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PERSPECTIVES

Scientific and technological innovations of wastewater treatment in China

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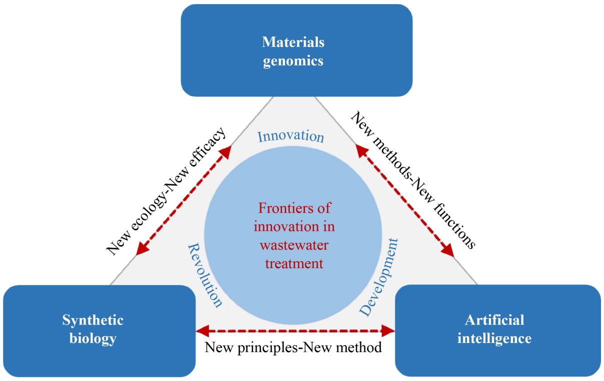
HIGHLIGHTS

- Wastewater treatment targets and processes change with demands.
- Research hotspots in wastewater treatment were described using bibliometrics.
- Five pathways for technology development were proposed.
- Material genetics, synthetic biology, artificial intelligence were highlighted.

GRAPHIC ABSTRACT



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ABSTRACT

The “dual-carbon” strategy promotes the development of the wastewater treatment sector and is an important tool for leading science and technology innovations. Based on the global climate change and the new policies introduced by China, this paper described the new needs for the development of wastewater treatment science and technology. It offered a retrospective analysis of the historical trajectory of scientific and technological advancements in this field. Utilizing bibliometrics, it delineated the research hotspots within wastewater treatment, notably highlighting materials genomics, artificial intelligence, and synthetic biology. Furthermore, it posited that, in the future, the field of wastewater treatment should follow the paths of technological innovations with multi-dimensional needs, such as carbon reduction, pollution reduction, health, standardisation, and intellectualisation. The purpose of this paper was to provide references and suggestions for scientific and technological innovations in the field of wastewater treatment, and to contribute to the common endeavor of moving toward a Pollution-Free Planet.

1 New demands for innovative development of wastewater treatment science and technology

1.1 Responding to global change: wastewater treatment technology needs urgent development

The continued worsening of global climate change and environmental pollution have created unprecedented challenges for humanity and urgently require a collective response from the international community. Since the signing of the Paris Agreement in 2015, there has been a significant acceleration in the establishment of a global environmental governance system. On August 15, 2023, the United Nations Environment Programme (UNEP) released “*The United Nations Environment Programme strategy for tackling climate change, biodiversity and nature loss, and pollution and waste from 2022–2025*”. This suggests that there is an urgent need to strengthen water environment management and accelerate digital

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transformation.

In recent years, the concept of "Planetary Boundaries" has provided a new perspective for addressing global environmental issues (Rockström et al., 2009). It emphasizes the wholeness of the earth's ecosystem, with water playing a central role in maintaining overall ecological stability. Scientific and technological innovations in wastewater treatment are crucial for promoting synergies between pollution reduction and carbon reduction, as well as sustainable development.

1.2 China's new policies boost wastewater treatment technology

Currently, China's wastewater treatment industry is encountering a new situation concerning carbon peak and carbon neutrality, pollution reduction and carbon synergy, emerging contaminants, equipment innovation, industrial standardization, and intellectualisation, as shown in Fig. 1.

In October 2021, the CPC Central Committee and the State Council issued the "*Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in full and faithful implementation of the new development philosophy*" and in June 2022, the "*Synergize the Reduction of Pollution and Carbon Emissions Program of Implementation*" was launched. These policies articulated the importance of synergistic innovation for pollution reduction and carbon reduction, and set higher requirements for water environment management. In January 2022, three ministries, including Ministry of Industry and Information Technology (MIIT), jointly issued the "*Action Plan for High-Quality Development of Environmental Protection Equipment Manufacturing Industry* (2022–2025)", calling for breakthroughs in key technologies. Additionally, environmental protection equipment was included as a key area in the "*National Industrial Base Development Catalogue* (2021 Edition)" in July 2022, providing directions for the development of environmental protection equipment. The "14*th Five-Year Plan for the Development of the Digital Economy*" and the "14*th Five-Year Plan to Promote the Implementation of Intelligent Water Conservancy Construction*" pointed out that the digital transformation of industry should be vigorously promoted. Therefore, the wastewater treatment process should achieve intelligent control and decision-making through the deep integration of information technology and water technology. On January 11, 2024, the CPC Central Committee and the State Council released the "*Opinions on Comprehensively Promoting the Construction of Beautiful China*", outlining the target path, key tasks, and major policies, and provides detailed initiatives. It also promotes green and low-carbon development, improves the quality of ecological environment so as to move toward a "Zero Pollution Planet".

