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Review

Systematic Assessment of Practical Challenges in Rural Domestic Sewage Treatment in China: Examining Treatment Models, Ecological Risks, and Management Dilemmas

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Abstract: The treatment and purification of rural domestic sewage (RDS) is a pivotal focus in enhancing the living environment in rural areas. Since 2008, special funds for comprehensive rural environmental improvement have been established by the Chinese government. Numerous projects have been implemented to treat RDS, resulting in a significant enhancement of China's rural sewage treatment ratio. However, current discussions often focus on technical investigations, process selection, and operation modes pertaining to urban sewage while overlooking the unique challenges posed by decentralized sewage treatment facilities in rural areas. This work aims to provide technical support for addressing rural sewage treatment and purification in China through an analysis of limitations associated with prevailing mainstream sewage treatment and separation technologies, ecological risks arising from new pollutants present in domestic wastewater, and subsequent management difficulties.

Keywords: rural domestic sewage; treatment technologies; ecological risks; management difficulties

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1. Introduction

The vigorous implementation of water pollution prevention and improvement in water environment quality are not only crucial aspects toward meeting growing demands for an enhanced quality of life but also practical responses aligned with the United Nations Sustainable Development Goals for 2030. China places significant emphasis on addressing rural domestic sewage (RDS) treatment/purification and considers it as one of the key strategic measures in combating pollution. In early 2018, the Central Office of the Communist Party of China and the State Council of China issued a "Three-Year Action Plan on Rural Human Settlements Rehabilitation". This action plan proposed region-specific differentiation in drainage methods and discharge destinations, along with classification and formulation of discharge standards for RDS treatment/purification. Simultaneously, a "Notice on Accelerating Local Formulation of Discharge Standards for Rural Domestic Sewage Treatment" was released to clarify the comprehensive requirements, control indicators, and discharge limits pertaining to RDS treatment and purification [1]. These policies have facilitated standardization efforts in rural sewage treatment and purification, as shown in Figure 1. As of 2022, China's rural sewage treatment ratio stands at approximately 31%, making an increase of 9 percentage points compared to its ratio in 2016 (22%).

