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Research Progress on Resource Recovery in Industrial Wastewater Treatment

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Abstract: The implementation of the strategy of circular economy and green development has changed people's understanding of industrial wastewater, which is no longer regarded as a burden, but has unlimited potential in resource utilization, and can bring good benefits to enterprises. The research focuses on the development of industrial wastewater resource recovery from three aspects: technological progress, policy support and economic pressure, and introduces the research results of scholars in recent years from the aspects of chemical energy conversion, water resource circulation and reuse, and the selective recovery of high value substances. It is suggested that in order to improve the efficiency of resource recovery, we should not only promote the development of industrial wastewater treatment technology, but also strengthen the governance of multiple stakeholders, and provide theoretical support for the sustainable development of industrial wastewater resource recovery.

Keywords: Industrial wastewater; Resource recovery; Treatment technology

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1. Introduction

With the continuous development of industrialization, the discharge of industrial wastewater has not been effectively controlled, which has a serious impact on the ecological environment. Many toxic substances in industrial wastewater will enter the soil and water through various ways, which will not only lead to the destruction of the ecological environment, but also accumulate in the food chain, which is enough to threaten human health. Therefore, the construction of an ecological society is conducive to the sustainable development of resources. Industrial wastewater is a complex system with a complex composition and a strong "duality". It contains a large number of pollutants, but also has a variety of valuable resources, which should not be regarded as a "burden" in the process of processing, but should be regarded as a recyclable resource. The valuable components contained in it are conducive to the realization of resource recycling. Practice shows that the recovery of industrial wastewater can bring benefits to many fields. Taking Ulsan City in South Korea as an example, the municipal sewage after treatment can be used for agricultural irrigation, industrial cooling, and so on, which promotes the sustainable utilization of water resources.

At present, the wastewater treatment technology is relatively backward, and the traditional governance model of "energy dissipation" is still used, which consumes a large amount of energy, and the pollutants are transferred or transformed through physical, chemical and biological processes, which is not conducive to the realization of material cycle, and many challenges are encountered in the development of the model. First, the system will emit a large amount of carbon dioxide, resulting in a larger carbon footprint. Second, the utilization rate of resources is low, and it is difficult to deal with the complex pollutants, which will have a negative impact on public health and the ecological environment [1]. This approach will not only bring a heavy burden to the environment, but also lead to the permanent loss of chemical energy, water resources and a series of valuable elements. By analyzing the life cycle, it is not conducive to the sustainable development of the environment and economy [2]. At present, the pressure of resource shortage in the world is increasing, and the shortage of fresh water has become a bottleneck for socio-economic development. At the same time, the supply chain of strategic resources such as lithium, potassium and phosphorus is not stable, and the geographical distribution is relatively concentrated. If traditional approaches are adopted in wastewater treatment, the waste will be regarded as waste solely, which is not in line with the requirements of circular economy, and will cause a serious waste of strategic resources [3]. Therefore, we should not only promote the upgrading of the industry, but also enhance the awareness of resource recovery, and make efforts to achieve the goal of carbon reduction and pollution reduction.

In this case, we should focus on the development of industrial wastewater treatment technology and explore how to recover resources from wastewater. Firstly, we should analyze the external environment and internal driving force of the development of the industrial wastewater treatment industry, from the three aspects of technological innovation, economic incentives and policy incentives. Secondly, we should analyze the three types of resources, analyze the challenges faced by them in the process of recovery, and explore the development of the recovery mechanism. Finally, the paper puts forward effective strategies to improve the efficiency of resource recovery from three aspects, which can provide theoretical support for the formulation of industrial policies and the innovation of technology.

2. Analysis of the current state of industrial wastewater treatment

2.1. Policy incentives

Under the guidance of "double carbon" goals, the treatment of industrial wastewater has become a key component in the process of carbon reduction. The National Development and Reform Commission issued the "Special Management Measures for Central Budgetary Investment in Energy Saving and Carbon Reduction" in 2024, which requires that energy saving and carbon reduction upgrading should be carried out in the petrochemical, steel and other fields, and the construction of waste recycling system should be supported by circular economy initiatives [4]. The implementation of this policy requires enterprises to guide the use of resources with central budget funds, and the transformation of water treatment technology should be more energy-saving and neutral. In 2022, six ministries jointly issued the "Implementation Plan for Industrial Wastewater Recycling", which clearly requires that the water reuse rate of large enterprises should reach 94% by 2025 [5]. In order to ensure the smooth implementation of the policy, it is necessary to deepen the legislation at the local level. For example, Lvliang City in Shanxi Province has formulated the "Regulations on the Utilization of Industrial Solid Waste", set up a special support fund, and encouraged enterprises to develop high-value solid waste utilization technology [6]. The introduction of the circular economy legislation and the formulation of strict emission standards have jointly promoted the development of resource recycling, and the implementation of a series of policies has made the development of industrial wastewater treatment more powerful, and the concept of regarding water as a resource has been gradually recognized.