China's new policies are accelerating scientific and technological innovations to promote low-carbon technology, original equipment, intelligent management and control, and highly simplified engineering.

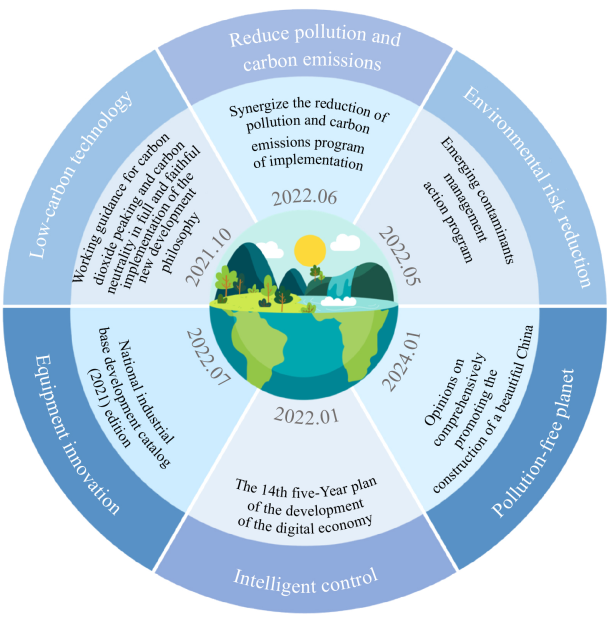

Fig. 1 China's latest policies related to wastewater treatment.

2 Scientific and technological innovations in wastewater treatment

2.1 The history of wastewater treatment technology development

Wastewater treatment technology can be traced back to the 18th century in the UK, when coagulation and sedimentation were mainly used to treat sewage. The acceleration of industrialization and urbanization exacerbated water pollution, leading to increased demand for water pollution control. These needs have evolved from suspended solids removal to killing pathogenic bacteria, removing nitrogen, phosphorus and organics, to quest for water reuse and health. These evolutions finally led to the development of pollutant metrics that have expanded from suspended solids to pathogens, BOD, total nitrogen, total phosphorus, emerging contaminants and ecotoxicity. Therefore, wastewater treatment processes have also been improved to meet changing demands and standards.

2.2 Frontier developments in wastewater treatment science and technology

As shown in Fig. 2(a), bibliometrics analysis of SCI papers on the topic of "water treatment" in the Web of

Science Core Collection database illustrated water remediation technology and machine learning were hot research topics in recent years. Current research hotspots in physical and chemical treatment focused on advanced oxidation technology. In particular, important development directions included the application of photocatalysis and nanomaterials, efficient removal of ammonia and nitrogen, utilization of green chemicals, short-flow processes and resource utilization of wastewater (Sun et al., 2022). As shown in Fig. 2(b), the analysis of scientific papers on the topic of "biological water treatment" using the aforementioned method revealed that environmental remediation, detoxification, consolidated bioprocessing, emerging contaminants and machine learning were the current research hotspots. The activated sludge method and the anaerobic-aerobic combined method were the two mainstream biological treatment technologies. The construction of functional bacterial colonies, high mass transfer bioreactors, and intelligent control of biological treatment were the development directions of biological water treatment (Jin et al., 2023).

At present, a new wave of global scientific and technological revolution and industrial change is emerging. New technologies such as material genomics, synthetic biology, and artificial intelligence are being integrated into scientific and technological research on wastewater treatment. Material Genomics integrates the threemaincomponentsofhigh-throughputmaterialcomputational design, high-throughput material experiments and material databases, accelerating the whole process from discovery to application of new materials for wastewater treatment to realize "on-demand design". It has been applied in the preparation of new high-efficiency catalysts, adsorbents, etc. Recently, we screened XGBoost as the best model to accurately predict the performance of metal organic frameworks (MOFs) for different pollutants from theoretical databases (Li et al., 2023).

Synthetic biology is used to design and modify biological systems to construct efficient degrading flora for typical environmental pollutants (Yang et al., 2022). It provides green solutions for pollution control and environmental remediation. It has also been used to develop microbial sensors that can monitor changes in water quality and detect pollutants. Additionally, it has been used to construct flora capable of degrading oil and heavy metal pollution.