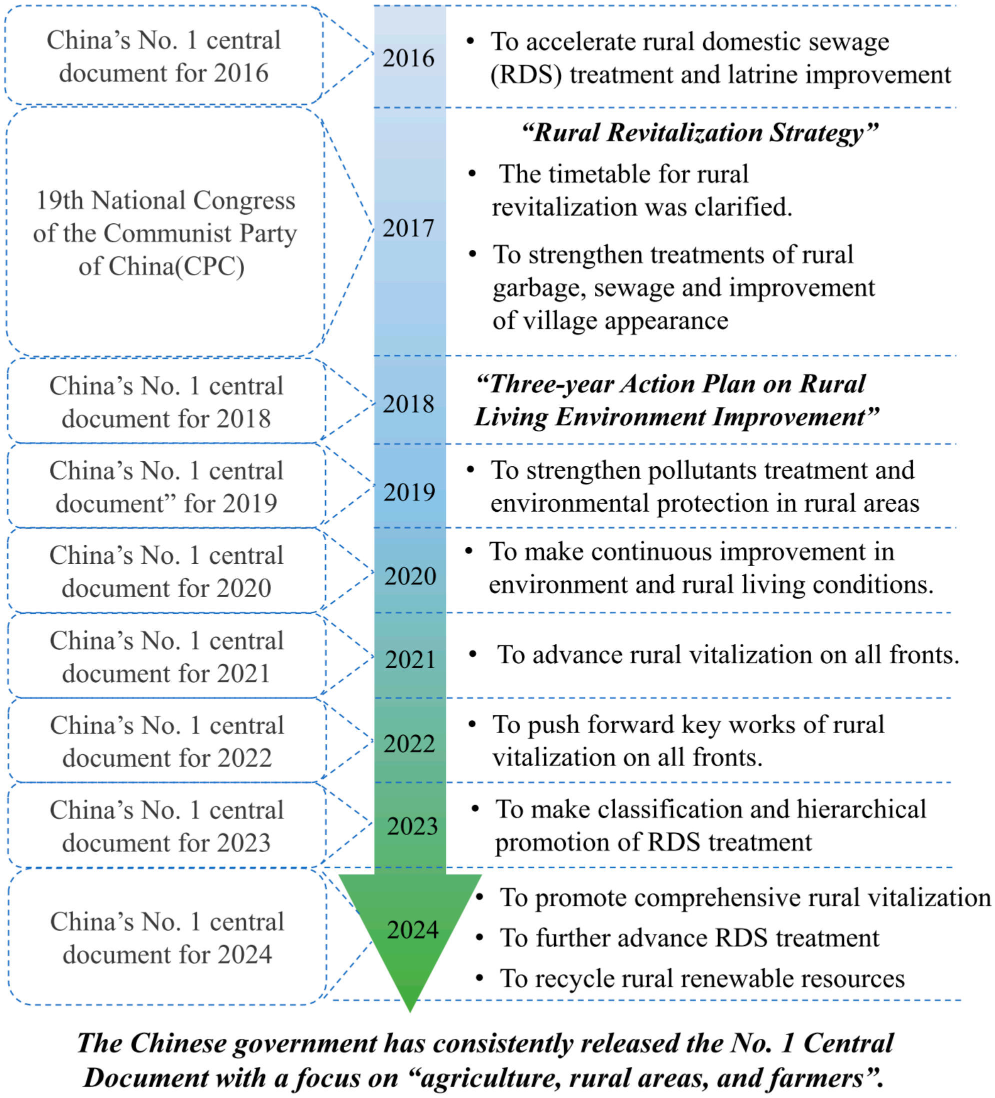

Figure 1. A roadmap outlining a series of policies related to rural revitalization and RDS treatment issued by the Chinese government.

Domestic sewage in urban areas is mainly collected through dense municipal pipelines and then centralized into wastewater treatment plants (WWTP) for treatment/purification and utilization [2]. However, the implementation and maintenance costs of such WWTPs are considerably high, with approximately 80% of the investments allocated to sewage collection [3]. In contrast to urban sewage, rural areas face challenges due to highly variable influent loading rates, long idle periods, and dispersed distribution of wastewater. These factors result in significant energy consumption in traditional continuous treatment/purification systems during periods without sewage influent [4]. Due to the lack of strict management and supervision, it is difficult to replicate urban pipeline construction and sewage treatment in rural areas. A large amount of untreated or incompletely treated RDS is directly or indirectly discharged into the front and back of houses [5]. The discharge of untreated rural wastewater not only represents a loss of potential bioenergy and nutrient resources but also serves as a primary contributor to aquatic pollution in surrounding surface water and groundwater. This will lead to environmental issues such as eutrophication while increasing health risks for local residents [6]. Therefore, decentralized sewage treatment/purification technology with low energy consumption, low cost, and easy operation has become an economically viable approach for rural areas that aligns with the principles of sustainable development.

Biological treatment, eco-treatment, and combined treatment are the mainstream treatment/purification technologies for rural domestic sewage currently [7]. Examples of typical biological treatment processes include three-compartment septic tank (ST), anaerobic digestion (AD), anaerobic–anoxic–oxic (A^2/O), and membrane bioreactor (MBR) [8,9]. Eco-treatment encompasses constructed wetlands (CWs), stabilization ponds, and multi-soil layers (MSLs) [10]. However, conventional single treatment/purification processes often fail to meet discharge standards due to uneven influent concentration, large variations in water flow rate, significant temperature fluctuations, and other factors, as observed by researchers [11]. In order to better address these issues, researchers have attempted to combine biological and ecological treatments and explored several effective solutions. Therefore, it is suitable for various RDS treatment projects.

Moreover, the presence of emerging contaminants (ECs) and microplastics (MPs) has been detected in a wider in RDS in recent years [12]. These pollutants will significantly affect the working environment of RDS treatment facilities, change the working hours of sewage treatment facilities, and are not conducive to the reuse of sewage resources. There are some different opinions regarding the research on removing ECs and their related ecological risks. Some studies indicate that CWs effectively reduce the ecological risk posed by novel pollutants like antibiotics in surface water environments after treatment [13]. In contrast, other studies suggest that antibiotic removal efficiency from sewage treatment facilities is limited, which may potentially impact aquatic ecosystems negatively [14]. Domestic sewage containing ECs can enter surrounding farmland and water bodies through irrigation and can be transmitted to humans through the food chain, posing a huge health risk to the regional ecology [15]. Therefore, a more comprehensive demonstration should be conducted on how domestic sewage treatment technology can effectively remove traditional and emerging contaminants and maximize resource utilization.

At present, various provinces in China have established a considerable number of sewage treatment facilities to deal with the environmental risks caused by rural domestic sewage. However, due to a lack of professional operation and maintenance, most sewage treatment facilities have not played their due role [16]. Furthermore, due to the neglect of agricultural background conditions in the early stage of rural sewage treatment/purification, the wrong path was taken in the treatment process, especially for some enterprises that have just entered the field of village and town sewage treatment. The obvious traces of urban experience have led to problems such as high operating energy consumption and difficult operation and maintenance after the project is completed [17]. In recent years, the approach toward RDS treatment has gradually transitioned toward adopting comprehensive methods based on local conditions. This approach has significantly improved the efficiency of rural sewage treatment/purification, but challenges such as low coverage of RDS collection pipelines, poor collection capacity, and lack of established operation and maintenance management mechanisms continue to hinder the development of RDS treatment and purification in China [18]. However, there is currently limited research available regarding the management difficulties associated with RDS treatment/purification.

