

Review

Research Progress on Integrated Treatment Technologies of Rural Domestic Sewage: A Review

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Abstract: The improvement of rural living standards in developing countries and the continuous upgrading of the rural industrial economy have prompted the diversification of rural areas and residential forms. Thus, an integrated rural sewage treatment process has gradually become the mainstream technology for rural sewage treatment. Numerous studies have reported the effects of ecological wastewater treatment. Meanwhile, the relevant process technologies, evaluations, and operating models of the integrated rural sewage treatment process have yet to be thoroughly summarized. This review aims to fill these gaps. First, the applicability of artificial wetland, soil infiltration, stabilization pond, and integrated rural sewage treatment process technology in rural sewage treatment are outlined and compared. Second, the process flow, technical characteristics, and economic indicators of typical integrated sewage treatment processes (i.e., Anoxic/Oxic (A/O) process, Membrane Bio-Reactor (MBR) process, biological contact oxidation process, Sequencing Batch Reactor Activated Sludge (SBR) process) are introduced. The engineering application effects of the integrated rural sewage treatment process in different countries are also described. Third, the practical and effective evaluation methods of the integrated rural sewage treatment process are introduced. Bearing in mind the current operation and maintenance management modes of the integrated rural sewage treatment process in developed and developing countries, combined with the national conditions of developing countries, the prospect section provides development proposals for further optimization and improvement of the integrated rural sewage treatment process in developing countries.

Keywords: rural domestic sewage; integrated treatment technologies; research progress



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1. Introduction

Rural sewage treatment is an important segment to promote the improvement of rural living environment. The General Office of the Communist Party of China (CPC) Central Committee and the General Office of the State Council issued the three-year action plan to improve rural human settlements in China [1]. The plan pointed out that improving rural human settlements and building beautiful and livable villages are important tasks in implementing the Rural Revitalization Strategy. Thus, rural sewage treatment was considered the main direction, and step-by-step rural sewage treatment was promoted. According to the 2019 Statistical Yearbook of Urban and Rural Construction of the Ministry of Housing and Urban-Rural Development, China has 2,513,000 natural villages, with a village population of 552 million. The total amount of sewage produced each year exceeds 8 billion tons. Nowadays, China's rural sewage discharge is still increasing, but villages and towns lack perfect sewage collection systems and sewage treatment devices [2]. In developing countries such as China, most rural areas are widely distributed. These rural areas have large regional economic and cultural differences, diversified residential forms, and aggregation and dispersion. In addition, the rural economy in developing countries lacks development, and local budgets are limited. Except for the rural areas adjacent to cities, where domestic sewage can be directly discharged into urban sewage treatment plants,

most rural areas cannot build sewage pipe networks and centralized sewage drainage systems. Rural sewage is difficult to treat effectively [3]. Dumping domestic sewage on the land at will is serious; it pollutes rural surface water and groundwater, thereby severely affecting the health and happiness index of rural residents [4,5].

At present, ecological treatment technologies are mostly used for decentralized rural sewage treatments, such as a subsurface wastewater infiltration system (SWIS) [6], constructed wetland (CW) [7], and stabilization pond [8]. According to the research of many scholars and demonstration applications, the ecological sewage treatment method has some disadvantages, such as large floor area, low pollution load, and unstable treatment effect. Integrated treatment has been an emerging technology of rural sewage treatment in recent years; it integrates independent reaction processes in the same reaction device to achieve integration, miniaturization, and convenient operation [9]. The traditional single mode can be combined into a composite process combining multiple methods, such as Membrane Bio-Reactor (MBR) integrated equipment [10], Anoxic/Oxic (A/O)/Anaerobic-Anoxic-Oxic (AAO) integrated equipment [11], sequencing batch reactor (SBR) [12], and biological contact oxidation process [13], into a combined treatment mode combining integrated equipment with ecological treatment technologies, such as CWs. Integrated treatment equipment, which has a good treatment effect, has been widely used in treating different contaminated water, such as livestock and poultry wastewater [14], printing and dyeing wastewater [15], and coking wastewater [16]. The application of integrated sewage treatment in rural sewage treatment is the future development trend. It can improve the effluent quality and reduce the floor area. Moreover, it is highly relevant to rural sewage treatment in developing countries.

The relevant process technologies, evaluations, and operating models of the integrated rural sewage treatment process have yet to be thoroughly summarized. The main objectives are as follows: (1) compare the applicability of ecological wastewater treatment with that of the integrated rural sewage treatment process; (2) introduce the process flow, technical characteristics, economic indicators, and the engineering application effect of typical integrated sewage treatment processes in different countries; and (3) describe the practical and effective evaluation methods of integrated rural sewage treatment process. Finally, bearing in mind the current operation and maintenance management mode of the integrated rural sewage treatment process in developed countries and developing countries, combined with the national conditions of developing countries, the prospect section provides development proposals for further optimization and improvement of the integrated rural sewage treatment process in developing countries.

