-magnitude differences in emission intensity,^{2,3} complicating accurate quantification of carbon emissions from WWTPs and formulation of effective mitigation strategies.

The emission intensity associated with energy and chemical consumption in WWTPs has exhibited a sustained upward trajectory; however, conventional emission factor methods fail to effectively capture these dynamic variations.^{4,5} Moreover, emissions from sludge treatment units (e.g., centrifugal dewatering) remain largely unmonitored, and their contribution may be comparable to that of traditionally recognized emission hotspots, such as anaerobic digestion.⁶ These issues highlight a core challenge of systematically assessing mitigation potential and designing feasible carbon-neutral pathways through refined identification of emission sources.

China, the world's largest wastewater treatment sector, emitted 53.0 Mt CO₂-eq in 2019,⁴ with WWTP-related CH₄ and N₂O emissions nearly tripling between 2005 and 2014,⁵ imposing enormous decarbonization pressure on the sector. Accordingly, selecting China's large-scale, heterogeneous wastewater infrastructure as the research context, we investigate the dynamic evolution of emission profiles, challenges in carbon accounting, and feasibility of decarbonization pathways.

EMISSION CHARACTERISTICS AND DRIVERS: FROM EXTERNAL UNCONTROLLABILITY TO INTERNAL MANAGEABILITY

From a life-cycle perspective, carbon emissions from WWTPs fall into three major categories: (i) direct emissions, including CH₄ and N₂O released during wastewater treatment and discharge, together with fossil-fuel-derived CO₂ from on-site operations; (ii) indirect emissions from purchased electricity and heat; and (iii) upstream/downstream emissions from chemical production, pipeline construction, and sludge disposal. Notably, pipeline construction alone can emit up to 400 g CO₂-eq·m⁻³ when amortized over a 30-year lifespan—comparable to the average intensity of direct emissions (550 g

CO₂-eq·m⁻³).³

Studies have shown significant differences in carbon intensity among wastewater treatment processes. Plants employing anaerobic-anoxic-oxic/anoxic-oxic (A²O/AO), physicochemical (PC), and oxidation ditches (OD) treatments produced the highest GHG emissions, contributing 33%, 16%, and 14% of the total, respectively. Comparatively, plants using A²O/AO, OD, and sequencing batch reactor (SBR) technologies generally exhibited the lowest emission intensity per unit of wastewater treated, while still meeting more stringent discharge standards.⁷ Indirect and upstream/downstream emission compositions are primarily driven by electricity consumption and chemical usage, and their relative contribution has increased over time. Following the 2015 upgrade of water quality discharge standards, emissions from carbon-source and phosphorus-removal agent consumption surged sharply. In 2020, emissions from electricity use, carbon-source and phosphorus-removal agent consumption collectively accounted for approximately one-third of the national total, surpassing direct wastewater treatment emissions.^{4,5}

Regional disparities are also pronounced, with carbon emissions heavily concentrated in rapidly developing and densely populated cities. Carbon intensity per unit of wastewater in northern and northwestern China is nearly twice that in southern China, attributed to carbon-intensive electricity structures and increased energy and material consumption driven by colder temperatures and lower rainfall. Numerous reclaimed water facilities constructed to alleviate water resource pressure are also significant carbon emitters in northern and northwestern cities.^{4,7} Furthermore, seasonal variations in carbon emissions have been observed, with periodic fluctuations during traditional Chinese holidays strongly correlated with urban population dynamics within specific urban areas. Seasonal variations in emission during specific stages of water treatment, particularly the centrifugal dewatering stage of sludge treatment, are also evident: winter CH₄ emission intensity is ~35% higher than in summer, driven by greater organic loading in winter sludge, increased CH₄ solubility at lower temperatures, and intensified release from mechanical disturbance.^{5,6}

Structural decomposition analysis reveals that before 2015, emission growth was primarily governed by treated wastewater volume and influent total nitrogen concentration; after 2015, carbon source addition intensity, phosphorus-removal agent consumption, and electricity consumption gradually became the dominant factors.⁵ During the same period, with China's increasing urban wastewater treatment rate (from 75% to over 95%) and stricter discharge standards, electricity consumption per unit of treated wastewater increased by 31.7%, and chemical consumption increased even more significantly.⁴

Collectively, these characteristics point to a key conclusion: carbon emissions from WWTPs are shifting from being "externally uncontrollable" (e.g., influent flow rate and water quality) to "internally manageable" (e.g., electricity and chemical consumption, and process selection for wastewater and sludge treatment). This shift theoretically underpins operational optimization and intelligent control, but heightens the need for precise emission source identification.