This work provides a critical review from the following aspects: (1) to identify the limitations of currently employed sustainable biotechnologies for efficient RDS treatment; (2) to summarize the ecological risks associated with RDS treatment models; (3) to conduct an in-depth investigation into the existing challenges faced by RDS management models. The objective of this article is to provide valuable insights into RDS treatment and management practices, particularly for developing countries grappling with similar issues.

2. Limitations of Mainstream Treatment/Purification Technologies for RDS

Previous research has primarily focused on the post-treatment methods of RDS, overlooking the significance of domestic sewage collection systems. This chapter provides an overview of the limitations associated with various domestic sewage treatment/purification technologies and, for the first time, addresses the deficiencies in RDS treatment from a pipeline collection perspective.

2.1. RDS Treatment/Purification

In the context of green and sustainable development, biological treatment technology is most widely used in rural sewage/purification treatment schemes, with representative technologies including ST, A/O, MBR, etc. However, with the increasing emphasis on rural living environment improvement and higher requirements for sewage discharge standards, the shortcomings of traditional biological treatment methods are being magnified. For example, there is evidence to suggest that relying solely on STs is unreliable in eliminating pathogens [8]. Similarly, membrane fouling issues are becoming increasingly frequent in MBR processes, leading to ineffective removal of pollutants from rural wastewater and, more severely, rendering sewage treatment facilities unusable. The A/O process, a biological treatment process, is a sequential anaerobic–aerobic treatment method that exhibits limited effectiveness; therefore, it can only be used as a pretreatment in conjunction with other technologies.

In recent years, ecological treatment has been widely applied in the field of RDS treatment/purification due to its cost-effectiveness, easy maintenance, and aesthetic improvements. The utilization of the ecological method concludes CWs (67.67%) and land infiltration (23.81%), as demonstrated by Xu et al. (2022) [19]. However, challenges faced by CWs include large space requirements, low removal efficiency in winter, and a decline in hydraulic conductivity due to substrate filling of the gaps over time [20]. This clogging hinders the fulfillment of effluent-related design requirements and necessitates increased investment for operation and maintenance of cleaning or replacement of clogged substrates via excavation. Additionally, it causes detrimental anoxic and anaerobic conditions within the system, which could lead to hygiene issues such as unpleasant odors and mosquito breeding. The CWs' clogging therefore hinders carbon neutralization efforts while affecting its further development and application. Similarly, multi-soil layer (MSL) systems experience diminished removal efficiency over time as filtration materials reach their saturation point with adsorption capacity; this significantly reduces suspended solids and nitrogen removal efficiency with irreversible consequences on extensive soil areas. Table 1 compares the advantages and disadvantages of several sewage treatment/purification processes, as well as the key principles for pollutant removal. Figure 2 shows the photographs of the main RDS treatment/purification technologies taken by the authors during the field investigation.

Table 1. Comparison of RDS processing technology adaptability.

Techniques	Removal Principles	Advantages	Disadvantages	Total Investment (CNY/m^3)	Effluent Stability
ST	The ST eliminates settled solids, grease, and a portion of residual organic matter via anaerobic digestion	Easy to install and save labor and time	Cannot remove nutrient loads substantially	400–1000	Inferior
A/O	A/O process connects the front anoxic section and the rear aerobic section in series	Simple process, low investment, and low operation cost; the anoxic/aerobic process has strong load shock resistance	Low phosphorus removal rate	900–1100	General
A^2/O	A^2/O process is a combination of traditional activated sludge process, biological nitrification and denitrification process, and biological phosphorus removal process	Better phosphorus removal than A/O, more stable effluent water quality	Larger reactor volume, higher energy consumption, and higher cost compared to A/O	1200–1500	Good
MBR	Highly efficient wastewater treatment process integrates high-efficiency membrane separation technology with traditional activated sludge process	Shock load resilience, effective pollutant reduction, small footprint, and low sludge production	High cost, membrane contamination, high energy consumption	2500–4000	Better

Table 1. *Cont.*

Techniques	Removal Principles	Advantages	Disadvantages	Total Investment (CNY/m^3)	Effluent Stability
CWs	Constructed wetlands (CWs) mainly use the physical, chemical, and biological triple synergy of soil, artificial media, plants, and microorganisms to treat sewage	Low construction and operation costs; easy maintenance and low technical content; buffering impact on hydraulic and pollution loads	Be limited by lowtemperature; large land area	200–550	Good
MSL	Multi-soil layers (MSLs) reduce organic matter and nutrients through a number of chemical, physical, and biological processes	Small footprint, zero energy consumption, easy operation and maintenance, eco-friendly, and odorless	Low pollutant removal efficiency; risk of blockage in long-term operation	200–400	Good