Artificial intelligence technology using modern information technology and intelligent algorithm models, integrating multi-dimensional data sources of wastewater treatment and data mining and intelligent analysis, provides efficient and accurate decision-making support for wastewater treatment processes (Zhao et al., 2020). It has been used for monitoring and early warning, accurate aeration, intelligent dosage control and energy management. A novel graph neural network model for screening environmental estrogens was developed in our group recently, achieving accuracy rates of 88.9% and 92.5% on the internal and external test sets, respectively (Fan et al., 2023).

3 Pathways for scientific and technological developments in wastewater treatment

3.1 Pathways for carbon reduction technologies for wastewater treatment

Direct carbon emissions from wastewater treatment are primarily composed of CO_2, CH_4, and N_2O. CO_2 is mainly generated from the energy consumption process of wastewater treatment facilities, while CO_2 generated from the degradation of water pollutants is recognized as a biogenic carbon emission. CH_4 mainly originates from anaerobic units of wastewater treatment, including pipeline networks, anaerobic tanks, septic tanks, anaerobic digesters for sludge, and so on. N_2O mainly arises from

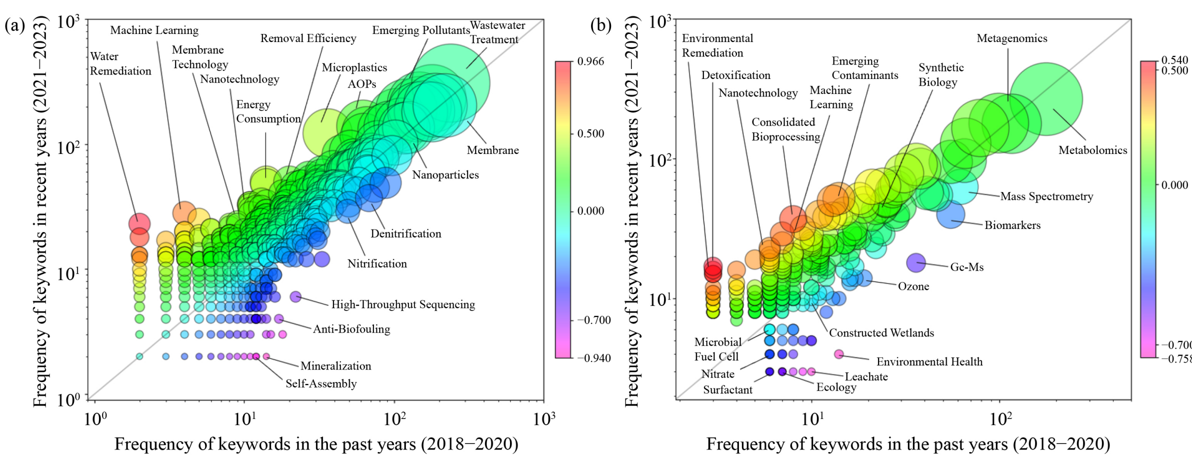

Fig. 2 Research hotspots of wastewater treatment: (a) physical and chemical treatment; (b) biological treatment.

the nitrification and denitrification stages (Li et al., 2022). Indirect carbon emissions are mainly the consumption of electricity, pharmaceuticals and so on. When considering carbon reduction in wastewater treatment, it is important to address three aspects: reducing carbon at the source, replacing carbon in the process, and sequestering carbon at the end. It is necessary to renovate and repair water supply and wastewater pipeline networks, optimize wastewater treatment processes, replace high-energy-consumption equipment, and implement intelligent management. Part of the carbon emissions from the heating and power supply process can be replaced by utilizing heat and organic matter in wastewater and sludge, recycling reclaimed water, and enhancing water ecosystems such as ecological buffer zones and wetlands. It is also important to enhance the capacity of carbon sequestration at the end.

3.2 Pathways for coupled carbon reduction and pollution reduction technologies for wastewater treatment

Processes that meet high water quality standards can be challenging to achieve with low carbon emissions. For example, the A^2/O + MBR process can emit up to 2.3 kg/m^3 of carbon, 2.83 times more than that of A^2/O process (Hu et al., 2021). Therefore, it is important to consider the coupling of carbon reduction and pollution reduction technologies. An example of process reconfiguration was presented in our group which involved influent carbon shift to recovery methane, algae-biofilm biofilm reactor for nitrogen and phosphorus removal and carbon capture, autotrophic denitrification, advanced denitrogenation and detoxification, intelligent process control for reduction of energy and chemicals consumption, CO_2 utilization to produce acetic acid, synergy of wastewater-sludge-gas processing, recovery of thermal energy, as shown in Fig. 3.