2. Common Treatment Technologies for Rural Sewage

At present, rural sewage treatment technologies mainly include CW, soil infiltration, stabilization pond, and integrated rural sewage treatment process, among many other treatment technologies. The treatment effect and characteristics are shown in Table 1 [8,17–21]. In developing countries, most rural areas are widely distributed. These rural areas have considerable regional economic and cultural differences, diversified residential forms, and aggregation and dispersion. In addition, developing countries lack rural economic development, and local budgets are limited. Except for the rural areas adjacent to cities, where domestic sewage can be directly discharged into urban sewage treatment plants, most rural areas cannot build sewage pipe networks and centralized sewage drainage systems [22,23]. In the case of large land areas in rural areas of developing countries, land treatment systems have received considerable attention in the past [24]. These land treatment systems include artificial wetland technology, soil infiltration technology, and stabilization pond technology, which mainly rely on the adsorption and filtration of fillers in the system, microbial degradation, or the enrichment and absorption of plants. The underground filtration system can remove more than 80% of nitrogen and phosphorus [25–27] by using intermittent operation and split distribution of wastewater treatment. However, the pollutant removal efficiency decreases considerably when the hydraulic loading rate (HLR)

increases, and serious blockage occurs when the HLR is $0.125 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ [23,28–30]. The low hydraulic load capacity of SWIS leads to a large operation footprint, thereby limiting its application in areas with land resource shortage. The CW system is mainly composed of substrate and plants. The biofilm-forming area around the substrate provides a growth site for various microorganisms, and the substrate can remove pollutants through different processes, such as adsorption and filtration [31]. Plants in CWs help remove nitrogen, phosphorus, and organic matter from sewage, create environmental diversity around the rhizosphere, and enhance microbial and chemical processes [32]. CWs have a very effective removal effect on biochemical oxygen demand (BOD) (85–90%) and total suspended solids (90–95%). However, an adequate oxygen supply is required for CW nitrification. CWs are inefficient in phosphorus removal. Thus, their use for phosphorus-rich sewage treatment is limited. The main limitations of CWs include land requirements and difficulties in treating high-concentration and high-toxic wastewater. In addition, CWs have matrix blockage during long-term operation, resulting in a sharp decline in the permeability coefficient and treatment performance of the matrix [33,34]. The water purification process of the stabilization pond sewage treatment system is similar to the self-purification process of water. However, it needs a large scale to achieve a high degree of treatment. Moreover, its treatment footprint depends on climatic regional conditions and sewage characteristics. The integrated treatment technology can choose centralized or decentralized integrated treatment according to the concentration degree of rural residence and the amount of sewage load. The integrated treatment design creates and assembles the process module according to the actual sewage quality characteristics and the characteristics of rural areas to make it whole. Its installation and transfer are extremely convenient. Moreover, the integrated internal process module can be selected according to the purpose of the discharged water quality. Different processes are introduced in Section 3. However, the integrated sewage treatment technology is in its infancy in developing countries, and its operation cost is relatively higher than the operation cost of other ecological sewage treatment technologies. In general, ecological treatment technologies, such as CW, soil infiltration, and stabilization pond, have the problems of large floor area, difficult operation in winter, substrate blockage, and low treatment efficiency. By contrast, integrated treatment technology has strong resistance to hydraulic and pollution loads, stable effluent quality, and excellent treatment effect. It can be applied to both decentralized and centralized rural areas and will become the mainstream development direction of rural sewage treatment.

Table 1. Comparison of rural domestic sewage treatment technology.

Technology Type	Technical Characteristics	Technical Disadvantages	Suitable Conditions	Res.
Constructed wetland technology	Convenient operation and maintenance, simple management, low investment and operation cost	Large floor area, difficult operation in winter, easily causes secondary pollution.	Areas with low population density, less pollution emission, less fund investment, and lack of technical talents	[17,31,32]
Soil infiltration technology	Low operating costs, good effluent effect, strong impact load resistance	The removal capacity is limited by soil adsorption capacity	Areas with idle land and appropriate temperature	[18,23,25–30]
Stabilization pond technology	Low investment and operation cost, simple maintenance, convenient operation	Longer hydraulic retention time, low treatment efficiency, large floor area	Suitable for areas with abandoned rivers, reservoirs, and ponds; small villages; and small domestic sewage discharge	[8]
Concentrated integrated processing technology	Strong resistance to hydraulic load and pollution load, high treatment efficiency, and strong treatment capacity	Technical and economic limits of the degree to which WWTPs can be cared for in rural areas	Areas of concentrated living and with high effluent quality requirements	[19,20]

Table 1. Cont.

