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Low-Carbon Technology Strategies and Development Trends Analysis for Urban Wastewater Treatment

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Abstract. Under the dual constraints of carbon reduction targets and continuous improvement in water quality, urban wastewater treatment is shifting from a single focus on compliance discharge to an integrated approach emphasizing pollution reduction, energy recovery, resource recycling, and greenhouse gas control. This paper, based on the theoretical framework of direct, indirect, and embodied carbon emissions, focuses on evaluating five low-carbon strategies: precise aeration combined with digital twin technology, short-cut denitrification—anammox, anaerobic digestion of sludge with filtrate synergistic management, microalgae carbon fixation coupled treatment, and continuous-flow intermittent aeration. Studies have shown that intelligent aeration can significantly reduce ineffective power consumption by providing oxygen on demand, but the effect is constrained by sensor quality, model transfer, and control safety; anaerobic ammonium oxidation can shorten the nitrogen conversion pathway, but still faces bottlenecks; sludge anaerobic digestion can achieve energy recovery, but the high ammonia nitrogen and refractory organic matter in the thermal hydrolysis filtrate will cause backflow load; the microalgae system has the potential for carbon sequestration and nutrient recovery. However, its large-scale application is limited by factors such as light, land area, and energy consumption for separating the algae from the water; continuous-flow intermittent aeration can enhance the utilization of carbon sources in raw water, but it is necessary to prevent the rebound of ammonia nitrogen during the non-aeration period. In the future, water quality, direct greenhouse gas emissions, energy, chemicals, resources and costs should all be coordinated within the entire life cycle framework.

Keywords: Urban sewage treatment, low-carbon technology, precise aeration, anaerobic ammonia oxidation, resource recovery

1. Introduction

Urban sewage treatment plants are crucial infrastructure for ensuring the water safety of cities and improving the quality of receiving water bodies. However, their operation simultaneously consumes electricity, chemicals and materials, and generates greenhouse gases during the processes of sewage transportation, biological treatment and sludge disposal. Traditional evaluations usually focus on meeting discharge standards and energy consumption per unit of water, which may overlook off-site water distribution and transmission, resource substitution, as well as direct greenhouse gas

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emissions. Li et al. proposed that the system boundary for achieving carbon neutrality in wastewater treatment should extend beyond the plant boundary, and that the sewer networks, reclaimed water utilization, energy recovery, and resource recovery should all be included in the unified accounting; At the same time, energy self-sufficiency does not necessarily equate to carbon neutrality [1]. Therefore, the core of low-carbon wastewater treatment is not merely to reduce electricity consumption, but to prevent the transfer of pollutants, energy consumption and carbon emissions between different units.

In recent years, research on low-carbon technologies has taken on multiple paths. Microalgae can assimilate nitrogen and phosphorus in wastewater and fix CO_2, providing the possibility for the resource utilization of pollutants and biomass [2]. Partial nitritation–anammox and anaerobic ammonium oxidation reduce the demand for aeration and external carbon sources by shortening the nitrogen conversion pathway [3]. Machine learning can predict the changes in ammonia nitrogen in the aeration tank, providing a basis for the blower to supply air on demand [4]. Full-scale intelligent control and digital twins are also being applied to aeration optimization and equipment management [5]. However, the system boundaries, functional units, and evidence scales adopted by different studies vary significantly. The electricity savings rate, pollutant removal rate, and resource output cannot be directly equated to the total life cycle net carbon reduction.

Based on this, this paper takes the sources of carbon emissions as a necessary background, and selects five representative strategies for evaluation: precise aeration and digital twin, partial nitritation–anammox - anaerobic ammonium oxidation, sludge anaerobic digestion and filtrate collaborative management, microalgae carbon fixation coupled treatment, and continuous-flow intermittent aeration. The review content includes the mechanism of action, research cases, carbon reduction advantages, limitations and future development directions. This article mainly addresses three questions. First, through which pathways do these technologies achieve carbon reduction? Second, what operational conditions constrain their carbon reduction effects? Third, in different wastewater treatment scenarios, how should these technologies be combined? Through the above analysis, this provides a reference for the technical transformation of urban wastewater treatment plants and the assessment of low-carbon performance.

2. The main source of carbon emissions from urban sewage treatment

2.1. Direct emissions from biochemical reactions and sludge treatment

Direct emissions mainly consist of methane (CH_4), nitrous oxide (N_2O), and a portion of fossil carbon dioxide (CO_2). The anaerobic microzones in the pipeline network and reactors, as well as the sludge thickening and digestion processes, may result in the formation of CH_4; During the nitrification and denitrification processes, when fluctuations occur in dissolved oxygen, the carbon-nitrogen ratio, or nitrite accumulation, N_2O may be released as an intermediate product. Li et al. emphasized that fossil source CO_2 formed by industrial organic substances and additional carbon sources should also be included in the accounting process [1]. Therefore, reducing direct emissions cannot rely solely on end-stage gas collection; instead, it is necessary to reduce the generation and emission of greenhouse gases through measures such as dissolved oxygen control, carbon source allocation, sludge age management, and continuous gas monitoring.