2.2. Economic motivations

Economic factors plays a crucial role in the implementation of the path of industrial water resource recovery. In the process of development, water resources have become more scarce, the price of energy has risen, and strategic resources have become more scarce, which has changed the economic calculation of industrial water treatment projects. The 2024 World Water Report points out that the world's water resources are becoming more scarce, with frequent floods, droughts, and overexploitation of groundwater in some regions, and the soil is dry. Some regions are under water stress, which has a serious impact on the ecological environment and agriculture. At the same time, the 2024 World Energy Outlook points out that the price of fossil fuels has been increasing, and the cost of traditional water treatment has increased. Compared to this, anaerobic digestion technology can not only recover energy, but also offset the cost of purchasing energy, and its economic competitiveness is increasing.

The price of strategic resources is increasing, the supply is decreasing, and the price is fluctuating, which is enough to show that the economic rationality of resource recovery is increasing. The increasing demand for natural resources in industrial production will cause serious environmental problems, and the increasing scarcity of resources will lead to the weakening of the stability of the global natural resource trade, and the price of resources will also change. The mining activity can release a large number of toxic substances, which in turn exerts a negative impact on the ecological environment [7]. With the continuous increase of global gold demand, the cost and difficulty of mining have increased, and the importance of gold recovery has been recognized. The chitosan interpenetrating metal organic framework has a gold removal efficiency of 68.88% in electroplating wastewater, achieving the purpose of gold recovery [8]. The convergence of economic factors has changed the cost-benefit analysis of industrial water treatment, and the industrial water treatment has changed from a cost center to a profit center.

2.3. Technological development

In the process of industrial development, the technology of resource recovery has been continuously updated, and the key enabling materials have been continuously innovated, which has laid the foundation for the upgrading of biological treatment technology. The performance of membrane materials has been significantly improved, which can control the pore size and surface charge, and can separate valuable resources from pollutants. For example, amine-modified polyamide ultrafiltration membrane can retain dye molecules, but cannot retain inorganic salt, which can significantly improve the separation efficiency [9].

In the field of biotechnology, the emergence of anaerobic process and microbial resource recovery technology has changed the traditional treatment model, changed the traditional "pollutant removal" to "resource synthesis", and used aerobic granular sludge as a biological carrier to enhance the system's tolerance and improve the efficiency of toxic wastewater treatment. At the same time, the use of microalgae-bacteria symbiotic system and the cultivation of special microbial strains can not only degrade organic matter, but also recover biomass and energy. The application of self-healing smart materials can solve the problem of complex industrial environments, and the function of the material can be restored after damage, which improves the stability of operation and the durability of equipment [10].

Generally speaking, the formulation of reasonable policies is conducive to the realization of strategic goals, and the economic value is increasing, which provides impetus for the development of the market, and the continuous upgrading of technology can support the realization of goals. The integration of the three elements can enhance synergy, and the traditional industrial water treatment model has changed, which is conducive to the development of the circular economy.

3. Pathways for resource recovery from industrial wastewater treatment

3.1. Efficient reuse and recycling of water resources

In the process of advanced oxidation, a large number of free radicals are produced, which have strong activity and can effectively eliminate refractory organic pollutants in water, and the water quality is improved, which is conducive to the reuse of water resources. Ozone oxidation is one of the more common technologies, which is usually used in conjunction with Fenton oxidation technology. If the conditions are met, the removal rate of organophosphorus pollutants can reach more than 87%. Some technologies can even decompose organophosphorus compounds into inorganic compounds, which can simplify the subsequent treatment process [11]. The most prominent advantages of these technologies are that they will not cause secondary pollution, and the reaction speed is relatively fast, which can be used for the pretreatment of industrial wastewater and the advanced purification of toxic and harmful substances, and the water reuse rate can be improved.