KEY BREAKTHROUGHS AND CASE STUDY INSIGHTS: FROM INTELLIGENT IDENTIFICATION TO MITIGATION POTENTIAL ASSESSMENT

Hybrid mechanistic–data-driven modeling has significantly advanced carbon-emission prediction. A recent study analyzed monthly operational

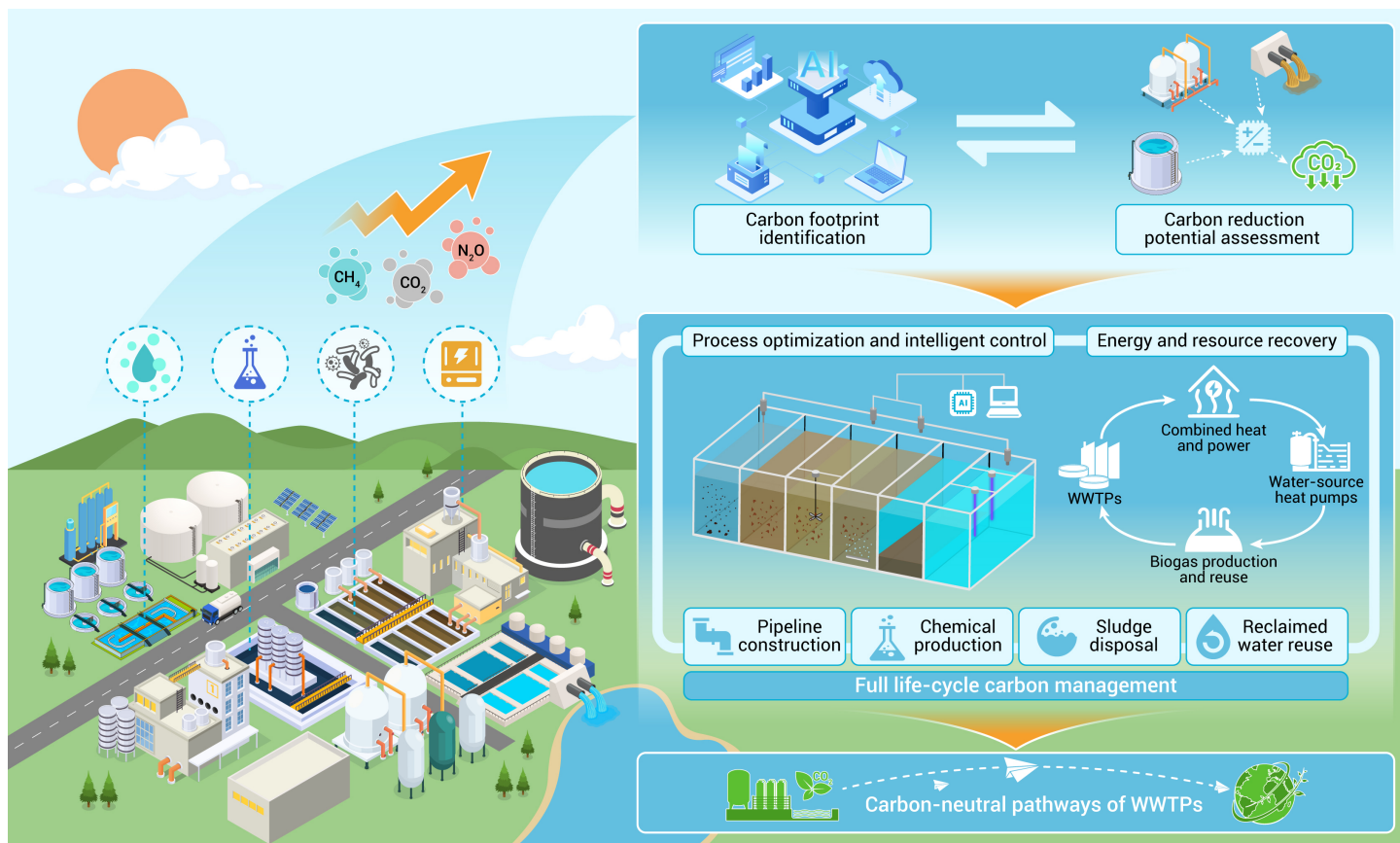


Figure 1. A data-driven framework for carbon-neutral pathways of WWTPs Accurate identification of carbon footprints and source-specific emission contributions enables refined assessment of reduction potential across different treatment processes. To completely unlock the mitigation capacity, three synergistic pathways should be adopted: process optimization and intelligent control, energy and resource recovery, and full life-cycle carbon management.

data from 6,228 WWTPs (2007–2020) and employed structural decomposition analysis (SDA) to quantify the contributions of various driving factors to carbon emission growth. The results showed that carbon emissions totaled 41.9 Mt CO₂-eq in 2020, with indirect emissions from energy and material consumption contributing nearly two-thirds. Structural decomposition analysis revealed that electricity intensity, carbon source, and phosphorus-removing agent consumption increasingly impact carbon footprint growth over time. Furthermore, the study employed quantile regression forests to benchmark median performance metrics under identical treatment conditions—including influent water quality, flow rate, treatment process type, season, and city—to assess potential for mitigating electricity and chemical consumption. The results indicated that optimized operation could reduce indirect emissions by ~12.6%.⁵

Researchers have developed an ecological knowledge-infused graph neural network model (EcoGNN-GHG) that embeds biological production pathways from wastewater treatment directly into its nodes and edges. This model delivers high-precision prediction of CH₄ and N₂O generation rates under dynamic water quality and operational conditions. Through interpretability analysis, it identifies the key governing factors and guides the formulation of a precise dissolved oxygen (DO) control strategy targeting critical water quality parameters.²