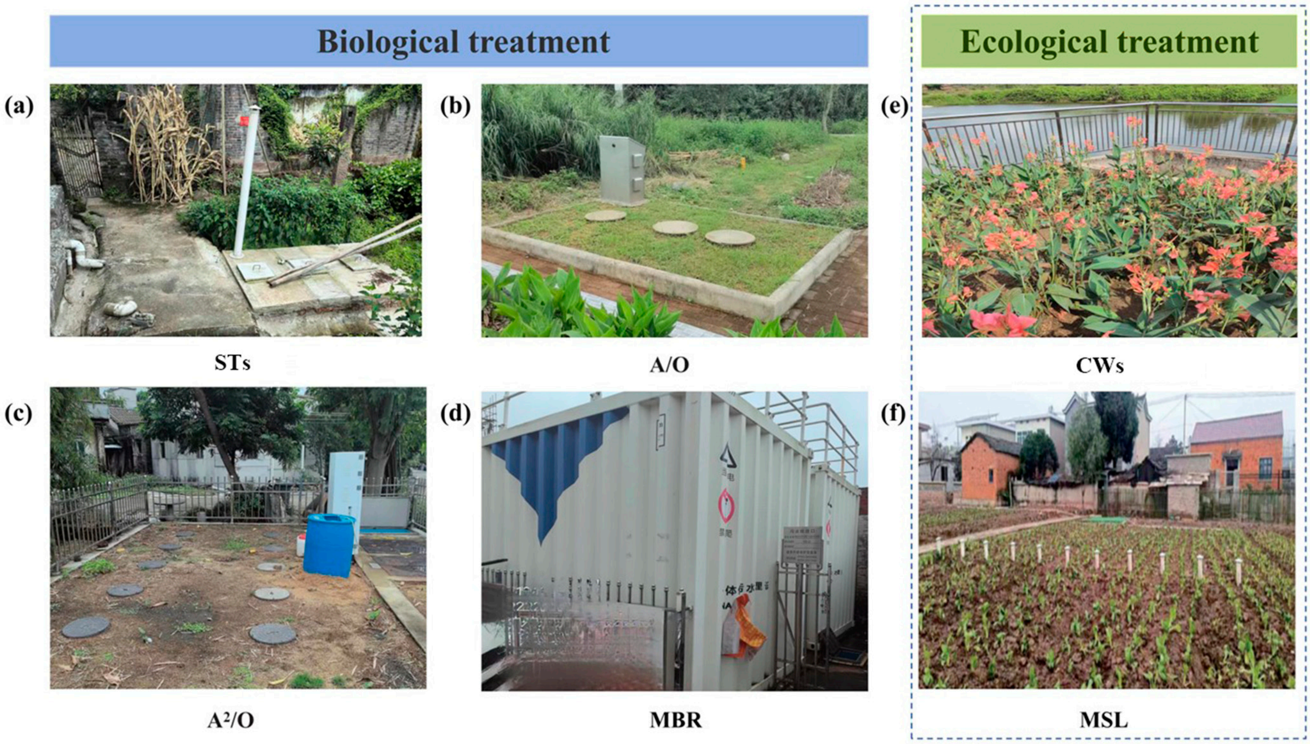

Figure 2. Physical drawing of rural domestic sewage (RDS) treatment/purification. (**a**) Three-compartment septic tanks (STs); (**b**) anaerobic–aerobic (A/O)) process; (**c**) anaerobic/anoxic/oxic (A^2/O) process; (**d**) membrane reactor (MBR); (**e**) constructed wetland system (CWs); (**f**) multiple-soil-layering systems (MSL).

2.2. RDS Collection

The current sewage collection subsystem is a centralized pipe network system that plays a crucial role in maintaining rural hygiene and preventing diseases. However, with the rapid development of rural areas and the promotion of sustainable development concepts, the limitations of centralized systems have become increasingly evident and garnered attention. Firstly, long-distance transportation through pipeline networks results in approximately 25% degradation of organic matter in sewage. Considering potential leakage, groundwater infiltration, and rainwater mixing caused by pipeline damage, up to 50% loss of available sewage resources can occur, exacerbating challenges in resource recovery and utilization. Secondly, due to the absence of insulation function within pipelines, significant dissipation occurs for low-level heat energy present in fresh sewage during transport. Lastly, long-distance transportation requires energy consumption, which becomes a critical consideration for sustainable rural development as China's construction progresses rapidly with an expanding pipeline system size.

Given that resource loss in sewage mainly results from long-distance transportation, researchers propose a decentralized sewage collection and treatment system based on "on-site treatment" principles. Situating this treatment system near the source of sewage effectively shortens the collection network while simplifying processes and enhancing robustness without compromising resource conversion efforts. Nevertheless, implementing economically beneficial decentralized processing systems requires substantial operational expenses and skilled operators; excessive dispersion could even increase cost consumption. Henceforth, meticulous planning becomes indispensable when considering such decentralization strategies.

3. Potential Ecological Risks Associated with RDS

RDS is an important cause of non-point source pollution in developing countries. Due to the direct discharge of large amounts of nutrients, such as N and P, as well as pollutants, such as detergents, into water bodies, many rural areas in China are suffering from serious harm caused by black and odorous water pollution [21]. A recent study showed that source apportionment analysis based on absolute principal component score–multiple linear regression revealed that RDS contributed the largest proportion (25.08%) to pollution alongside industrial sewage [22].