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2.2. Indirect emissions from aeration, pumping and equipment operation

Electricity consumption is the main source of indirect emissions from wastewater treatment. Among them, aeration usually dominates, while booster pumps, reflux pumps, agitation, membrane cleaning and sludge dewatering also contribute to the continuous load. Yue et al. pointed out that the processes of aeration, sludge thickening, and others account for the majority of the energy consumption in a wastewater treatment plant. Inaccurate prediction of ammonia nitrogen load can easily lead to the long-term excessive supply of air by blowers [4]. Xu Liang's calculation for a certain sewage treatment plant in Guangdong showed that electricity consumption accounted for 95.21% of its total indirect carbon emissions, while PAC and PAM combined accounted for 4.79%; The unit electricity consumption of the sewage treatment plant decreases as the treatment scale increases [6]. This result indicates that the aeration and pumping systems are the key areas for energy conservation. However, the specific proportion varies depending on the process, discharge standards, grid emission factors, and treatment scale, and should not be directly applied to other wastewater treatment plants.

2.3. Embodied emissions from pharmaceutical materials, construction, and resource usage

The production and transportation of coagulants, additional carbon sources, membrane materials and equipment, the construction of structures, the transportation of sludge for dewatering, and the long-distance distribution and transmission of reclaimed water all result in embodied emissions. In the case of Xu Liang, although the emission proportions of PAC and PAM are lower than that of electricity, they still constitute emission sources that can be reduced through precise dosing [6]. If the calculation boundary is limited to the factory's electricity meters, it may mistakenly classify high chemical consumption, high material use, or long-distance pumping as low-carbon solutions; On the contrary, the substitution of biogas for purchased energy, the use of reclaimed water for conventional water sources, and the recycling of nitrogen and phosphorus for fertilizer can contribute to net carbon reductions. conventional water sources, and the recycling of nitrogen and phosphorus instead of chemical fertilizers can contribute to net carbon reductions. Therefore, the technical evaluation should clearly define the construction period, operation period, direct emissions, resource substitution, and the final destination of the products, to prevent the environmental burden from being transferred from one link to another [1].

3. Analysis of typical low-carbon wastewater treatment technology strategies

3.1. Precision aeration, machine learning and digital twin technology

Precision aeration uses online data such as ammonia nitrogen, dissolved oxygen, flow rate, temperature and sludge condition as inputs. Through soft measurement or predictive models, it determines the short-term oxygen demand, and then dynamically adjusts the frequency of blowers, valve openings and aeration zones. Yue et al. compared recurrent neural networks, long short-term memory networks, random forests and support vector machines, and reconstructed dynamic features through historical time windows; The results show that feature reconstruction has enhanced the accuracy, robustness and uncertainty representation ability of each model, among which the random forest achieved the best overall performance [4]. These methods can transform the traditional "fixed safety margin" oxygen supply into an on-demand oxygen supply that varies with the load, thereby reducing excessive aeration without altering the main structure.

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Engineering applications further demonstrate that prediction and control need to be coordinated with the equipment execution system. Zhou Run et al. took a sewage treatment plant with a designed capacity of 100,000 m^3/d and using the improved Bardenpho process as the research object, and compared the data from 14 months before and after the intelligent control renovation. After the renovation, the daily electricity consumption of the aeration system was reduced by 28.4%. At the same time, the fluctuation of DO in the aerobic zone was significantly reduced, and the control response time was significantly shortened [5]. This case demonstrates that intelligent control can simultaneously reduce energy consumption and improve operational stability. However, comparisons before and after in a single plant may still be affected by factors such as water inflow load, seasons, and equipment updates.

The performance of the model is highly dependent on the input variables and the quality of the data. Bagherzadeh et al. compared various feature selection methods in total nitrogen prediction and found that reasonable variable selection could increase the prediction accuracy by approximately 20%. The combination of mutual information selection and gradient boosting machine performed particularly well; However, the coefficient of determination of the test set is still limited, indicating that the optimal model based on a wastewater treatment plant may not possess the ability to generalize across different operating conditions [7]. Therefore, intelligent control should not only focus on offline fitting accuracy, but also incorporate sensor calibration, abnormal data identification, model rolling update, process constraints, and manual intervention mechanisms. The proper positioning of digital twins should be to assist in multi-objective decision-making, rather than being a black-box controller that is disconnected from the biological processing mechanism.

3.2. Shortcut nitrogen removal–anammox and coupled processes

The partial nitritation–anammox process relies on stable nitrite production in the partial nitritation stage, followed by the conversion of ammonium and nitrite to nitrogen gas by anammox bacteria. This approach can reduce the need for aeration and external carbon sources, while retaining more incoming organic matter for anaerobic energy production.

