The Sustainable Development Model of Rural Domestic Sewage Treatment in China

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Abstract. With the successive promulgation of rural environmental governance policies in China, rural sewage treatment has become a hot topic. In response to the problem of traditional unified sewage collection and treatment model being difficult to adapt to in rural China, this article systematically investigates academic literature and engineering projects in China since 2000. The main problems existing in the existing rural governance are: the design scale of the project is too large; the water quality of the project inlet design is too high; the sewage pipe network is blocked and damaged; the sewage treatment facilities are not acclimated to the local conditions. Therefore, this article proposes a new model of rural sewage treatment and resource utilization that is 'source separation, classified discharge, qualitative treatment, and recycling', and provides three utilization scenarios and suitable technologies. In addition, it also explores the economic performance of this new model. The new sewage treatment concept proposed in this study will provide reference for further improving the rural sewage treatment rate in China.

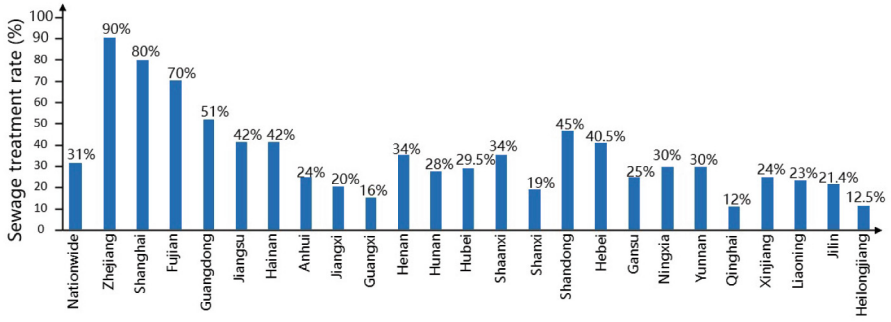
Keywords: Rural Domestic Sewage · Treatment Model · Rural Environment · Domestic Sewage · China

1 Introduction

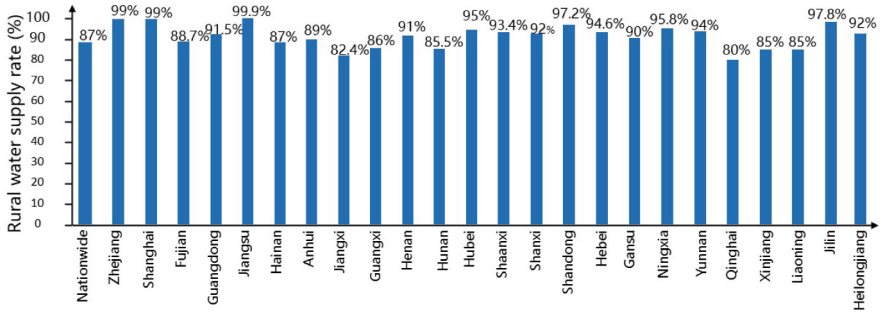
China has invested a large amount of construction funds, aiming to create a beautiful ecological and livable countryside, so that farmers can have a greater sense of gain and happiness in rural revitalization [1]. According to research data from the Prospective Industry Research Institute, the investment in rural sewage treatment in China has shown a rapid growth trend, with a cumulative investment of over 300 billion RMB (Renminbi) from 2016 to 2021. At present, rural areas in China involve 520000 administrative villages, with a population of 55.4% in the country. The annual sewage volume exceeds 10 billion tons [2], accounting for nearly 50% of urban sewage. According to the Bulletin of the Second National Pollution Source Survey of China, the discharge of chemical oxygen demand, ammonia nitrogen, total nitrogen and total phosphorus in rural domestic sewage reached 4.9962 million tons, 245 million tons, 446.5 million tons

C.-H. Weng (Ed.): ACEER 2023, LNCE 336, pp. 256–265, 2024.
https://doi.org/10.1007/978-981-99-5716-3_22

and 36.9 million tons respectively. According to data from the Ministry of Ecology and Environment of China in 2023, the average treatment rate of rural sewage in China is 31%, with economically developed areas ranging from 30% to 90% (see Fig. 1). The current urban domestic sewage treatment rate in China has reached 97.89% [3], while the rural domestic sewage treatment rate is much lower than that in urban areas. Compared with the popularization rate of rural tap water in China [4], the statistical rural sewage treatment rate is much lower than the popularization rate of tap water. Therefore, a large amount of rural sewage cannot be effectively treated, and China's rural sewage still needs to increase its treatment efforts.