Technology Type	Technical Characteristics	Technical Disadvantages	Suitable Conditions	Res.
Small-sized integrated processing technology	Small volume, high efficiency, stable effluent quality, the back end can realize the reuse of water resources	Relatively high construction and operation cost, low volume load rate, poor regional adaptability	Single or multiple households in scattered areas	[21]

3. Integrated Rural Sewage Treatment Process

Integrated sewage treatment is the integration of pretreatment, secondary treatment, and advanced treatment. The main processes include the A/O process, MBR process, biological contact oxidation technology, and SBR-activated sludge process. In many European countries, the SBR process, moving bed biofilm reactor, biological rotary table, and trickling filter technology are the main technologies. The integrated treatment process in Japan mainly adopts the combined process of anaerobic–aerobic–secondary precipitation. Several typical processes are introduced as follows.

3.1. A/O Process

A/O process is a treatment process in which anaerobic and aerobic equipment are successively connected in series. A is an anoxic/anaerobic tank that mainly deals with nitrogen and phosphorus in sewage, and O is the aerobic tank that mainly removes organic matter in the sewage. The specific process flow is shown in Figure 1. The A/O process is relatively mature. It has stable operation, high bearing load, and good treatment effect on organic matter and ammonia nitrogen. Moreover, this process does not easily produce sludge bulking. The process has high efficiency and low cost. It is widely used in sewage treatment in various fields. Research on process-influencing factors, such as the number of sections, sludge reflux ratio, flow distribution ratio, dissolved oxygen (DO) value, carbon–nitrogen ratio, HRT, external filler reinforcement, and micro-electrolysis reinforcement, has been recently carried out. Optimizing the process conditions can improve the treatment efficiency of pollutants through the A/O process. G. Gao et al. [35] used a four-stage influent A/O process to treat low carbon–nitrogen ratio wastewater. They found that the denitrification effect is the best when the influent flow is 20:35:35:10. For the A/O process, the appropriate influent quality guarantees the stable operation of the system. It pays special attention to the influent temperature, pH value, DO value, and BOD/total nitrogen (TN) value, ensuring that the temperature of influent quality is higher than 15 °C, pH value is greater than 6.5, DO value is less than 0.5 mg/L, and BOD/TN value is maintained at approximately 5–7. The aeration volume and sludge discharge volume of the aeration tank are adjusted in time. The usual A/O process takes the pushing flow operation model without the reflux process to reduce construction cost and operating energy consumption. However, the effluent quality cannot meet the high discharge standard. Additionally, the excess sludge yield still needs to be further reduced to improve applicability in rural areas because most rural areas lack the sludge treatment capacity. Therefore, the A/O process must be explored to improve further the removal efficiency of pollutants in wastewater [36,37].

3.2. Membrane Bio-Reactor (MBR) Process

The MBR's operation principle involves fixing the membrane module made of special materials in the MBR reaction chamber, and then the sewage flows into the MBR reaction chamber after anaerobic treatment. The molecular membrane of MBR has a good filtration function. Thus, it can intercept the microorganisms in the sewage to the submembrane, increase the residence time of pollutants in the reactor, and further improve the efficiency of sewage treatment. The specific process flowchart is shown in Figure 2. Compared with the traditional activated sludge process, this process has remarkable advantages: it can achieve high-quality effluent, a small floor area, and a low sludge production rate [38].

The effective solution to reducing the operation cost and management difficulty of the MBR process is to control membrane pollution. For example, membrane pollution can be controlled by optimizing the overall operation process and operating conditions of the MBR process, thereby ensuring a good and stable treatment effect; reducing energy consumption; developing efficient, high-performance, pollution-resistant, and economically feasible membrane materials; and adding filler to the system to improve the sewage mixture characteristics. Faria et al. [39] constructed a biofilm reactor through the anaerobic mixed sludge bed–MBR process to remove persistent pollutants in domestic sewage. They found that the membrane pollution is reduced, the removal rate of several persistent pollutants can reach more than 84%, and the removal rate of chemical oxygen demand (COD) can reach 98%. Udomkittayachai et al. [40] introduced conductive media for the energy consumption reduction in an electrochemical MBR to improve nitrogen removal and mitigate membrane fouling.