Du et al. constructed a partial denitrification - anaerobic ammonium oxidation coupled process. The results showed that the type of carbon source and temperature variations would significantly affect the nitrogen removal performance of the system [8]. From this, it can be seen that the type of carbon source and the structure of the functional microbial community significantly affect the stability of the coupled process. One cannot merely rely on theoretical chemical ratios to select operating parameters.

Wang et al. identified several key challenges for mainstream anammox, including biomass retention, stable partial nitritation, low-temperature stress, interference from actual influent components, and effluent nitrate control. They proposed to enhance retention using biofilms or granular sludge, inhibit nitrite-oxidizing bacteria through low sludge age and limited oxygen supply, and select pre-treatment and coupling processes based on regional water quality [9]. Overall, the advantages of this technology lie in reducing aeration and carbon sources in the reaction pathway. However, its limitations include a long start-up period, a narrow process window, and a slow recovery of the microbial community. In the future, emphasis should be placed on developing low-temperature acclimation, partial denitrification coupling, and online nitrogen component control, while simultaneously monitoring N_2O to avoid new direct emissions resulting from energy-saving operations.

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3.3. Sludge anaerobic digestion, energy recovery and co-management of filtrate

Anaerobic digestion of sludge converts volatile organic compounds into biogas through stages such as hydrolysis, acidification, acetogenesis and methanogenesis, while also achieving sludge stabilization and reduction. Thermal hydrolysis pretreatment can facilitate cell lysis and the release of organic substances, but it also alters the composition of the digestion filtrate. Tan Xuejun and others found through comparison that the concentrations of TN and NH_3-N in the high-temperature hydrolyzed advanced anaerobic digestion liquor were significantly higher than those in the ordinary anaerobic digestion, and the biodegradability of the residual organic matter was poor [10]. Therefore, while pre-treatment enhances the gas production potential, it may also transfer more nitrogen and recalcitrant organic matter to the liquid phase.

Li et al. further evaluated the feasibility of co-processing the thermal hydrolysis–anaerobic digestion filtrate by large and medium-sized urban wastewater treatment plants. Their research showed that the co-processing of thermal hydrolysis–anaerobic digestion filtrate could achieve stable compliance, but it would increase the system's electricity consumption and the demand for additional carbon sources [11]. This indicates that the energy benefits of the digestion unit cannot be evaluated independently from the main system. The reflux load of filtrate, additional aeration, and carbon source addition should all be included in the net carbon reduction calculation.

Anaerobic digestion is suitable for centralized wastewater treatment plants with large amounts of sludge, stable heat demand, and facilities for biogas utilization. Its carbon reduction effect depends on the organic matter conversion rate, methane collection rate, digestion tank heating, biogas purification, digestion liquid treatment, and the final disposal of the sludge [1, 10, 11]. Engineering optimization should prioritize enhancing the efficiency of local biogas combined heat and power generation or purification utilization, and directing the high ammonia nitrogen filtrate into the side-stream shortcut nitrogen removal - anaerobic ammonium oxidation unit; For the scheme of directly flowing back to the main stream, the maximum blending ratio should be determined based on the processing capacity margin, seasonal temperature and the carbon-nitrogen ratio of the incoming water.

3.4. Microalgae carbon sequestration coupling treatment and resource utilization

Microalgae utilize photosynthesis to absorb CO_2 and assimilate nitrogen, phosphorus and some organic substances present in wastewater, forming algal biomass that can be further processed into fertilizers, feed raw materials or bioenergy. You et al. believe that microalgae wastewater treatment not only has the potential for nutrient recovery and carbon reduction, and can be coupled with high-rate algal ponds, photobioreactors, and CO_2 utilization from flue gas or biogas [2]. Xu Tongtong et al. further explained the carbon sequestration process from the perspectives of the Calvin cycle, carbon concentration mechanism and environmental influencing factors, and pointed out that light intensity, photoperiod, temperature, pH, CO_2 concentration, as well as the interaction between algae and bacteria, all affect the efficiency of carbon sequestration [12]. Compared to converting nitrogen and phosphorus into sludge or nitrogen gas, this strategy emphasizes pollutant retention and resource recovery.

The limitations of microalgae technology are also quite prominent. Light attenuation, variations in day and night as well as seasons, low temperatures, algal species contamination, land occupation, and energy consumption for algal-water separation will reduce the overall economic and environmental feasibility. Xu Tongtong et al. summarized that although closed and adherent photobioreactors are easy to control, their manufacturing costs can be significantly higher than those

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of open raceway ponds. The capture of microalgae, substrate transportation, and reactor maintenance are also major cost sources [12]; You et al. pointed out that currently, there is no cultivation system that can be widely replicated under different water quality conditions [2]. Therefore, the microalgae process is more suitable for scenarios where there is better lighting conditions, accessible sites are available, and there are channels for biomass disposal. In the future, efforts should be made to develop symbiotic algae and bacteria, low-energy harvesting methods, and biomass cascade utilization. The calculation of carbon reduction benefits should be based on actual substitute products rather than theoretical production volumes.