3.3 Synergistic technology development path of “carbon reduction, pollution reduction and health” for wastewater treatment

In recent years, elevated effluent toxicity caused by secondary metabolites produced during wastewater treatment and water quality health risks associated with long-term exposure to low concentrations of complex contaminants at the end of the treatment, have become growing concerns (Zhang et al., 2023). To address these issues, people must concentrate on pollution, climate change and their dual impacts on water quality risk prevention and control mechanism of the core issues. In wastewater treatment carbon reduction, pollution reduction goals based on the increase in the “risk prevention and control” connotation, coupled to form a “carbon reduction-pollution reduction-health” synergistic technology system. The system should prioritize scientific and technological innovations aimed at controlling water quality and health risks, rather than only focusing on the control of emerging contaminants. Resourceful and environmentally friendly solutions should be proposed, taking into account the entire wastewater elements and should be guided by carbon emission reduction and risk effect indicators.

3.4 Development paths of the standardisation system for synergistic effect of pollution reduction and carbon emission

Since the release of the “*Trial Discharge Standard of Industrial Three Wastes* (GB J4-73)” in 1973, China’s wastewater pollutant emission standards have been gradually upgraded, experienced by the comprehensive to industry-focused, and then to the comprehensive and industry-based emission standards parallel structure system. China has over 900 water treatment standards, which are divided into eight categories: methods, technology, materials, equipment, discharge, quality, management, and engineering. However, the number of standards varies significantly between different sub-divisions. It was found that the number of standards for wastewater treatment engineering, quality and management was low, while standards for low-carbon water treatment were particularly lacking. In the future, it is recommended to promote the development of a standard system that covers the entire low-carbon water treatment chain. This system should include

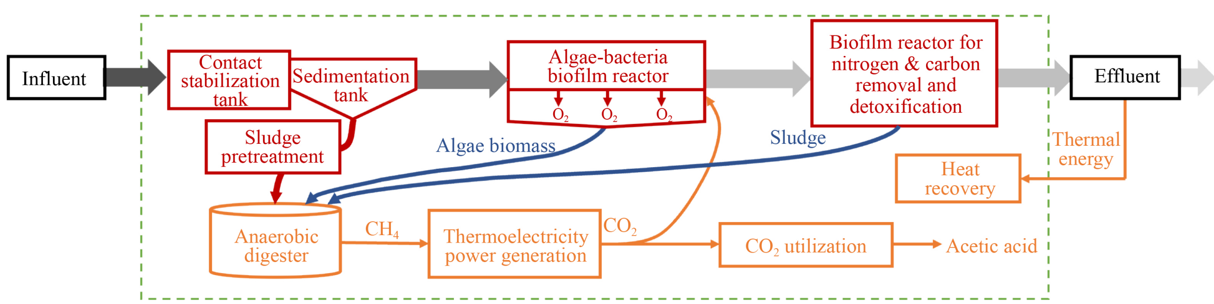

Fig. 3 An example of process reconfiguration for coupled carbon reduction and pollution reduction technologies for wastewater treatment.

"carbon accounting - synergistic reduction technology of carbon and pollution - equipment - materials - engineering - evaluation - management". This entire system can facilitate and support the synergistic effect of carbon and pollution reduction in wastewater treatment and also empower scientific and technological innovations.

3.5 Intelligent development paths for wastewater treatment

The intelligent transformation of wastewater treatment industry, should focus on promoting big data-driven functional materials and process optimization researches. A holographic database of functional materials for wastewater treatment should be constructed based on multi-dimensional information on the physical properties (atomic types, phases, structures, etc.) and reaction energies (action parameters, adsorption energies, catalytic activities) of the functional materials, with intensive data management and data interconnection. Then it can be oriented to the efficient removal of conventional pollutants, characteristic pollutants and new pollutants. It can also use artificial intelligence technology to predict the potential structure and function of functional materials, locate the key reaction steps, and focus on biodegradable materials, new materials of metal-organic skeleton, molecular sieve materials, etc., to build new functional materials with high adsorption, catalytic properties, and new functional materials without secondary pollution (Al Sharabati et al., 2021). Regarding process reconstruction, the optimization of synergistic control of conventional, characteristic, and new pollutants should be guided by focusing on multi-objective and short-flow wastewater treatment processes (Kang et al., 2023). Additionally, new wastewater treatment processes in the context of dual-carbon should be reconstructed using mechanism modeling, simulation, multi-objective decision-making, and experimental validation.