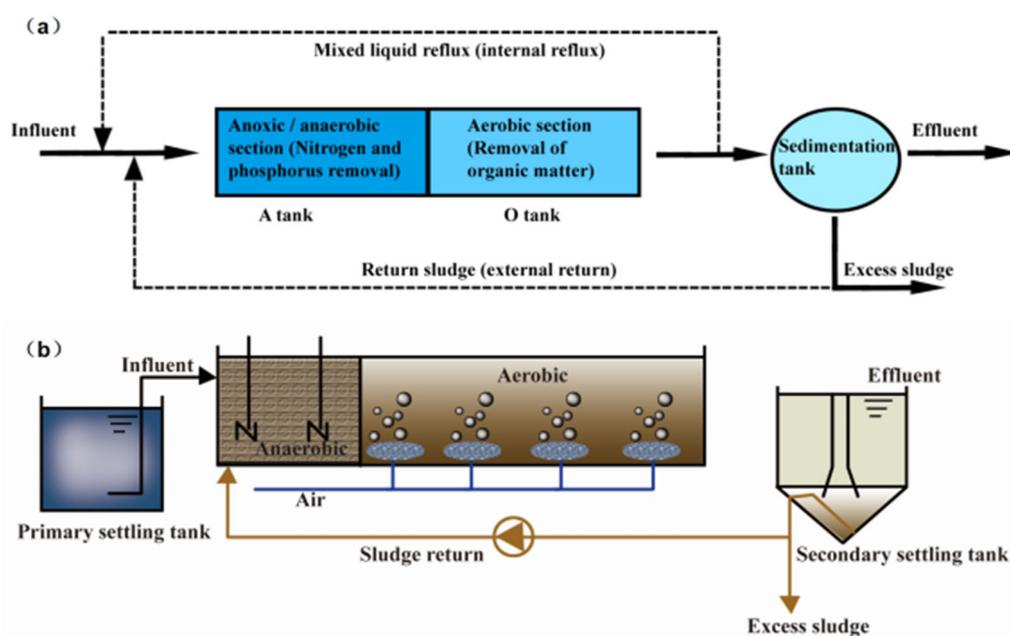


Figure 1. A/O process flow (a) and schematic diagram (b).

3.3. Biological Contact Oxidation Process

The operation principle of biological contact oxidation technology is to fill a large number of carriers in the reaction chamber, make microorganisms adhere to the carriers and form a biofilm, and purify domestic sewage through biodegradation. The specific process flowchart is shown in Figure 3. This technology has the advantages of activated sludge and biofilm processes. It can effectively treat domestic sewage, reduce energy consumption, and control the problem of sludge bulking. At present, the exploration of a new filler carrier and the study of its derived multilayer biological contact oxidation tank are aimed at solving the problems of biofilm blockage, high filler replacement frequency, and poor nitrogen treatment effect of the biological contact oxidation method [11,41]. Given that biological contact oxidation is considered the main process, the performance of filler, inlet water quality conditions, and hydraulic retention time are critical to the stable operation of the process. The filler with uniform biofilm distribution, no obvious mud accumulation, large porosity, and difficult plugging is selected to ensure good filler performance. The key to the biological contact oxidation process is to monitor the biofilm condition on the filler surface, regulate the influent water quality conditions, and ensure appropriate hydraulic retention time.

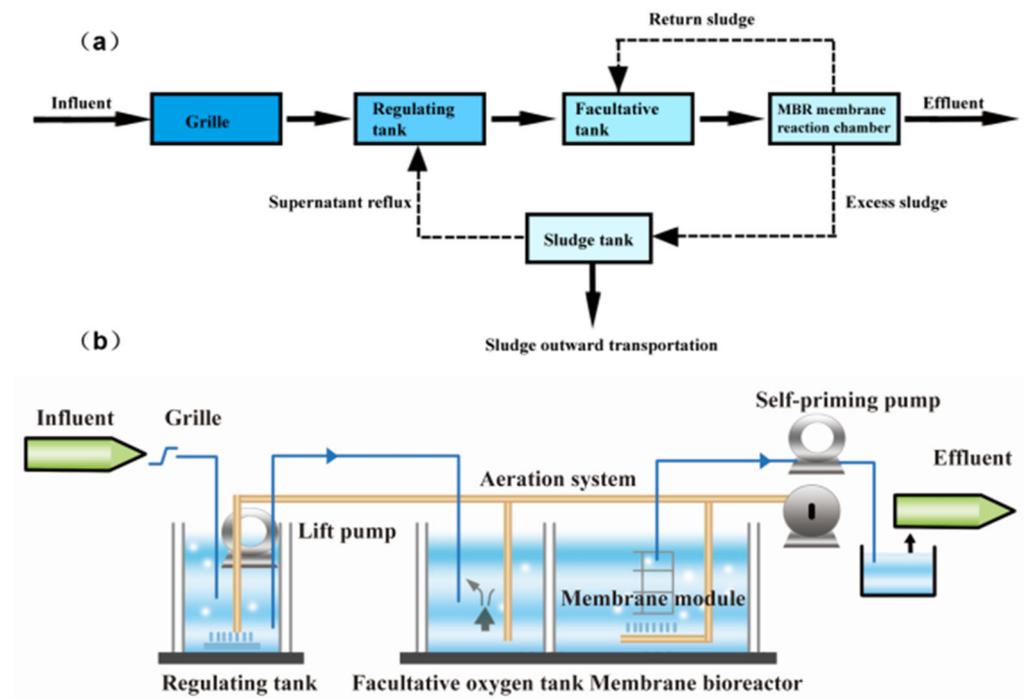


Figure 2. MBR process flow (a) and schematic diagram (b).

