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A Review of Rural Wastewater Pollution Control in China

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Abstract

Against the backdrop of rural revitalization, wastewater pollution in rural China has become a key issue restricting sustainable rural development. Rural wastewater sources are diverse and dispersed. It has triggered a series of problems, including the deterioration of the aquatic environment and agricultural non-point source pollution. To address these issues, China has developed an integrated governance technology system and implemented a governance model that combines decentralized and centralized approaches. However, it continues to face practical challenges regarding funding, operations and maintenance, regulation, and public participation. Therefore, this article will systematically review the main sources, emission characteristics, and current status of wastewater pollution in rural China. Summarize the practical effectiveness of mainstream governance technologies and application models. Conduct an in-depth analysis of the core constraints across the entire governance process. Based on typical cases from Jiangxia District in Wuhan, the entire province of Anhui, and Heyang County in Shaanxi This paper proposes optimization pathways from five dimensions: policy support, diversified financing, technological adaptation, regulatory implementation, and resource utilization. This paper proposes optimization pathways from five dimensions: policy support, diversified financing, technological adaptation, regulatory implementation, and resource utilization. The aim is to provide theoretical references and practical support for the transition of rural wastewater treatment—from periodic, concentrated remediation to a normalized, long-term, and sustainable mode of development—thereby contributing to China's realization of its goals for rural ecological revitalization.

Keywords

rural wastewater, pollution control, rural water environment, decentralized treatment, resource recovery

1. Introduction

With the continuous advancement of China’s rural economic transformation and urbanization process, rural production and lifestyles have undergone significant changes. As a result, the discharge of rural wastewater has continued to increase, and wastewater pollution has become increasingly prominent, emerging as a major challenge restricting the implementation of the rural revitalization strategy and threatening rural ecological security. At present, rural environmental pollution in China is characterized by multiple pollution sources, dispersed distribution, and strong concealment, making its control far more difficult than centralized urban pollution treatment [1]. Over the past two decades, China has achieved remarkable progress in water pollution control. The coverage rate of urban and rural sewage treatment facilities has steadily increased, and the sewage

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treatment rate has gradually approached the level of developed countries. Urban wastewater treatment plants have played a central role in pollutant reduction [2]. However, constrained by geographical conditions, economic development levels, and population distribution, the overall level of rural wastewater treatment still lags significantly behind that of urban areas [3].

Rural domestic sewage is the primary source of rural wastewater pollution. It is characterized by large fluctuations in water volume, dispersed discharge locations, and high concentrations of nitrogen and phosphorus pollutants. Direct discharge without treatment can easily lead to ecological problems such as surface water eutrophication and nitrate contamination of groundwater [4]. By 2024, the coverage rate of rural sewage treatment in China had exceeded 45%. Nevertheless, grassroots governance still faces multiple challenges, including technological incompatibility, inadequate operation and maintenance systems, insufficient financial support, and weak supervision. As a result, many treatment facilities remain idle after construction, and the effectiveness of pollution control is difficult to sustain [3].

Existing studies mainly focus on the selection of individual treatment technologies and the development of localized treatment models, while research on the entire process of rural wastewater management, the establishment of long-term governance mechanisms, and region-specific treatment strategies remains relatively limited [5]. Therefore, this paper systematically reviews the sources of rural wastewater pollution in China, treatment technology systems, application models, and existing problems. Based on practical experiences from typical cases in China, optimization pathways emphasizing local adaptation, targeted governance, and long-term operation and maintenance are proposed, with the aim of providing theoretical support and practical references for improving rural wastewater treatment efficiency and enhancing the quality of the rural water environment.

2. Major Sources and Current Status of Rural Wastewater Pollution in China

Wastewater pollution sources in rural China are characterized by diversification, decentralization, and regional differences. Pollution sources can be clearly divided into three categories: rural domestic sewage, agricultural production wastewater, and township industrial wastewater. The cumulative emissions from these pollution sources inflict sustained damage upon rural aquatic ecosystems.