(a) National rural sewage treatment rate from 2021 to 2022



(b) Popularization rate of rural tap water in China

Fig. 1. Current situation of rural water supply and sewage treatment in China.

In order to comprehensively promote the improvement of rural living environment, China has issued a series of policy documents and standards. Overall, our rural sewage treatment has gone through three stages (see Fig. 2): the embryonic stage (before 2015), the growth stage (from 2015 to 2015), and the mature stage (after 2045). Overall, the foundation of rural domestic sewage treatment is weak, and the task remains arduous. Between 2016 and 2021, the rural sewage treatment rate in China only increased by about 6%, and the rural sewage treatment rate is still at a relatively low level. Therefore, through literature research (Period: since 2000; Tool: Citespace) and on-site investigation, this article summarizes many main aspects that restrict rural sewage treatment:

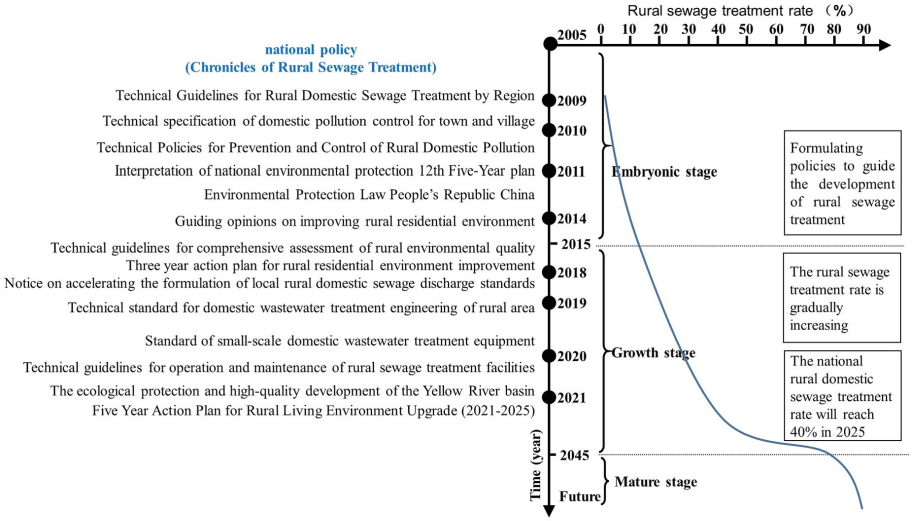


Fig. 2. Development history of rural sewage treatment of China.

(1) **The engineering design scale is too large.** At present, the designed discharge volume of rural domestic sewage is 100–150 L/ (person · day) for calculation, but the actual value is only 50% of the design value. This is mainly because the construction of rural sewage pipelines in China is relatively small, and latrine pits are commonly used in rural areas, where feces and urine are directly utilized as resources. However, some miscellaneous water such as laundry water in daily life is directly discharged through courtyard infiltration, only kitchen water and bath water are discharged through the sewer. The inflow of sewage treatment facilities depends on the actual rural population and water usage habits. The large designed water volume leads to high investment, sedimentation of sewage pipe networks, and difficulty in normal operation of treatment facilities.

(2) **The design water quality of the engineering inflow is relatively high.** The design of sewage treatment engineering is based on the mixed concentration of black water and gray water, usually with a COD concentration of 250-300mg/L in the influent, which deviates greatly from the actual situation. The inlet water quality of sewage treatment facilities depends on the discharge path of sewage from farmers' homes, and the inlet water quality of each row of the project should be reasonably designed based on the actual drainage habits of local residents.

(3) **The sewage pipe network is blocked or damaged.** The construction and maintenance of rural sewage pipelines are not in place, and there are serious issues of mixed connection, wrong connection, and damage. The problem of not building household collection pipes in the construction of sewage pipe networks is quite common, and treatment facilities cannot receive sewage. A large number of villages have not built sewage collection pipelines, and sewage is transported through rainwater pipelines, polluting surrounding water bodies.