4 Outlook

"Double carbon" strategy is accelerating the promotion of scientific and technological innovations in wastewater treatment, and the development trend of low-carbon technology, original equipment, healthy water quality, industry standardization and intelligent control is becoming more and more clearer. Wastewater treatment industry should take the advantage of the current historical opportunity and utilize the latest scientific and technological advancements to develop a new business model of "water treatment plus", i.e., to create a new system that synergizes carbon reduction, pollution reduction, health, and intelligentization. Furthermore, it is important to emphasize the integration and fusion of new technologies such as material genomics, synthetic biology and artificial intelligence in wastewater treatment. This will contribute to high-level scientific and technological innovations, leading to high-quality water environmental protection and healthy development, and ultimately moving toward a zero-pollution planet.

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Conflict of Interests The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Al Sharabati M, Abokwiek R, Al-Othman A, Tawalbeh M, Karaman C, Orooji Y, Karimi F (2021). Biodegradable polymers and their nano-composites for the removal of endocrine-disrupting chemicals (EDCs) from wastewater: a review. Environmental Research, 202: 111694

Fan F, Wu G, Yang Y, Liu F, Qian Y, Yu Q, Ren H, Geng J (2023). A graph neural network model with a transparent decision-making process defines the applicability domain for environmental estrogen screening. Environmental Science & Technology, 57(46): 18236–18245

Hu Y, Liang M, Zhang Y, Wang K (2021). Study on operation efficiency and carbon emission characteristics of A^2/O + MBR process. China Environmental Science, 41(9): 4439–4446 (in Chinese)

Jin L, Sun X, Ren H, Huang H (2023). Hotspots and trends of biological water treatment based on bibliometric review and patents analysis. Journal of Environmental Sciences (China), 125: 774–785

Kang D, Zhao X, Wang N, Suo Y, Yuan J, Peng Y (2023). Redirecting carbon to recover VFA to facilitate biological short-cut nitrogen removal in wastewater treatment: a critical review. Water Research, 238: 120015

Li J, Wang J, Mu H, Hu H, Wang J, Ren H, Wu B (2023). Prediction of adsorptive activities of MOFs for pollutants in aqueous phase based on machine learning. ACS ES&T Engineering, 3(9): 1258–1266

Li L Q, Wang X H, Miao J Y, Abulimiti A, Jing X S, Ren N Q (2022). Carbon neutrality of wastewater treatment: a systematic concept beyond the plant boundary. Environmental Science and Ecotechnology, 11: 100180

Rockström J, Steffen W, Noone K, Persson Å, Chapin F S III, Lambin E F, Lenton T M, Scheffer M, Folke C, Schellnhuber H J, et al. (2009). A safe operating space for humanity. Nature, 461(7263): 472–475

Sun X, Jin L, Zhou F, Jin K, Wang L, Zhang X, Ren H, Huang H (2022). Patent analysis of chemical treatment technology for wastewater: Status and future trends. Chemosphere, 307(Pt 4): 135802

Yang Z, Sun H, Zhou L, Arhin S G, Papadakis V G, Goula M A, Liu G, Zhang Y, Wang W (2022). Bioaugmentation with well-constructed consortia can effectively alleviate ammonia inhibition of practical manure anaerobic digestion. Water Research, 215: 118244

Zhang H, Quan H, Song S, Sun L, Lu H (2023). Comprehensive assessment of toxicity and environmental risk associated with sulfamethoxazole biodegradation in sulfur-mediated biological wastewater treatment. Water Research, 246: 120753

Zhao L, Dai T J, Qiao Z, Sun P Z, Hao J Y, Yang Y K (2020). Application of artificial intelligence to wastewater treatment: A bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. Process Safety and Environmental Protection, 133: 169–182

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Hongqiang Ren an academician of the Chinese Academy of Engineering and currently holds positions as a professor, doctoral supervisor, and dean at School of the Environment, Nanjing University. He is the head of National Excellent Engineer Team “Industrial Wastewater Treatment Technology and Equipment”, and the project leader of Basic Science Center Project of the National Natural Science Foundation of China (Water Quality Risk Control Engineering). He has long been engaged in the innovative research on industrial wastewater treatment and prevention and control of water pollution in industrial parks, published more than 300 peer-reviewed papers and 5 monographs, authorized more than 120 invention patents in China and over 40 patents in the US and the European Union, presided over the compilation of more than 100 international and domestic standards. He has won a total of 17 important awards including 3 second prizes of the National Technological Invention Award, 1 second prize of the National Natural Science Award, 1 Ho Leung Ho Lee Foundation Science and Technology Innovation Award, 7 first prizes of the Provincial and Ministerial Science and Technology Awards, 1 ISO Outstanding Contribution Award, and 1 China Standard Innovation Contribution Award.