2.1 Core Sources of Rural Wastewater Pollution

2.1.1 Rural Domestic Sewage

Rural domestic sewage is the most widespread and largest source of rural pollution. It mainly includes kitchen wastewater, laundry wastewater, toilet flushing water, and wastewater generated from small-scale household livestock and poultry breeding. This type of wastewater is characterized by random discharge patterns, low collection rates, and significant fluctuations in pollutant concentrations. In the densely water-networked areas of the south, rural domestic wastewater has become a major contributor to nitrogen and phosphorus pollution in water bodies [6]. It is estimated that the annual discharge of domestic sewage in rural China is approximately 1.1037 billion to 1.6565 billion tons. Less than half of them were effectively processed. The direct discharge of large quantities of sewage into ditches and ponds—containing pollutants such as organic matter, nitrogen, and phosphorus—not only contaminates water bodies but also fosters the proliferation of mosquitoes and the spread of diseases, thereby serving as a primary cause of the blackening and foul odor of rural waters [6]. In rural areas of southern China, washing wastewater accounts for a relatively high proportion of domestic sewage. The water quality exhibits characteristics of low nitrogen and phosphorus but high COD, imposing differentiated requirements regarding compatibility with treatment processes [7].

2.1.2 Agricultural Production Wastewater

Agricultural production wastewater mainly exists in the form of non-point source pollution, which is far more difficult to control than point source pollution. It mainly includes farmland runoff wastewater, large-scale livestock and poultry breeding wastewater, and aquaculture wastewater. Farmland runoff carries large amounts of chemical fertilizers and pesticide residues, while nitrogen, phosphorus, and pesticide-related organic pollutants enter water bodies through rainfall runoff. Particularly in the hilly and mountainous regions of southern China and the irrigated plains of northern China, the concentrations of nitrogen and phosphorus in farmland drainage are relatively high, posing a serious threat to regional water environments [4]. Wastewater

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generated from large-scale livestock and poultry breeding contains high concentrations of pollutants such as chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total nitrogen (TN), total phosphorus (TP), and suspended solids (SS). Nitrogen and phosphorus emissions from livestock and poultry breeding account for approximately 30% and 70% of total agricultural source emissions, respectively. Due to the lack of wastewater treatment facilities among small-scale farmers, direct discharge is common, and untreated wastewater can easily cause deterioration of surface water quality and groundwater contamination [1]. In aquaculture, wastewater containing residual feed and fishery pharmaceuticals can easily degrade water quality in aquaculture areas, thereby further increasing the regional water pollution load [4].

2.1.3 Township Industrial Wastewater

Township industries are mainly composed of small workshops and small-scale processing factories, involving sectors such as food processing, building materials, and textiles. These industries generally face problems including small production scales, inadequate environmental protection facilities, and substandard wastewater treatment. Most enterprises operate with outdated technologies and insufficient investment in environmental protection, while wastewater treatment facilities are often rudimentary or even absent. As a result, industrial wastewater with high pollutant concentrations, strong toxicity, and poor biodegradability is directly discharged without adequate treatment. Harmful substances contained in the wastewater, such as heavy metals and persistent organic pollutants, can contaminate water bodies and soils, thereby affecting crop quality and human health. In addition, illegal discharge and leakage by some enterprises further increase the difficulty of pollution control [2]. When combined with rural domestic sewage and agricultural production wastewater, township industrial wastewater substantially increases the complexity of rural water pollution management.