Currently, the treatment of RDS primarily focuses on the removal of conventional pollutants and pathogens such as COD, nitrogen, and phosphorus, with limited research conducted on ECs. With the improvement of rural living standards, more and more types of antibiotics and emerging pollutants are being detected in rural water environments. Although these ECs are typically present at ng/L to μg/L levels, their potential adverse effects on human health and ecosystems are a cause of concern [23]. Previous studies have shown that direct discharge of rural domestic sewage may lead to the enrichment of nonylphenol in rural water environments. However, research in this area still requires long-term observation [24]. ECs, including pharmaceutical and personal care products, steroid hormones, and pesticides, have been identified in RDS treatment facilities across countries [25]. Several studies have demonstrated that CWs and soil filters can effectively reduce environmental risks posed by these organic compounds to surface water environments, while toxicological assessments have also shown a reduction in health risks to the food chain [26]. However, studies have shown that carbamazepine, caffeine, ofloxacin, and dehydrated erythromycin detected near the discharge outlet of sewage treatment facilities pose a serious threat to most aquatic species, including algae, fish, and plants [27]. Feng et al. (2024) [28] discussed the influence of ofloxacin on rural domestic sewage treatment by aerobic biofilm system. This exploration includes the analysis of biofilm resistance characteristics, bacterial community composition, and functional gene modules. OFL exposure weakened the performance of aerobic biofilm systems for rural sewage treatment. Although OFL exposure caused biofilm resistance, with the increase in OFL exposure concentration, the number of living cells, some dominant genera, and genes involved in carbon degradation, ammonia oxidation, and phosphorus adsorption decreased. In aerobic biofilm systems, OFL mainly weakens the removal of COD, NH_4^+-N, and TP by affecting the bacterial community. Therefore, further research is needed to develop strategies for managing and removing the ECs from RDS.

In many rural areas of China, three-format STs and biogas digesters are widely used for the treatment of residential sewage or fecal waste. However, their efficacy in pollutant removal is limited, rendering them potential sources of pollutants, pathogens, antibiotics, and antibiotic resistance genes (ARGs). Unutilized antibiotics in living organisms can be excreted into sewage treatment facilities through feces, and some antibiotics can even be directly discharged into the water environment. More and more studies have shown that residual antibiotics after sewage treatment can lead to the emergence of antibiotic-resistant bacteria (ARBs) and ARGs. It is worth noting that when feces and urine are used as organic fertilizers or reused as irrigation water in farmland without harmless treatment, they can promote the spread of ARBs and ARGs through the food chain into organisms, seriously endangering agricultural ecology [29]. Consequently, the transmission of ARBs and ARGs through the food chain has become a highly valued issue for the global public; it has been recognized as a major health challenge by the World Health Organization [30].

Reports of MPs/nano-plastics detected in rural domestic sewage treatment facilities are increasing. MPs have the characteristics of small volume, large specific surface area, and strong hydrophobicity, so it is easy to adsorb organic pollutants and may carry chemicals with hazardous substances [31]. MPs are not only the release source of toxic pollutants in domestic sewage but also the transport carrier of other toxic and harmful substances. The current sewage treatment facilities make it difficult to effectively treat MPs, resulting in a large number of MPS entering the rural water environment at the drainage area, causing incalculable harm to the entire ecosystem. It is more and more common that MPs/nano-plastics can be directly or indirectly absorbed by organisms in the water environment and then enter the human body through the biological food chain, causing harm to human health. Additionally, MPs can cause considerable harm to crops. A tracking experiment on polystyrene MPs in wheat seedlings revealed that these particles accumulate in the xylem of roots before moving upward along the stem [32]. Furthermore, they reduce the water conductivity in wheat roots, inhibit root and stem growth, decrease wheat photosynthetic activity, and induce severe oxidative damage. The shape, size, and type of MPs significantly influence their removal efficiency during wastewater treatment processes. Larger-sized MPs exhibit better removal performance in anaerobic processes; sheet-like MPs are easier to remove compared to fibrous MPs. However, rural decentralized domestic sewage treatment facilities generally exhibit poorer removal efficiency for MP particles. The artificial CW systems only achieve approximately a 50% removal rate for such contaminants. So far, there is a lack of adequate attention given to MPs and antibiotics in RDS treatment, and investigating the ecological toxicity and removal mechanism of these emerging pollutants could be a potential avenue for future research.

4. Management Dilemma of RDS Treatment/Purification System

Despite the strong determination of the Chinese government to improve the rural living environment, some unsolved problems are still obstacles to the effective treatment of sewage in rural areas.