(4) **Sewage treatment facilities are not suitable for rural areas.** The normal operation rate of rural domestic sewage treatment facilities is not high, and the situations that cannot operate normally include large design scale, abnormal operation of facilities, shutdown of facilities, substandard effluent quality, incomplete or damaged pipeline network, and low inlet water quality (see Fig. 3).

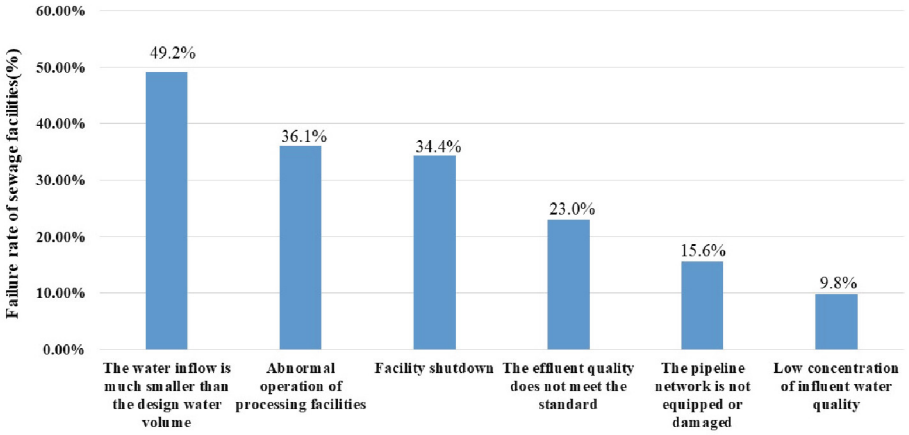


Fig. 3. Proportion of abnormal operation of rural sewage treatment facilities.

The reasons for the above-mentioned problems in rural domestic sewage are mainly due to copying the urban drainage treatment model and neglecting rural water usage habits from the source (see Fig. 4). The traditional mixed discharge mode of sewage makes it difficult to fully utilize organic resources and pollute the environment. Urine and feces are internationally recognized as the second phosphate rock, and the traditional drainage mode of phosphorus is extremely wasted in landfills. Phosphorus is a nonrenewable resource, and the existing phosphorus resources can only be used for 100 years. In recent years, China has emphasized resource recycling in rural sewage treatment, especially feces and water resources [5].

Based on the concept of resource recycling, combined with the practice of existing rural sewage treatment projects, this paper proposes a new low-carbon ecotype treatment model of "classified treatment and recycling" of rural sewage, which aims to provide a reference for the future development of differentiated treatment and resource utilization of rural sewage in different regions of China.

2 Comparative Analysis of the Characteristics of Rural Sewage Treatment Models at Home and Abroad

Various countries have attempted various operational models to achieve rural sewage treatment. For example, there are five rural sewage treatment modes in the United States [6], namely, homeowner awareness mode, maintenance contract model, operating permit

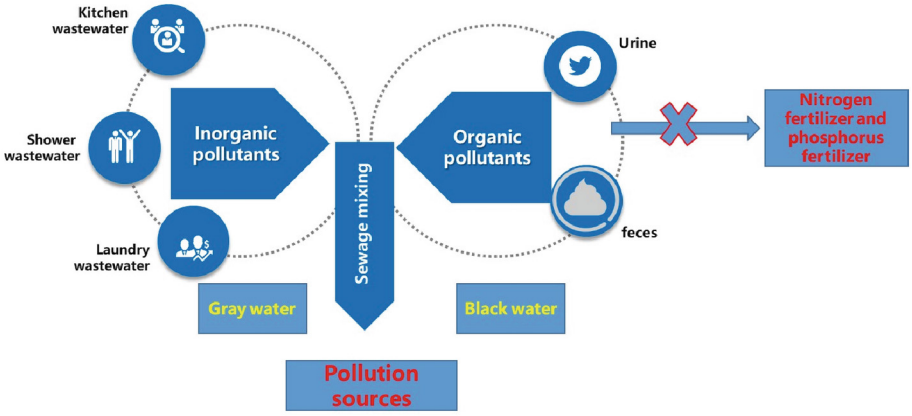


Fig. 4. Unified sewage discharge mode.