Moreover, addressing the long-overlooked emissions from sludge treatment, recent studies have, for the first time, quantified the CH₄ and N₂O emission intensities from mechanical treatment units. Cross-seasonal field monitoring conducted at four typical Chinese WWTPs showed that CH₄ and N₂O emissions from centrifugal dewatering units contributed about 16% and a comparable proportion of fugitive emissions from anaerobic digestion, respectively, thereby broadening the carbon accounting boundary.⁶ This finding indicates that focusing exclusively on conventional hotspots such as anaerobic digestion may significantly underestimate the overall carbon footprint of the entire facility.

These case studies, from national-scale analysis to plant-level mechanistic

modeling and unit-process emission quantification, demonstrate that data-driven tools provide actionable intelligence across wastewater management scales. Collectively, these breakthroughs underscored a pivotal realization: significant carbon reductions can be achieved through refined management practices and intelligent control, without altering the core treatment process. However, their generalizability across different plants and processes requires systematic validation. The stable deployment of optimal control strategies, such as dynamic DO regulation, identified by these models remains constrained by real-world challenges, including sensor reliability, financial limitations, and personnel training requirements. Moreover, emissions from sludge treatment units remain largely excluded from mainstream carbon management frameworks, leading to a systematic underestimation of the actual mitigation potential. Therefore, achieving substantial emission reductions and ultimately attaining carbon neutrality necessitates coordinated, systemic interventions across multiple dimensions, rather than relying solely on localized optimization of operational parameters.

PATHWAYS TO CARBON NEUTRALITY: FROM PASSIVE CARBON REDUCTION TO PROACTIVE CARBON MANAGEMENT

Realizing carbon neutrality demands systematic collaborative efforts across multiple distinct yet interconnected domains and governance levels. We propose a hierarchical framework in which data-driven tools serve as the central nervous system—serving not only prediction but also enabling action.