3.5. Continuous flow intermittent aeration and optimization of operating modes

Continuous flow intermittent aeration maintains continuous water supply while periodically switching between aeration and non-aeration states, allowing the biochemical system to alternate between aerobic and anoxic conditions. This approach can facilitate nitrification, denitrification, and utilization of influent carbon sources. Chen Lin and others conducted a productive experiment at the Shandong Xiajin Sewage Treatment Plant. Different aeration–non-aeration cycles have a significant impact on the denitrification effect and the stability of ammonia nitrogen. Among them, an appropriate aeration–non-aeration cycle yields the best overall results. After adopting intermittent aeration, the total nitrogen removal capacity of the system was significantly enhanced. Under conditions of a low carbon-nitrogen ratio and without adding external carbon sources, the total nitrogen in the effluent could still be stably maintained at the level of the Class 1A discharge standard [13]. This case demonstrates that continuous flow intermittent aeration can utilize existing structures and equipment, and through optimization of operation mode, reduce unnecessary aeration and the need for additional carbon sources.

The advantage of this technology lies in its ability to optimize operation by utilizing the existing tank capacity and equipment, with a relatively low renovation threshold and the potential to reduce excessive aeration and the need for additional carbon sources. The duration of the non-aeration period needs to be balanced between ammonia nitrogen removal and denitrification. If the shutdown period is too short, the denitrification potential may not be fully realized; If the aeration period is too long, ammonia nitrogen may rebound. Too frequent start-stop of the fans will also increase the burden on operation management and equipment [13]. The current cases mainly demonstrate the nitrogen removal and carbon source saving effects, but do not separately quantify the aeration power consumption and the reduction in greenhouse gas emissions.

4. Common challenges and development directions

4.1. Common challenges

The current research still faces issues such as inconsistent boundaries and functional units for carbon accounting, significant differences in the scales of evidence across different studies, and the burden transfer during the resource utilization process; at the same time, reducing aeration energy consumption and chemicals may affect the stability of pollutant removal, and even increase N_2O emissions. Therefore, the carbon reduction effects of different technologies still need to be compared under consistent system boundaries, functional units, and assessment methods as well as over a long period of operation.

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4.2. Development direction

Future research should shift from individual equipment energy conservation to system collaboration, and establish a full life cycle evaluation framework covering water quality, greenhouse gases, energy, chemical materials, resources and products, as well as costs; combining mechanism models, machine learning and digital twins to enhance the applicability of technologies wastewater treatment plants; based on factors such as water inflow quality, temperature, land conditions and treatment capacity, a technical combination is carried out, and the actual net carbon reduction effect is verified through long-term full-scale demonstrations.

5. Conclusion

The core of low-carbonization in urban sewage treatment is not to merely implement scattered energy-saving measures for traditional processes, but to reconfigure the paths of pollutant transformation, energy utilization, and resource recycling. The five types of strategies discussed in this article have different applicable boundaries. Precise aeration and digital twin technology can rapidly reduce ineffective oxygen supply, but they rely on high-quality sensors, data, and secure control. shortcut nitrogen removal - anaerobic ammonium oxidation has a relatively high potential for energy savings through shortening the nitrogen, but it is sensitive to low temperatures, bacterial retention, and nitrite supply. Anaerobic digestion of sludge can achieve energy recovery. However, the high ammonia nitrogen and difficult-to-degrade organic matter in the thermal hydrolysis–anaerobic digestion filtrate will increase the main treatment load. Therefore, in-plant collaborative accounting needs to be carried out. The microalgae system can simultaneously fix CO_2, recover nutrients and form biomass. However, its large-scale application is still limited by factors such as light, space occupation and harvesting costs. Continuous-flow intermittent aeration can enhance nitrogen removal and reduce the need for additional carbon sources by utilizing the existing pool capacity. However, it is necessary to prevent the rebound of ammonia nitrogen during the shutdown period. From this, it can be seen that no single technology can be universally applied the operational conditions of different cities and sewage treatment plants. The future should be based on the bottom line of achieving stable compliance and net carbon reduction throughout the entire life cycle. Intelligent control, low-carbon biological processes, sludge energy recovery and resource recovery units should be hierarchically combined based on the conditions of the plant site, gradually forming a measurable, verifiable and replicable technical system, and promoting the transformation of wastewater treatment plants from pollution-endpoint treatment facilities to a platform for coordinated management of water, energy, carbon and nutrients.

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