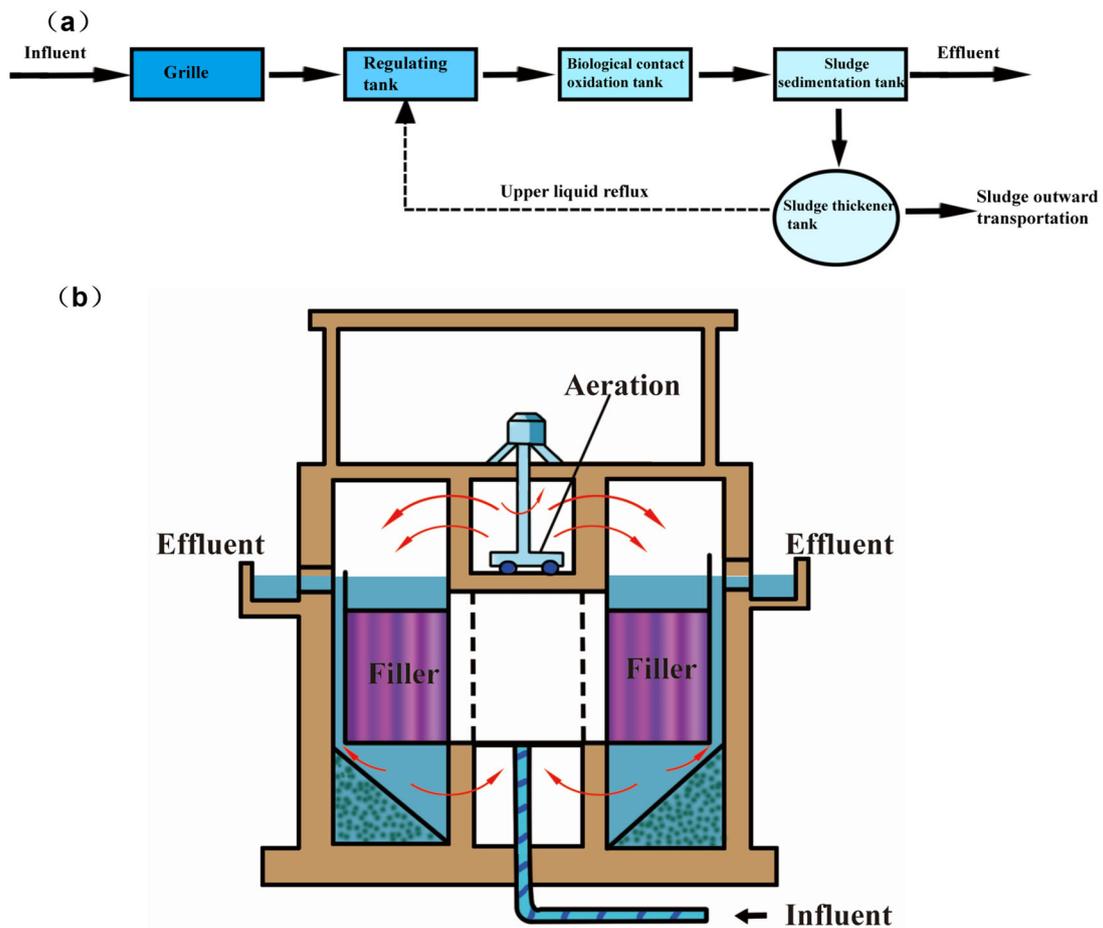


Figure 3. Biological contact oxidation process flow (a) and schematic diagram of the schematic diagram tank (b).