2.2 Current Status of Rural Wastewater Discharge and Treatment

Affected by topography, population distribution, and economic development levels, rural wastewater discharge and treatment in China exhibit significant regional differences. In plain areas, where populations are relatively concentrated and pipeline construction is more convenient, wastewater collection and treatment rates are comparatively high. In contrast, mountainous and hilly regions are characterized by complex terrain and scattered settlements, resulting in high pipeline construction costs and wastewater treatment rates far below the national average [3]. From a spatial perspective, rural treatment facilities are relatively well developed in economically advanced eastern regions, whereas central and western regions lag behind due to limited economic development and insufficient investment in pollution control. These areas generally have low sewage pipeline coverage, inadequate treatment facilities, or inefficient facility operation. In particular, the mountainous regions of southwestern China and the arid and semi-arid regions of northwestern China face substantial difficulties in wastewater collection and treatment, and wastewater pollution causes more severe damage to fragile ecological environments. From a temporal perspective, rural wastewater discharge has increased year by year, with significantly higher discharge volumes during peak agricultural production seasons and holiday periods, causing periodic impacts on the water environment [4].

Overall, rural wastewater management in China is still characterized by an emphasis on construction rather than operation and maintenance. Although the coverage rate of rural sewage treatment facilities has steadily increased, many facilities remain idle due to the lack of professional operation and maintenance, insufficient funding, and technological incompatibility, resulting in an actual operational rate of less than 60%. Untreated rural wastewater continuously flows into rivers and lakes or infiltrates into groundwater, leading to varying degrees of black and odorous water problems in more than 30% of China’s rural administrative villages. This directly affects the compliance rate of rural drinking water sources and seriously threatens the health of rural residents as well as the sustainable development of agriculture [5].

3. Existing Technologies and Models for Rural Wastewater Pollution Control

After years of practical exploration, China has established a rural wastewater treatment system that integrates source control, process interception, and end-of-pipe treatment. A governance model dominated by decentralized treatment and supplemented by centralized treatment has gradually taken shape, with technologies and management models increasingly adapting to the needs of dispersed rural wastewater management.

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3.1 Mainstream Technologies for Rural Wastewater Treatment

From the perspectives of treatment principles and process characteristics, current rural wastewater treatment technologies can mainly be classified into three categories: physical treatment, chemical treatment, and biological-ecological treatment. Each type of technology is suitable for different pollution scenarios and treatment requirements.

3.1.1 Physical Treatment Technologies

Physical treatment technologies mainly rely on processes such as screening, sedimentation, and filtration, and are primarily used to remove suspended solids, sediment, and other impurities from wastewater as a pretreatment method. Screening and grating are the most commonly used pretreatment technologies in rural wastewater treatment and are mainly applied to remove large solid pollutants from wastewater in order to protect the normal operation of subsequent treatment facilities. Sedimentation technology separates suspended particles from wastewater through gravity and can be divided into natural sedimentation and coagulation sedimentation. Due to its simple equipment and low operating cost, it is widely applied in rural centralized sewage treatment stations. Filtration technology further purifies water through the interception effect of porous media. Among these methods, sand filtration is commonly used in rural wastewater treatment because of its low cost and simple operation [7]. This type of technology has the advantages of low cost, simple operation, and no secondary pollution, making it suitable for decentralized household treatment and pretreatment processes in small rural treatment stations [1].

3.1.2 Chemical Treatment Technologies

Chemical treatment technologies rapidly degrade pollutants through processes such as coagulation sedimentation, chemical oxidation, and disinfection. These technologies are mainly applied in the emergency treatment of black and odorous water bodies and in the pretreatment of breeding wastewater in rural areas. Chemical coagulation is the most commonly used chemical treatment technology in rural wastewater management. By adding coagulants, suspended solids, colloids, and some organic matter as well as nutrients such as nitrogen and phosphorus can be effectively removed from wastewater. Chemical oxidation and chemical precipitation methods are mainly used for the targeted treatment of township industrial wastewater and high-concentration breeding wastewater, enabling the degradation of refractory organic pollutants and the removal of heavy metals and phosphorus pollutants [2]. Although chemical treatment technologies have high treatment efficiency, they also face problems such as high chemical costs, the generation of chemical sludge, and a high risk of secondary pollution. Therefore, they are mainly suitable for emergency treatment rather than routine rural wastewater management [4].