4.1. The Development of RDS Treatment/Purification Lags behind in Terms of Conceptualization

The RDS treatment and purification in China has been initiated relatively late and lacks practical experience. In certain regions, there has been an extensive reliance on urban models during the exploration process, resulting in insufficient understanding of the actual conditions in rural areas and limited awareness regarding the utilization of sewage resources. Moreover, there has been an excessive focus on achieving standard discharge without considering the agricultural background conditions at the initial stage of RDS treatment. Consequently, this approach has led to a detour in the treatment path, particularly for newly established enterprises involved in village and town sewage treatment projects that exhibit clear traces of urban experience. These issues have resulted in challenges such as high energy consumption and difficulties with operation and maintenance after project completion. It is important to note that advanced processes may not always be suitable for RDS treatment/purification, and solely pursuing strict discharge standards does not align with the realities faced by rural areas. In Yunnan Province alone, less than one-third of its sewage treatment facilities are operating normally; construction without subsequent use or “exposure to the sun” phenomenon frequently occurs. Therefore, it is crucial to adopt treatment technologies that are aligned with rural realities while being cost-effective and capable of utilizing nearby resources when addressing domestic sewage treatment needs in these areas.

However, the utilization of RDS resources in China is still in its nascent stages. The increasing contradiction between "discharge and use" is primarily attributed to factors such as a lack of standardized regulations, technological dysconnectivity, and significant funding gaps. Consequently, there exists a substantial gap between the current level of sewage resource utilization and the desired goal of creating beautiful rural areas. Our perspective emphasizes that the delayed progress in sewage treatment is particularly evident due to an excessive focus on facility construction rather than operational management, prioritizing technological content over capabilities, and emphasizing treatment and purification instead of resource utilization. Therefore, it becomes imperative to adopt appropriate technical strategies based on low-carbon and green concepts while adhering to local conditions with a recycling-oriented objective. In light of the national "dual carbon" strategy, treating RDS also plays a crucial role in reducing pollution and carbon emissions; thus, its core concept should embody principles of being green, low-carbon, and circular.

4.2. The Governance Structure

Within the current hierarchical framework, the county government issued policy requirements to the town government and then issued them to the village committee level by level for implementation, without any responsibility for the results [33]. The transmission of information across different levels is impeded, resulting in increased time costs and decreased efficiency. Furthermore, due to the rotational system of local leadership, county governors tend to prioritize short-term performance rather than emphasizing long-term development of domestic sewage. Consequently, this governance structure heightens the risks of policy implementation failure despite granting absolute authority and power to the county government over their subordinates.

Another governance defect lies in the limited knowledge of rural residents regarding domestic sewage and their exclusion from project management [34]. Improving the enthusiasm of rural residents to participate in environmental governance is an important means to improve the rural living environment [35]. In addition, through the improvement of the rural residential environment, villagers' participation in village public affairs and village cohesion will be enhanced to lay a mass and ecological foundation for subsequent industrial landing and industrial development [36]. However, currently, most farmers have not actively participated in the construction and management of village sewage treatment facilities. Consequently, due to this lack of understanding about the sewage treatment/purification process, rural residents exhibit reluctance toward managing such facilities. Given that they are the primary beneficiaries, appropriate and cooperative utilization by rural residents is crucial for ensuring the smooth operation of these systems. Unlike urban settings where centralized WWTP prevails, rural areas typically employ decentralized systems on a smaller scale. In such decentralized setups without user involvement or input, mechanisms present significant risks for inefficient project operations.

The experience of sewage treatment in foreign countries is different from that in China. One is represented by the old developed countries in Europe and America, which have basically completed the integration of urban and rural areas due to their urbanization history of nearly 100 years. In these countries, the same legal system for sewage treatment is usually applied in rural and urban areas, but after the 1970s and 1980s, due to the emphasis on source pollution, some amendments were proposed for rural areas or decentralized sewage treatment. The other is the Japanese model. In the process of rural sewage treatment, health problems, construction problems, and environmental problems exist at the same time. In order to accelerate the integration of urban and rural areas and regulate and manage the health, construction, and environmental protection in rural areas, Japan has established a legal system for rural sewage treatment that is different from cities and has built an implementation system under the leadership of the government in progress with citizen participation.

4.3. The Issue of Financial Unsustainability

Depending on the subsidies for operation and maintenance, financing is generally not sustainable or reliable due to the discontinuity of government subsidies caused by the local leadership rotation system. This system entails frequent transfers of officials across administrative boundaries, posing a risk of interrupting the funding for RDS treatment facilities.

An optional financial plan or model for the sewage treatment/purification systems in rural areas is currently absent. The hierarchical Chinese governance structure dictates that city/county/town governments await directives from the higher authorities rather than establishing a sustainable financial source for sewage treatment/purification systems. Local governments primarily allocate their resources and funds toward completing construction projects and bolstering their political status, neglecting the long-term operational efficiency of these systems. Despite limited subsidies available to sewage treatment systems, local governments at various levels exhibit reluctance to explore alternative viable financial sources.