model, responsible management entity (RME) operation, responsible management entity (RME) ownership model, which are mainly determined according to water environment sensitivity and process complexity [7, 8]. The operation mode of rural sewage treatment in South Korea is divided into direct management by local governments and entrusted management [9]. The infrastructure of EU countries is well-established, and they mainly use centralized management to treat rural sewage [10]. Rural areas are charged 30% of the standard for urban residents, ensuring the good operation of the system. In Japan, rural sewage is mainly treated jointly by the government, third-party institutions, and users. There are three modes of treatment: piped treatment, centralized treatment in villages and towns, and purification tanks [7, 10]. The operation is mainly carried out by third-party companies, and farmers are required to pay pollution discharge fees. The successful experiences of various countries provide valuable experience for China to carry out rural sewage treatment in the future.

At present, there are three main types of sewage treatment models in China [11], namely the piped treatment model (connected to the urban sewage pipeline network for unified treatment), the centralized treatment model (constructing centralized sewage treatment facilities), and the decentralized treatment model (constructing decentralized sewage treatment facilities). The characteristics of each model [12] are shown in Table 1. (1) The operation effect of the Nanotube processing model is relatively good, and it should be adopted in rural areas within 3km of urban sewage treatment plants (sewage treatment pipelines can usually extend for about 5km [9], and investment in pipelines beyond this range will greatly increase). (2) The centralized processing mode often lacks professional facility operation and post maintenance [13], requires large investment, and is not suitable for rural areas with low population density and dispersed population. In addition, there are significant differences in the production and lifestyle of rural areas compared to urban areas. The daily fluctuations in the quality and quantity of rural domestic sewage [7] have led to an increase in the difficulty of sewage treatment. Finally, many centralized sewage treatment systems in China do not operate or have poor operational effects. (3) For the decentralized treatment model, it is unrealistic to

build sewage treatment plants in many rural areas due to low population density and dispersed households, but the construction cost of decentralized treatment is relatively high. Therefore, cost-effective decentralized sewage treatment technology is sustainable and necessary for rural areas [15]. In addition, the difficulty of operating sewage treatment technology is also a major factor limiting the decentralized treatment of rural sewage. Although some researchers have attempted to develop low-cost and easy to operate sewage treatment devices, such as a multi soil layered sewage treatment system (MSL) [16], its practical application effect still needs to be verified.

Table 1. Characteristics of rural sewage treatment mode in China.

Model	Connotation	Characteristic	Applicable conditions
Nanotube processing	Incorporate rural domestic sewage pipelines into the municipal pipeline network for unified treatment by urban sewage treatment plants	Low investment, short construction cycle, fast efficiency, and convenient management	Suitable for areas close to urban sewage plants (about 3 km [14])
Centralized processing	Build a new supporting sewage pipe network collection system to collect and treat residential sewage uniformly	Unified collection, transportation, and processing	Suitable for central villages, residential areas, or natural villages with a certain population and relatively concentrated residential areas
Decentralized processing	Sewage is collected by multiple households or single households and then treated separately	Flexible layout, cost saving of pipeline network, and simple structure	Suitable for non ecologically sensitive areas, villages with scattered populations, or villages with unsuitable elevation and terrain for laying pipeline networks