In the process of membrane separation, the selective permeability mechanism is used to filter the pollutants, which is an effective method to improve water quality and reuse water resources. The ultrafiltration membrane has been modified, and the hydrophilization and photocatalytic functions have been enhanced, which can play an important role in improving the separation efficiency and resisting pollution. It can remove a variety of pollutants, including heavy metals, COD, and so on [12]. This technology has been widely used in the purification of river water, industrial wastewater and domestic sewage, and can also save energy and reduce the occurrence of phase change, which can play an important role in the production of reclaimed water and the construction of circulating water system.

3.2. Efficient conversion of chemical and thermal energy

Industrial wastewater contains a certain amount of thermal energy and chemical energy. If it can be converted efficiently, it is an effective way to recover resources. In the process of chemical energy recovery, anaerobic digestion technology can convert organic matter into methane, which can be used as energy. Microbial fuel cells can directly convert chemical energy into electricity, and the battery system can be combined with aluminum slag filler to improve the efficiency of heavy metal wastewater treatment [13]. In the process of thermal energy recovery, the textile dyeing industry can recover waste heat and cooperate with the treatment process to reduce energy consumption. Although the technologies are different, they all reflect the significance of transforming the wastewater treatment paradigm [14].

In the process of energy recovery, we should pay attention to whether the technology is economically viable, and the premise is to improve the energy conversion efficiency and achieve energy balance. For low-concentration wastewater, the energy density is relatively low, and the energy recovery is not economically viable, so we should improve the conversion efficiency, optimize the process, and adopt the method of combined heat and power generation to treat other waste streams and improve the energy output. In the next stage of research, we should focus on increasing the energy output, reducing the cost and improving the stability of the system, so as to promote the commercial application of industrial wastewater energy recovery.

3.3. Selective recovery of nutrients and high-value materials

Industrial wastewater is a potential reservoir of various valuable substances, including inorganic salts, nutrients, precious metals and so on. Struvite crystallization can recover nitrogen and phosphorus, and stripping absorption can recover ammonia nitrogen, which can promote the recycling of nutrients [15,16]. In the process of recovering precious metals and heavy metals, ion exchange and adsorption technology can play an important role because of their strong selectivity [17]. In the process of removing inorganic salts, crystallization and other processes can achieve zero liquid discharge of wastewater [18].

The economic benefits of the technology depend on the value of the products, and the higher the purity, the more valuable the product. The purity of the product will have a direct impact on the quality of the salt, which requires continuous optimization of the recovery process to improve the purity of the product and meet the needs of the market, which is the fundamental way to achieve the goal of resource recovery.

4. Analysis of strategies for enhancing resource recovery efficiency

4.1. Synergistic integration of industrial wastewater treatment technologies

In the process of industrial wastewater treatment, the model of pollution control is changing, and the environmental remediation and resource utilization are gradually unified. In this process, we should pay attention to the low consumption and high efficiency of the process, and the integration of different unit technologies can play the role of complementarity, so as to make up for the shortcomings of a single technology and improve the efficiency of resource utilization. For example, ozone catalytic oxidation technology can be used to deal with chemical wastewater, which can play the role of VPSA-O_2, use pressure swing adsorption technology to enrich oxygen, and create a good environment for oxidation reaction, which can play the role of catalytic oxidation, and destroy refractory organic matter. In this way, the energy consumption of the whole system can be reduced and the treatment efficiency can be improved. At the same time, the integration of activated carbon adsorption and photocatalytic oxidation can play the role of activated carbon, concentrate pollutants on the catalyst surface, and enhance the reaction rate, which can destroy dye molecules and recover resources [19].

Technological coupling can make up for the shortcomings of traditional technology, build a closed-loop system, and promote the transformation of waste into resources. For example, the integration of hydrogen technology and microbial fuel cells can not only purify water, but also convert chemical energy into electricity, obtain high-value hydrogen, and achieve the purpose of energy recovery and pollution control [20]. The process coupling method can break the limitations of the traditional linear model, optimize the energy flow and material flow, recover valuable substances, and achieve the goal of pollution reduction. The construction of industrial wastewater treatment system should be sustainable, and the emission of pollutants should be close to zero.