According to relevant economic theories and previous successful experience, attracting social funds to participate in rural domestic sewage treatment/purification projects can improve the long-term effectiveness of sewage treatment. However, attracting such investment for RDS treatment systems poses challenges. Given that sewage treatment/purification is a public resource without direct economic benefits, the government lacks incentives to develop strategies for attracting private capital [37]. At present, some provinces adopt PPP projects (Public–Private Partnership) for sewage treatment construction, but relevant departments report that the preliminary preparation and approval process of PPP projects takes a long time, and it is difficult to put the projects into storage. The institutions have raised the financing interest rate of PPP projects, affecting the enthusiasm of social capital to participate in PPP projects, resulting in the inability to complete the procurement of some projects and the difficulty in financing some projects that have started construction.

4.4. The Current RDS Discharge Standards Necessitate Enhancement

Although the Chinese government has proposed a series of local standards, the majority of RDS discharge standards in China still closely resemble urban discharge standards (Figure 3). In contrast to urban areas, numerous rural regions face challenges such as insufficient funding for water pollution control and low environmental awareness. In addition, the modes and requirements of sewage collection, storage, treatment standards, discharge standards, and back-end utilization in rural and urban areas are also different. Consequently, a significant volume of untreated RDS is discharged without adhering to appropriate discharge standards, resulting in an escalating issue of soil and water pollution in these regions.

Furthermore, the local standards lack clarity regarding the requirements for monitoring frequency and sampling time. The quality and quantity of RDS exhibit significant seasonal and temporal fluctuations, which consequently affect the effluent quality of treatment facilities. Therefore, the frequency and sampling time of effluent monitoring play a crucial role in obtaining accurate water quality monitoring results. Relying solely on a single sampling analysis of effluent from RDS treatment facilities to assess compliance with water quality standards would yield inadequate scientific, representative, and standardized evaluation outcomes. Currently, only Hubei Province has stipulated requirements for the sampling method of treatment facility effluents by explicitly employing mixed samples. In contrast, other local standards fail to specify monitoring frequency and sampling time parameters, potentially introducing substantial human-induced factors during their practical implementation.

China is a nation grappling with the challenge of water scarcity. Water reclamation emerges as the most efficacious approach to conserve water resources. According to a report, exclusively reclaiming gray water (GW) can result in a reduction in potable water consumption, ranging from 29% to 47%. However, current grading methods solely concentrate on effluent discharges and regrettably overlook effluent recycling. Ensuring water quality security becomes the pivotal factor in wastewater recycling endeavors. Nevertheless, China's existing system for recycled water falls short of meeting the safety requirements for reclaimed water [38]. Therefore, when formulating standards, it is imperative to elucidate the intended end-use of sewage as an initial step toward promoting its reuse.