3 New Models for Rural Sewage Treatment

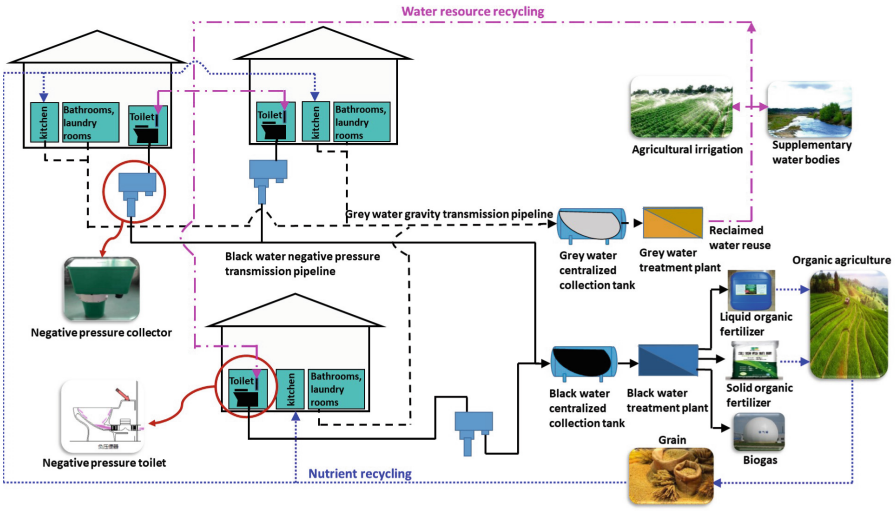
3.1 Model and Concept

This article proposes a new rural sewage treatment model of "source separation, classified discharge, qualitative treatment, and recycling", and its technical schematic is shown in see Fig. 5. There are three specific models based on the size of the rural population served.

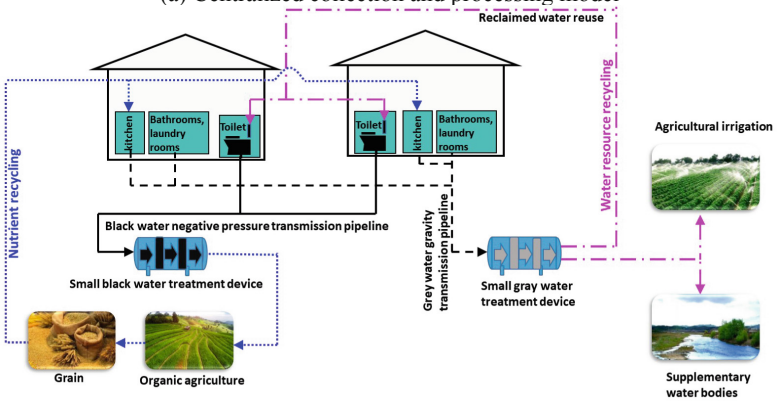
- **Centralized collection and processing model.** The characteristic of this model is to classify and collect domestic sewage from the source, forming two sewage transmission pipelines. The first pipeline is to mix and collect kitchen washing sewage, shower sewage, and other lightly polluted domestic miscellaneous water. After being collected through the pipeline, it is transported to the gray water treatment station. After simple and low consumption "physicochemical + ecological" treatment, the effluent quality can reach the standard of recycled water quality, which can be reused for agricultural irrigation nearby sprinkling, flushing or supplementing natural water bodies to achieve the recycling of water resources. The second pipeline mainly collects toilet drainage, and the toilet is a negative pressure collection toilet (the water consumption of stool/urination is 1L/0.1L each time). The collected black water is transmitted to the black water treatment station (black water recycling center) through the negative pressure collection and transmission system, where the rural agricultural wastes such as straw, livestock manure and kitchen waste are mixed in proportion to produce solid organic fertilizer and liquid organic fertilizer through anaerobic/aerobic fermentation, The fermented fertilizer should be applied to nearby farmland to achieve a virtuous ecological cycle of nutrients such as C, N, and P.
- **Decentralized collection and processing model.** This mode is similar to the centralized collection and processing mode, with the main difference being that the number of people serving is relatively small. Therefore, small gray water and black water treatment devices are used, and after treatment, they are directly reused on site.
- **Decentralized collection and centralized processing model.** When farmers are scattered, it is recommended to use an anhydrous toilet for black water collection. The generated feces and urine are packaged and stored in biodegradable bags in a fecal collector. Professional operators collect feces regularly and return the produced organic fertilizer to the countryside in proportion to the amount of recovered feces and urine, achieving a virtuous cycle of this model.