Process optimization and intelligent control

Intelligent control of process optimization offers one of the most direct and economically efficient strategies for mitigating on-site carbon emissions. By leveraging real-time sensor data and AI-driven algorithms, plant operators can dynamically adjust key operational parameters to optimize pollutant removal and minimize GHG generation. For instance, real-time monitoring combined with AI-driven regulation of DO, recirculation ratios, and chemical dosing can suppress CH₄ and N₂O formation. Moderate elevation of DO under

high acetate concentrations can inhibit methanogenesis; while maintaining DO at 2–3 mg·L⁻¹ during nitrite accumulation significantly reduces N₂O emissions.² The strength of data-driven control becomes apparent: operators can identify the “sweet spot” that minimizes chemical usage while ensuring compliance, thereby shifting from a conservative dosing approach to a precise strategy.

Energy and resource recovery

Promoting technologies such as high-efficiency anaerobic digestion, combined heat and power (CHP), and water-source heat pumps enables recovery of thermal energy from effluent and conversion of a significant portion of the wastewater's chemical energy into biogas, thereby advancing energy self-sufficiency and resource-efficient recovery at WWTPs.^{3,4} Data-driven analytics can optimize the balance among biogas production, heat recovery, and electricity consumption, maximizing net energy gains. International and domestic demonstration projects confirm the technical feasibility: some Danish plants achieved 150%–180% energy self-sufficiency by 2019,⁵ while China's Yixing demonstration plant (~1,000 m³·d⁻¹) achieved 80% self-sufficiency with 30%–50% lower nitrogen removal costs.⁴

Full life-cycle carbon management

Process optimization and resource recovery are primary “within-the-gate” mitigation strategies, but they must be assessed within a higher-level full life-cycle carbon management framework. This framework extends the accounting boundary from direct and energy-related emissions to the entire value chain emissions—including pipeline construction, chemical production, and sludge disposal—thereby ensuring that operational-level reductions are not negated by an increase in emissions elsewhere in the value chain. Mechanical sludge treatment units, for instance, represent significant emission hotspots, yet they are systematically excluded from most accounting protocols.⁶ Integrated data platforms are essential for tracking and verifying emissions across all scopes. Some forward-looking studies further suggest recognizing water conservation as a form of avoided emissions, since reducing water consumption indirectly lowers the energy and chemical inputs required for treatment.³

These three pathways operate in synergy, progressively reinforcing one another: intelligent control optimizes the efficiency of existing facilities; energy recovery reduces reliance on external electricity at its source; and comprehensive life-cycle management prevents emission reductions from being offset by increases in other processes. By advancing precise carbon accounting methodologies, enhancing data coverage and availability, and implementing technological and managerial interventions, we can fully unlock the carbon reduction potential and accelerate progress toward carbon neutrality for WWTPs (Figure 1).

OUTLOOK AND CONCLUSION

Looking ahead, over the next 3–5 years, standardized deployment of integrated real-time monitoring platforms paired with data analytics models should be prioritized, enabling carbon accounting to evolve from episodic

estimation to continuous, verifiable management. Concurrently, carbon accounting and management frameworks should systematically incorporate overlooked emission sources such as those arising from mechanical sludge treatment. A persistent challenge lies in ensuring the generalizability and adaptability of data-driven models and control strategies across diverse configurations of WWTPs.

In the long term, policymakers should prioritize enhancing carbon trading mechanisms, strengthening green finance policies, and refining technical standards, as these measures can collectively incentivize relevant sectors to proactively pursue carbon reduction initiatives. Effectively addressing these challenges necessitates interdisciplinary collaboration integrating environmental engineering, data science, and economics, thereby fostering synergistic technological advancements and institutional innovation.

Pollution control and carbon reduction are not conflicting goals but synergistic ones. Through technological innovation and system optimization, WWTPs can evolve from carbon emitters into carbon managers—shifting from passive emission regulatory compliance to active carbon-neutral planning pathways—and thereby contribute significantly to global climate targets.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.