3.1.3 Biological-Ecological Treatment Technologies

Biological-ecological treatment technologies are currently the most widely applied core technologies in rural areas. These technologies purify wastewater through the natural degradation effects of microorganisms and plants and mainly include aerobic biological treatment, anaerobic biological treatment, and ecological treatment. They combine low operational and maintenance requirements with ecological benefits and are well suited to decentralized rural wastewater management. Among aerobic biological treatment technologies, the biofilm process and biological contact oxidation process are characterized by low sludge production, strong resistance to shock loading, and simple management, making them suitable for decentralized rural sewage treatment. Anaerobic biological treatment technologies, such as septic tanks and biogas digesters, feature simple structures, low costs, and convenient maintenance. They can simultaneously achieve pollutant degradation and biogas resource recovery and are therefore widely used in rural household treatment scenarios. Ecological treatment technologies rely on natural ecosystems composed of aquatic plants, microorganisms, and soil to purify wastewater. Their core forms include constructed wetlands, ecological ponds, and land treatment systems. These technologies are characterized by low cost, low energy consumption, environmental friendliness, and favorable landscape effects, making them the mainstream technologies for decentralized rural wastewater treatment at present [6]. Such technologies offer advantages including low operation and maintenance costs, low energy consumption, good ecological benefits, and strong adaptability to decentralized rural management. They have been widely promoted in provinces such as Yunnan, Jiangsu, and Zhejiang and have become the preferred technologies for end-of-pipe rural wastewater treatment [6].

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3.2 Mainstream Models of Rural Wastewater Management

In accordance with village distribution patterns and geographical conditions, China has gradually developed three core models for rural wastewater management.

3.2.1 Centralized Treatment Model

The centralized treatment model is suitable for administrative villages located near urban areas and with relatively dense populations. Under this model, rural sewage is connected to municipal sewer networks and treated collectively by urban wastewater treatment plants. This model features high treatment efficiency and standardized operation and maintenance. However, due to the high cost of pipeline construction, it is mainly applicable to densely populated suburban areas. This model has been widely implemented in Jiangxia District of Wuhan. In response to the high population density of suburban administrative villages, the district promoted integrated rainwater-sewage diversion renovation and pipeline construction across the entire area, connecting rural sewage to urban wastewater treatment plants for unified treatment. This approach achieved standardized and intensive management of suburban rural sewage and effectively addressed the problem of insufficient operation and maintenance capacity of village-level treatment facilities [7].

3.2.2 Decentralized Treatment Model

The decentralized treatment model is suitable for remote villages with dispersed residential distribution. This model adopts methods such as household septic tanks, village-level small treatment stations, and courtyard ecological treatment systems to achieve on-site wastewater treatment. Due to its low pipeline construction cost and strong adaptability, it has become the preferred treatment model in mountainous and hilly areas. Ecological technologies such as constructed wetlands and oxidation ponds are particularly widely used in mountainous rural areas because of their simple operation and maintenance, with application rates exceeding 70%. This model has been ext ensively promoted throughout Anhui Province. In response to the province's large proportion of mountainous and hilly regions and dispersed village settlements, Anhui adopted the principle of "household-based treatment and local utilization" and promoted decentralized treatment processes such as "septic tank + constructed wetland" and "anaerobic fermentation + ecological oxidation pond." At the same time, an operation and maintenance system featuring "county-level coordination, township-level responsibility, and village-level implementation" was established, significantly improving the rural domestic sewage treatment rate across the province [8].

3.2.3 Resource Recovery and Utilization Model

The resource recovery and utilization model integrates wastewater treatment with agricultural production. Treated effluent is reused for farmland irrigation and forest land replenishment, while sludge is composted and returned to farmland after harmless treatment, thereby achieving a win-win outcome between pollution control and agricultural productivity enhancement. This model represents an important development trend in rural wastewater management [6]. A mature application of this model has been established in Heyang County, Shaanxi Province. In response to rural population decline and high agricultural water demand in the Guanzhong region, the county developed a full-process resource utilization system consisting of "on-site wastewater treatment – reclaimed water irrigation – sludge composting and farmland application." Treated effluent meeting discharge standards is preferentially used for farmland irrigation, orchards, and forest land replenishment, substantially improving water resource utilization efficiency. This practice provides a replicable experience for rural wastewater management in northern dry farming regions [9].