3.4. SBR Process

The SBR process is an intermittent activated sludge process with a discontinuous working condition. Sewage enters the SBR reactor intermittently and periodically and circulates in different treatment processes or functional states in each cycle in sequence. The most remarkable advantage of this process is that it divides the passage time of anoxic and aerobic reactions; that is, it does not need the sludge reflux process and reduces the floor area [42]. The specific process flow is shown in Figure 4. However, some changes in water quality and environmental conditions may affect the denitrification efficiency of the whole system. At present, people tend to design different SBR operation modes to improve the denitrification performance of the system. Zhao et al. [43] adopted the operation mode of A/O/A-SBR and changed the reaction time of each operation stage to realize the synchronous removal of N and P in sewage. The results showed that under the operation condition of a single 6 h cycle, the removal effects of COD, TN, and total phosphorus (TP) can reach 96.8%, 96.3%, and 94.3%, respectively. The SBR process has simple operation and maintenance management and good impact load resistance [44]. However, given the intermittent operation of “take time to exchange space,” the total parameter variables of the automatic control system of the equipment are considerable, and the requirements for high-precision instruments and scales are high [45]. Therefore, improving the automatic control technology of the equipment and the precision of the flow dose instrument can effectively reduce the operation and maintenance costs of the SBR process.

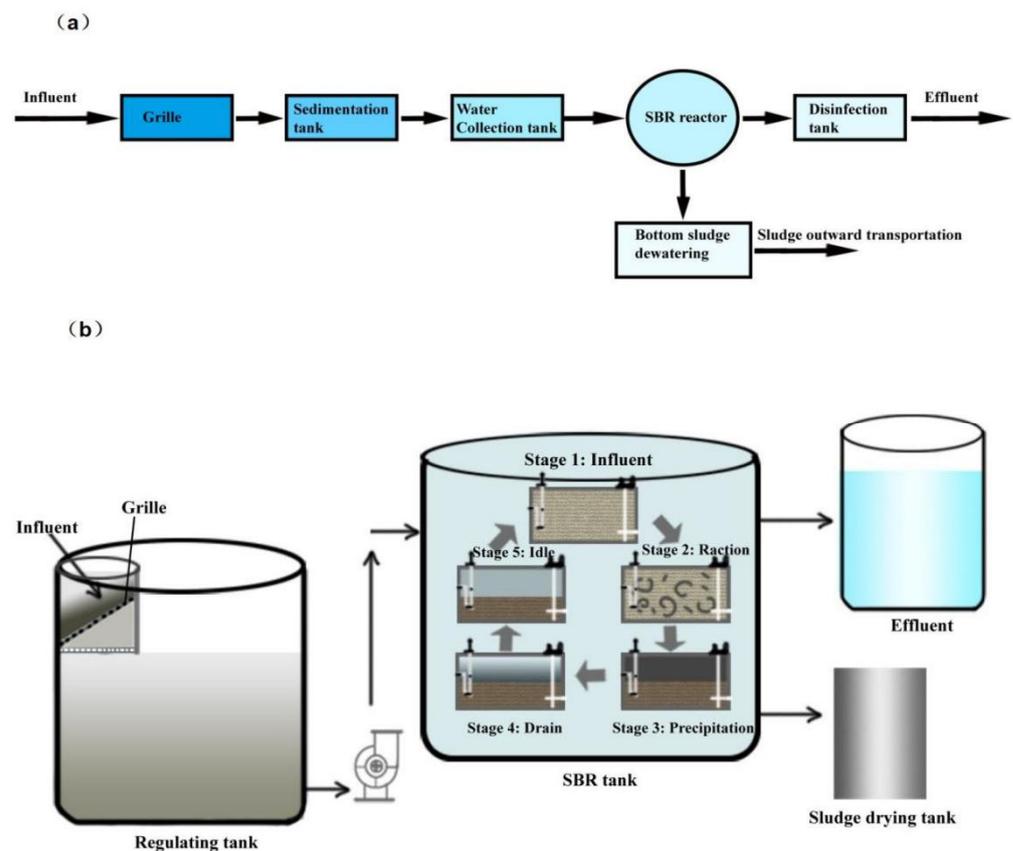


Figure 4. SBR process flow (a) and schematic diagram (b).

3.5. Economic Indicators of the Integrated Rural Sewage Treatment Process

The main technical and economic indicators of different processes are compared according to the characteristics of different treatment processes. They are also analyzed from the aspects of effluent quality, operation management, floor area, construction difficulty, and investment and construction cost (assuming that the treatment capacity of each process

is 120 m³/d). The results are shown in Table 2. Among them, the total investment of each process refers to practical technology of rural sewage treatment [46]. In terms of effluent quality effect, the effluent treated by the integrated sewage treatment process (A/O process, MBR process, biological contact oxidation process, and SBR process) can reach the first-level discharge standard (GB18918-2002), whereas the effluent quality of the traditional ecological treatment technology (CW, land treatment system, and stabilization pond) can only reach the second-level discharge standard (GB18918-2002). Compared with the traditional ecological treatment technology, the integrated treatment process has increased the impact resistance of water quality and quantity in the sewage treatment process. In addition, the outstanding advantages of the integrated sewage treatment process are small volume, saving land occupation area, convenient operation and maintenance of internal process modules, and overcoming the problem of matrix blockage and replacement in ecological treatment technology. Compared with the traditional process, the integrated sewage treatment has the disadvantage of high initial investment cost; however, this concern is not the main problem based on the sewage treatment effect and operation and maintenance management. In the future, the integrated treatment can be further improved in this regard.