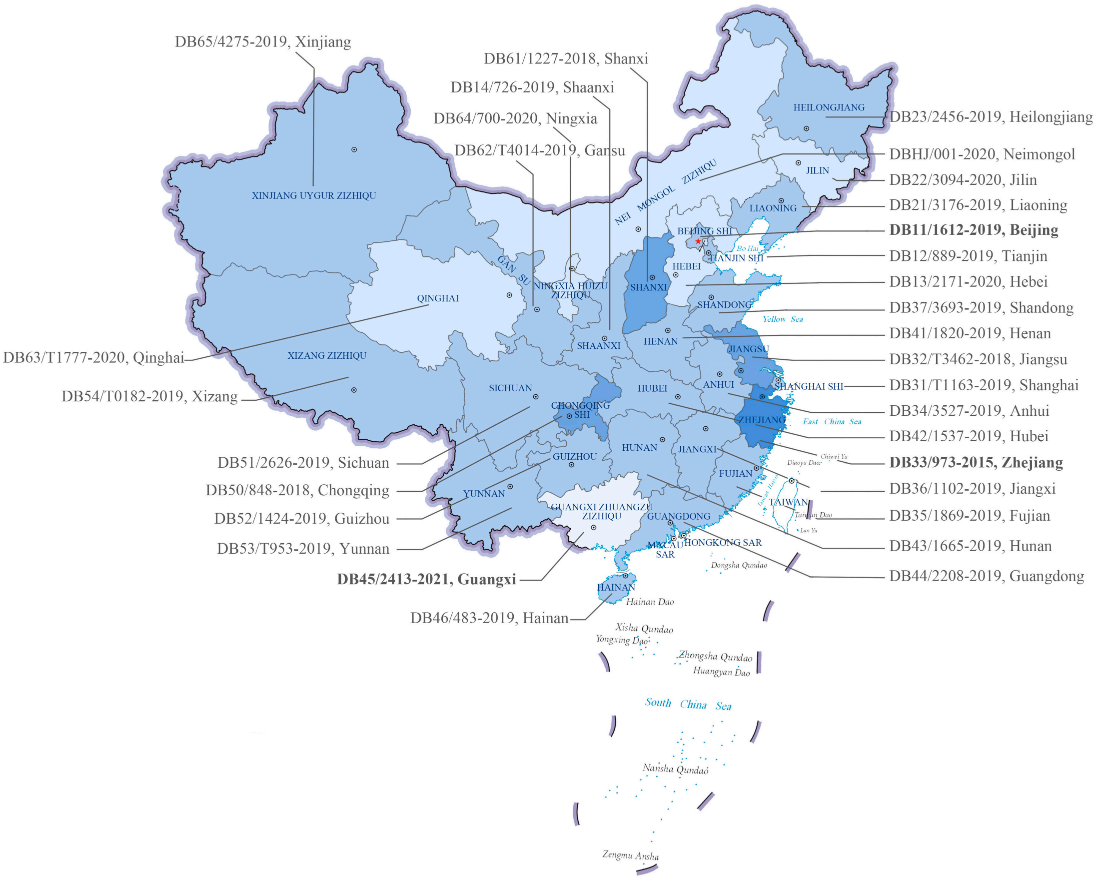

Figure 3. Current status of issued provincial standards for RDS treatment/purification in China.

5. Prospects of Rural Domestic Sewage Treatment/Purification Technology

At present, some progress has been made in rural domestic sewage treatment technology, but the question of how to more scientifically and reasonably promote the low-carbon sustainable treatment of rural domestic sewage in the future is still facing challenges.

5.1. Local Utilization

The dispersion characteristics of rural domestic sewage show that this non-point source pollution should be treated by in situ method. The area and scale of the rural sewage treatment process should be highly concerned. The process with a large area and large treatment capacity is obviously not suitable for the carbon neutralization treatment of rural sewage. Therefore, an appropriate rural sewage treatment process should minimize its size and volume in order to treat rural sewage from a single family or small community. Moreover, since the large wastewater pipeline network is not available in rural areas, in situ biological and ecological treatment processes are essential for rural wastewater. Rural sewage has polluted the water environment of nearby rivers and lakes, which can be repaired by ecological in situ treatment processes such as ecological ponds.

5.2. Combined Technologies

The design and construction of rural domestic sewage treatment/purification process should meet the requirements of decentralized in situ treatment in terms of minimization, adaptation to climate and temperature changes, and acid and alkali resistance. The upgrading and improvement of filter materials in biofilter technology should focus on improving service life and wear resistance and preventing clogging and scaling. The comprehensive application of two or more biotechnology should also be the appropriate scheme to effectively remove multiple pollutants in rural sewage carbon neutralization treatment. For example, the A/O process can be combined with a constructed wetland to improve the removal rate of organic matter and effluent quality. The coupling of CWs and biofilm processes can improve the nitrogen removal effect. Biofilter can also be combined with anammox to treat COD and nitrogen.

5.3. Low Maintenance Cost

The expenditure for the design, construction, operation, and maintenance of rural wastewater biotechnology should be low-cost and affordable for rural use, especially for rural wastewater treatment in developing and underdeveloped countries. On the one hand, high cost and high consumption will obviously bring more carbon emissions in the process of wastewater treatment. On the other hand, rural sewage treatment/purification needs to realize long-term stable operation, which is complex and has high maintenance cost, high cost, and high consumption. For example, the constructed wetland technology is facing maintenance problems such as plant decay and filter blockage, which will further increase the cost of rural wastewater treatment. Biofilm technology should be regularly maintained to eliminate membrane pollution and prolong the service life of membrane components. Therefore, in future research and development of rural domestic sewage treatment technology, more attention should be paid to sustainable methods and low-cost solutions to reduce expenditure and maintenance costs.

6. Conclusions

In recent years, China has continuously invested significant amounts of manpower in RDS management and achieved phased results. After decades of upgrading and development, certain conventional sewage treatment/purification processes have been improved and enhanced in terms of performance and effectiveness; however, they still exhibit some limitations. Firstly, most traditional treatment processes are challenging to manage and maintain on a daily basis due to their sensitivity to fluctuations in environmental temperature, water quality, humidity, and other factors. Additionally, emerging evidence indicates the presence of new pollutants in treated domestic wastewater that can hinder the efficiency of RDS treatment facilities and impede further utilization of sewage resources. Finally, outdated sewage treatment concepts, inappropriate governance structures, potential political risks, discontinuous financial support, and an urgent need for improvement in governance standards pose challenges that must be addressed for the sustainable operation of RDS treatment/purification systems.

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Abbreviations

Abbreviations	Annotation
RDS	Rural domestic sewage
STs	Septic tanks
AD	Anaerobic digestion
A/O	Anaerobic–aerobic
A^2/O	Anaerobic–anoxic–oxic
MBR	Membrane bioreactor
CW	Constructed wetland
MSL	Multi-soil layer
ECs	Emerging contaminants
MPs	Microplastics
ARGs	Antibiotic resistance genes
ARBs	Antibiotic-resistant bacteria

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