4. Problems and Optimization Pathways in Rural Wastewater Management

4.1 Core Problems in Rural Wastewater Management

Currently, rural wastewater treatment in China remains subject to numerous core constraints, with insufficient technological adaptability standing as the primary issue. Some regions have blindly copied urban sewage treatment processes, resulting in the application of integrated treatment equipment characterized by high energy consumption and high operation and maintenance costs, which are difficult to sustain in rural areas. Meanwhile, low-cost and easily maintainable ecological technologies have not been sufficiently promoted, leading to a serious mismatch between technological supply and actual rural needs [3]. The lack of funding

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and operational maintenance systems are equally prominent issues. Funding for governance relies excessively on central and local fiscal subsidies, while social capital demonstrates low willingness to participate and faces obstructed channels for engagement. After facilities are constructed, professional operation and maintenance teams are often absent, and there is a persistent shortage of operational funds for electricity, chemicals, and daily maintenance. Consequently, problems such as "facilities can be built but cannot be afforded, operated, or properly managed" are widespread [5]. In terms of supervision and public participation, the rural environmental protection supervision system remains inadequate. Responsibilities among departments overlap, and grassroots regulatory capacity is seriously insufficient, making it difficult to effectively control illegal wastewater discharge. At the same time, villagers generally have weak environmental awareness, and behaviors such as random wastewater dumping and damage to treatment facilities occur from time to time, resulting in relatively low public participation in environmental governance [1].

4.2 Optimization Pathways for Rural Wastewater Management

In response to the aforementioned issues. Efforts need to be made in a coordinated manner from multiple dimensions, including technology, funding, management, and resource utilization. Construct a long-term governance system adapted to rural realities At the technological level, the centralized urban treatment approach should be abandoned. Instead, treatment strategies should be developed according to local topography, village distribution, and pollution characteristics, with priority given to low-energy ecological technologies. At the same time, rural sewage treatment in key river basins should be incorporated into integrated watershed pollution prevention and control systems [8]. At the funding level, dependence on a single source of fiscal investment should be reduced by establishing diversified financing models and introducing professional third-party institutions to achieve the integration of "construction–operation–supervision" [9]. At the management level, a county-based governance priority evaluation system should be established to allocate resources scientifically. In addition, a three-level supervision mechanism linking counties, townships, and villages should be developed, and operational effectiveness should be incorporated into grassroots performance assessments [10]. At the resource utilization level, governance systems should adapt to the new characteristics of rural population decline by establishing full-process resource recovery systems, thereby achieving localized wastewater treatment and recycling [11].

5. Conclusion

In summary, China has achieved phased progress in rural wastewater management. By 2024, the coverage rate of rural sewage treatment had exceeded 45%. An integrated technical system combining source control, process interception, and end-of-pipe treatment has been comprehensively established. Treatment approaches centered on biological-ecological technologies combine low operation and maintenance requirements with ecological benefits and are well suited to the core demands of decentralized rural management. Three major management models—centralized treatment, decentralized treatment, and resource recovery and utilization—have been successfully implemented in regions with different geographical and economic conditions, such as Jiangxia District in Wuhan, Anhui Province, and Heyang County in Shaanxi Province. However, rural wastewater management as a whole still faces major challenges, including insufficient technological adaptability, shortages in funding and operation and maintenance, lagging supervision and assessment mechanisms, and inadequate public participation.

Future rural wastewater management should be based on actual rural conditions and adhere to the core principles of ecological sustainability, low cost, easy maintenance, and resource recovery. Through coordinated efforts in technology, funding, management, and resource utilization, precise pollution control and long-term governance can be achieved, thereby continuously improving the quality of the rural water environment and providing strong water environmental support for rural ecological revitalization.

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