4.2. Establishment of an assessment framework for wastewater resource recovery

In the process of promoting the transformation of industrial wastewater treatment, we should pay attention to the importance of resource recycling and build a scientific and reasonable assessment system to make a comprehensive evaluation of the environmental benefits and real value of resource recycling. The traditional assessment method only focuses on the cost and technical efficiency, and does not pay attention to the impact of the whole process of resource recycling on the ecological environment and energy consumption. Therefore, it is necessary to combine LCA, TEA and other methods to analyze the environmental impact, economic benefits and resource consumption in the whole process of technology operation and construction, and to make a comprehensive analysis of the utilization of products. For example, the waste heat in industrial wastewater can be recovered through the water source heat pump, and the LCA method can be used to analyze it to see whether it can save energy and reduce carbon emissions, which can make up for the shortcomings of the economic aspect and provide a basis for decision-making [21]. In the process of building this evaluation system, we should guide the capital to the most sustainable and efficient path, and build an indicator system with the help of "carbon footprint", "environmental gains and losses", "resource recovery purity" and other indicators, and make a horizontal comparison of the effectiveness of various technologies. For example, the low-carbon operation and control strategy focuses on the analysis of this system to find out the process combination that can save costs and reduce carbon emissions [22]. Systematic analysis of cutting-edge research shows that hydrothermal technology can convert solid matter in industrial wastewater into resources, which has unlimited potential for decarbonization, which can only be proved by comprehensive evaluation [23]. The establishment of this framework can guide the technological innovation to achieve systemic excellence, promote the transformation of localized optimization, and make industrial wastewater treatment an important part of urban mining and low-carbon development.

4.3. Strengthening the multi-stakeholder governance model

In the process of industrial development, we should make efforts to improve the efficiency of resource recovery and make every effort to build an ecological governance system, which requires the joint efforts of all parties, including enterprises, governments and research institutions. Governments should introduce reasonable standards, formulate reasonable regulations and introduce forward-looking policies to help enterprises achieve the goal of carbon reduction and enhance resource recovery efficiency. Enterprises should not only play a role in the end-of-pipe treatment, but also actively invest in the development of advanced technology, integrate resource recovery into the value chain, and play an active role in the process of implementation. Research institutions should provide strong technical support for enterprises to continuously innovate, and strive to solve the problems of system integration and high-value recovery. In the process of market operation, we should set reasonable prices for products and improve the efficiency of resource recycling, so that more advanced technologies and funds can be introduced, and the value chain of "pollution control–resource regeneration–economic benefits" can be formed, so as to improve the efficiency of resource circulation in the whole industry.

5. Conclusion

At present, the treatment of industrial wastewater is in the stage of strategic transformation, and the focus has changed from the elimination of a single pollutant to the comprehensive utilization of resources. The integration of various technologies is deeper, and the system has been optimized, so that water, energy and resources can be recovered at the same time, and the evaluation framework has been built, which can not only analyze costs, but also analyze the whole life cycle, and can grasp the real value of resource recovery.

In the next stage of research, we should pay attention to two aspects, one is to achieve intelligent operation through data, the other is to carry out green recycling with the help of new materials. In the field of intelligent system, we should pay attention to the use of water quality data and operation data, and use machine learning model to make predictions and optimize. In the process of operation, the model can predict the quality of effluent and analyze the abundance of microorganisms, without too much data, but can bring a new way for the development of data strategy and improve operational efficiency. At the same time, the intelligent model combines the advantages of genetic algorithm and neural network, and is used in the electrocoagulation water treatment system, which can not only predict the operation parameters accurately, but also save energy and reduce dependence on professionals. In the field of new materials, the principle of resource recovery can be used to develop new reactants. For example, sludge can be converted into biochar through pyrolysis, which can not only adsorb pollutants, but also activate persulfate, and use waste to treat waste, so as to achieve the purpose of resource recovery and improve the efficiency of dye wastewater treatment. The above breakthroughs can promote the development of industrial wastewater treatment system in the direction of intelligence, sustainability and efficiency.

Disclosure statement

The author declares no conflict of interest.

References

[1] Chu W, Li X, Li P, et al., 2025, Enhanced Treatment of Low C/N Domestic Wastewater in a Membrane Photobioreactor: Operational Control of Microalgal-Bacterial Symbiosis for Synergistic Pollutant and Antibiotic Resistance Genes Removal. Journal of Environmental Management, 394(22): 127398.

[2] Shen Y, 2021, Municipal Wastewater Treatment Technology: Toward Low-Carbon and Green Development. Journal of Suzhou University of Science and Technology (Engineering and Technology Edition), 34(3): 1–16.

[3] Bai C, Duan P, Xu X, et al., 2025, Repurposing Waste Chemicals to Engineer Redox Mediators for Selective Active Species Modulation in Photo-Fenton-Like Systems. Angewandte Chemie International Edition, 2025: e202520565.