Table 2. Comparison of common technological and economic indicators.

Project	A/O Craft	MBR Craft	SBR Craft	Biological Contact Oxidation	Constructed Wetlands	Land Purification System	Stability Pond
Effluent quality	GB 18918-2002 Class I B emission standard	GB 18918-2002 Class I A emission standard	GB 18918-2002 Class I B emission standard	GB 18918-2002 Class I A emission standard	GB 18918-2002 Secondary emission standard	GB 18918-2002 Secondary emission standard	GB 18918-2002 Secondary emission standard
Effluent flexibility	Good	Good	Better	better	General	General	General
Adaptability of water volume	Good	General	Better	Better	General	Inferior	Good
Effluent stability	Good	Better	Better	Better	Good	General	General
Sludge production	little	less	less	little	-	-	-
Operation management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management	Simple process operation and convenient operation and management
Maintenance work	Less process equipment and easy maintenance	Complex process equipment	Less process equipment and easy maintenance	Less process equipment and easy maintenance	Less process equipment and easy maintenance	The process is easily blocked	Less process equipment and easy maintenance
Main land occupation m ² /m ³ ·d	0.83	1.33	1.00	0.92	4–10	10–40	50–200
Total investment yuan/m ³	2200–3200	2800–3800	2500–3500	2000–3000	150–400	100–400	1000–1200
Operation cost yuan/t	0.35–0.45	0.45–0.65	0.40–0.55	0.30–0.40		<0.2	

Table 2. Cont.

Project	A/O Craft	MBR Craft	SBR Craft	Biological Contact Oxidation	Constructed Wetlands	Land Purification System	Stability Pond
Labor quota person				1–2			
Difficulty of construction		Easy				General	
Construction cycle month		1–2				0.5–1	

4. Application of Integrated Rural Sewage Treatment Projects in Different Countries

4.1. Integrated Treatment of Purification Tank in Japan

A purification tank is a system widely used for the integrated treatment of rural sewage in Japan. By 2011, more than 8.6 million purification tanks had been built in Japan [47]. The tank comprises an anaerobic filter, a contact oxidation tank, a sedimentation tank, and a disinfection tank (see Table 3 for the tank capacity specifications of the purification tank system) [48]. The bearing volume of each internal processing unit changes according to the user population of the purification tank. The purification tank is mainly used for sewage treatment with the family as the unit when the user population is less than five. In comparison, it is mainly used for household sewage treatment when the user population is between six and ten. Purification tanks with a user population between eleven and fifty are mainly used for sewage treatment in cluster communities. Fillers are added to the anaerobic filter and contact oxidation tank; thus, microorganisms can be fully enriched on the fillers to increase the sewage treatment efficiency. The purification tank treatment system has the advantages of small volume, low cost, simple operation, stable sewage quality after treatment, and good suitability for decentralized sewage treatment in rural areas.

Table 3. Volume of each compartment in the purification tank system.

Use Population/Person	Anaerobic Filter/m ³	Contact Oxidation Pool/m ³	Sedimentation Tank/m ³	Sterilization Chamber
≤5	1.5	1.0	0.3	
6–10	$1.5 + (n - 5) \times 0.4$	$1.0 + (n - 5) \times 0.2$	$0.3 + (n - 5) \times 0.08$	$0.2 \times n \times 1/96$
11–50	$3.5 + (n - 10) \times 0.2$	$2.0 + (n - 10) \times 0.16$	$0.7 + (n - 10) \times 0.04$	

Note: “n” represents the number of people using the purification tank device.

4.2. Biological Contact Oxidation Integrated Treatment in Britain

Activated sludge biological contact oxidation integrated treatment is widely used in rural sewage treatment projects in Britain. The treatment system comprises a primary sedimentation tank, filter bed (air injection or rotary sprinkler irrigation), and secondary sedimentation tank. The types of integrated sewage treatment equipment developed from the activated sludge biological contact process system (Table 4) include stable contact activated sludge type, delayed aeration activated sludge type, extended biofiltration type, and rotary biological contact type [49]. Each type of equipment comprises modular and highly integrated units, which can be used only after being assembled on-site during construction. The characteristics of this sewage treatment system include convenient operation and management and stable effluent quality. The activated sludge unit in the equipment extends the biological filtration function. It is also equipped with a rotating biological contact tank to improve the sewage treatment capacity. In the UK, different types of integrated sewage treatment processes are adopted based on population concentration. The activated sludge process and extended biofiltration process do not produce sludge in the operation process, but the energy consumption is high. The rotating biological contactor has low energy consumption but relatively low pollution removal efficiency.