3.2 Performance Analysis

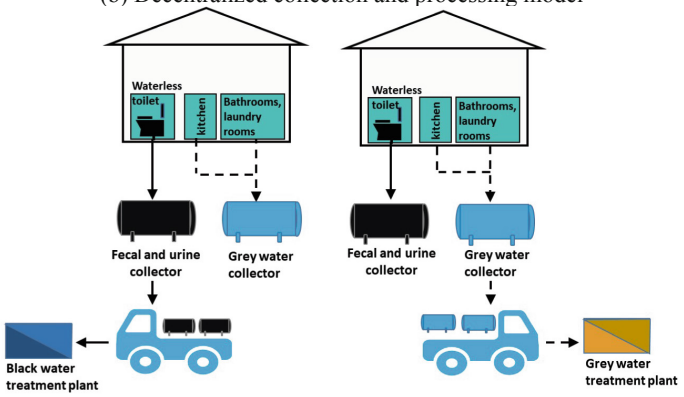
To further elaborate on the economy of the rural sewage treatment model proposed in this study, this study takes a rural area with 300 people and a centralized collection and treatment model as an example for economic accounting analysis. According to the reference values of gray water design discharge and black water design discharge in the "Design Standards for Building Water Supply and Drainage" GB50015-2019, the treatment scale of gray water and black water in this project is calculated to be 33.15 m^3/d and 1.775 m^3/d respectively, with an investment of approximately 4.34 million RMB (Table 2). The annual operating cost of black water and gray water is 127400 RMB, and the investment recovery period is 8.31 years. It can be seen that the investment benefits of this new model are significant and have strong promotion and application value.



(a) Centralized collection and processing model



(b) Decentralized collection and processing model



(c) Decentralized collection and centralized processing model

Fig. 5. The new rural sewage treatment model based on source separation.

Table 2. Benefit analysis of new model of rural sewage treatment.

Investment, operation and maintenance, and benefits of the project			Cost/10000 RMB
Initial investment	Grey water collection system, black water collection system		134
	Black water and gray water resource utilization treatment stations (separate resource utilization, gray water pre-treatment + artificial wetland; black water production organic fertilizer)		300
Operation and maintenance expenses	The direct operating cost of grey water resource treatment is generally 0.4~0.6 RMB/ton of water		1.21
	The direct operating cost of black water resource treatment is generally about 0.2 RMB/ton of sewage		0.064
Benefit analysis	Water saving benefits	Black water (saving about 2628 m^3/year, water price 5.95/m^3)	1.564
		Grey water (water saving of about 657m^3/year, water price of 5.95/m^3)	7.2
	Energy Saving benefits	Saving 120000 RMB/year of medication	0.036
		Reduce electricity consumption for nitrogen and phosphorus removal by approximately 5400 kWh (electricity price 0.56/kWh)	0.3024
	Economic performance	Bioorganic fertilizer (6.27 tons per year, priced at 1500 RMB/ton)	15.9
		Biogas (7.83 tons per year, priced at 3.5 yuan/Nm^3)	27.4

Note: Water and electricity prices are calculated based on Zhengzhou city.

4 Conclusions

This paper has been proposed a new rural sewage treatment model based on the intensive and economical utilization of water resources, namely "source separation, classified discharge, negative pressure collection, and resource utilization". The major differences from the existing rural sewage treatment models can be addressed as below:

(1) The new sewage treatment model has achieved the full resource utilization of sewage. Grey water can be used for irrigation and domestic miscellaneous water after being treated to reach recycled water; Black water is made into organic fertilizer and ultimately returns to farmland.
(2) Compared with traditional sewage treatment models, the new sewage treatment model has good water saving benefits, energy saving benefits, and economic performance.

However, the following limitations of the study should be noted. Firstly, further research and development are needed to develop black water solid-liquid separation technology with high water content to improve the efficiency of fecal and urine treatment and better achieve resource utilization. Secondly, the model proposed in this study was only demonstrated in some regions and did not involve rural areas in all climate regions of China.

Acknowledgment. I acknowledge support from the National Key Research and Development Program of China (2021YFC3201302), China Postdoctoral Science Foundation (No. 2022M711288), Advanced Technology Demonstration Project of the Ministry of Water Resources of the People's Republic of China (SF-202206), and Yellow River Engineering Consulting Co., Ltd. Project (2022KY007).

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