[4] National Development and Reform Commission, 2024, Implementation of the Special Management Measures for Central Budgetary Investment in Energy Conservation and Carbon Reduction. Energy Conservation & Environmental Protection, 41(4): 1.

[5] Six Ministries and Commissions Jointly Issue the Implementation Plan for Industrial Wastewater Recycling. Recyclable Resources and Circular Economy, 2022, 15(1): 40.

[6] Regulations of Lvliang City on the Utilization of Industrial Solid Waste, Lvliang Daily, August 2, 2025, (3), DOI: 10.28546/n.cnki.nlvrb.2025.001689.

[7] Xie S, Bashir M, Malik M, et al., 2025, Global Value Chains, Renewable Energy Investments and Mineral Resources Trade: Implications for Sustainable Development Goals in Emerging Economies. Journal of Environmental Management, 2025(394): 127659.

[8] Wu Y, Luo J, Wang S, et al., 2025, Chitosan-Interpenetrated Metal Organic Framework for Targeted Recovery of Gold from Gold-Electroplating Wastewater. Water Research, 288(Pt B): 124736.

[9] Zhao Y, Chen W, Li Z, et al., 2025, Preparation and Properties of Diethylenetriamine-Aminated Polyamide Spiral-

Wound Ultrafiltration Membranes for Dye-Salt Separation. Polymer Materials Science & Engineering, 41(5): 68–76.

[10] Wang Y, Lian Y, Zhao S, et al., 2025, Advances in Construction and Applications of Self-Healing Superhydrophobic Materials. Journal of Shandong University (Natural Science Edition), 60(10): 59–78.

[11] Peng Y, 2022, Experimental Study on Treatment of Refractory Organophosphorus Wastewater by Advanced Oxidation Technology, thesis, Zhengzhou University.

[12] Jiang X, Zhu Y, Tao C, et al., 2023, Research Progress on Application of Modified Ultrafiltration Membrane Technology in Water Treatment. Chemistry, 86(9): 1091–1096.

[13] Li M, 2024, Study on the Performance of Two Types of Aluminum Sludge Lightweight Fillers Coupled with Constructed Wetland-Microbial Fuel Cells for Treating Heavy Metal Wastewater, thesis, Xi'an University of Technology.

[14] Si T, 2023, Research on Synergistic Technology of Wastewater Waste Heat Recovery and Treatment in a Printing and Dyeing Enterprise, thesis, Guangdong Ocean University.

[15] Zhang R, Liu Y, Fu J, et al., 2024, Research Progress on Struvite Precipitation for Treatment of High-Concentration Nitrogen and Phosphorus Wastewater. Environmental Pollution & Control, 46(8): 1175–1183.

[16] Xu S, Chang R, Men X, et al., 2024, Enhanced Technologies for Improving Nitrogen and Phosphorus Removal in Constructed Wetlands and Their Application in Nonferrous Metal Industrial Wastewater Treatment. Nonferrous Metals (Extractive Metallurgy), 75(4): 120–128.

[17] Liu S, Chen N, Xu M, et al., 2023, Recovery and Detection Methods of Precious Metal Secondary Resources. Metallurgy and Materials, 43(11): 64–66.

[18] Li W, 2023, Research on Resource Recovery and Zero-Liquid-Discharge Process for High-Salinity Wastewater. Leather Manufacture and Environmental Technology, 4(4): 132–134.

[19] Wang L, Chen L, He X, et al., 2022, Resource Recovery Treatment of Dye Wastewater by Activated Carbon Adsorption Coupled with Photocatalytic Oxidation Technology. Dyeing and Finishing, 48(11): 33–36.

[20] Alcaide F, Sirés I, Brillas E, et al., 2024, Coupling Wastewater Treatment with Fuel Cells and Hydrogen Technology. Current Opinion in Electrochemistry, 45(3): 1–12.

[21] Zhou S, Qi S, Liu J, et al., 2024, Life Cycle Assessment of Environmental Impacts of Water Source Heat Pump Energy Recovery in Municipal Wastewater Treatment Plants. Energy and Environment, 42(1): 170–172.

[22] Chen J, Li W, Huang O, et al., 2024, Low-Carbon Operation and Control Strategies for Wastewater Treatment Plants Based on Cost Reduction and Efficiency Enhancement Goals. Industrial Water Treatment, 44(8): 53–60.

[23] Feng J, Strathmann T, Guest J, 2025, Hydrothermal-based Wastewater Solids Management for Targeted Resource Recovery and Decarbonization in the Contiguous U.S.. Environmental Science & Technology, 59(38): 20389–20400.