Table 4. Features of small sewage treatment equipment.

Type	Range (p.e)	Advantage	Disadvantage
Activated sludge: contact stability	30–20,000	No raw sludge is formed, and the secondary sludge is stable with low output, no smell, and strong compactness; it can reach the effluent of 30:20	It needs continuous energy and maintenance to ensure ventilation and pump operation. Power failure will seriously affect the treatment effect of the system, and excessive water volume will lead to the loss of activated sludge.
Activated sludge: delayed aeration	17–30,000	No raw sludge is produced, and the secondary sludge is stable with low output and no smell; it can reach the effluent of 30:20	High energy consumption, ventilation, sludge removal, and regular inspection are required during maintenance.
Extended biofiltration	15–450	No raw sludge is formed that can treat intermittent effluent; it can reach the effluent of 30:20	Odor will be generated, and the final sludge is difficult to dehydrate with high energy consumption. Effective operation requires continuous energy supply and regular inspection and maintenance.
Rotary biological contactor	5–40,000	The energy consumption and water loss are low; it can reach the effluent of 30:20	It is necessary to remove sludge and maintain the engine regularly. Overload operation is strictly prohibited. Power failure will reduce the removal efficiency.

Note: “p.e” is population equivalent.

4.3. Local Integrated Processing System in New Zealand

New Zealand mainly adopts a rural sewage local integrated treatment system. By 2010, approximately 270,000 local processing systems had been built and applied in China [49]. The treatment system is an integrated sewage treatment system based on ecological treatment and integrated anaerobic and aerobic treatment. The septic tank sewage treatment is generally regarded as integrated anaerobic and aerobic treatment, which can be used as the pretreatment of the local treatment system. In the design, the septic tank must be free from water leakage, and the amount of sewage treated and the total amount of solids in sewage should be based on the size of the septic tank. Size is the key factor affecting the treatment effect. In general, the effective volume of a septic tank is determined according to the number of users (see Table 5 for details) [50]. As the post-treatment part of the local treatment system, the soil infiltration system plays an important role in the local absorption of sewage. The following factors are mainly considered: (1) soil type: the soil with abundant colloidal particles is selected to increase the absorption, complexation, and precipitation reaction of soil to ions in sewage, thereby improving the treatment capacity of the system; (2) hydraulic load and pollution load: based on the soil environmental capacity, the water quality and quantity treated at the front end of the septic tank must be adjusted according to the treatment capacity of the soil infiltration system; and (3) design of infiltration ditch: a hydraulic load of the capillary filtration of the soil infiltration ditch is generally between 0.03 and 0.04 m³/m • d [51]. The design of the infiltration ditch shall be reasonably arranged according to the site pollutant load and hydraulic load. The matrix and effect of the in situ treatment system on the removal of pollutants in sewage are shown in Table 6 [52].

Table 5. Effective volume of septic tank.

Use population/person	≤3	4–6	7–9
Effective volume setting/m ³	≥1.5	≥2.0	≥2.5

Table 6. Contaminant removal matrix and removal capacity of on-site processing system.

Pollutant	Removal Approach	Removal Effect
BOD	Soil adsorption and biological oxidation	90–95%
Nitrogen	Volatilization, denitrification, and crop absorption	70–80%
Phosphorus	Soil adsorption fixation and plant absorption	85–95%
Organic compound	Volatilization, photolysis, and biodegradation	75–85%
Pathogen	Adsorption, drying, radiation, and biological phagocytosis of soil system	99%

5. Evaluation Method of Integrated Rural Sewage Treatment Technology

Given the development of various integrated rural sewage treatment technologies, selecting sewage treatment processes suitable for local conditions in different rural areas is important. However, the adaptability analysis of the integrated rural sewage treatment process indicates that this process is a complex whole composed of environmental, social, economic, and other factors. A systematic evaluation method must be adopted to evaluate scientifically the integrated treatment technology in rural areas from many aspects. This approach can effectively determine the efficiency, economy, applicability, and social impact of the treatment technology. Countermeasures and measures can also be proposed to prevent or reduce the adverse impact according to the evaluation results. Moreover, scientific and reasonable decisions can be made to promote similar technologies in rural areas. According to the literature review, the evaluation methods of integrated rural sewage treatment technology mainly include single-factor evaluation, multifactor weighted evaluation, expert scoring, fuzzy comprehensive evaluation (FSE), Bayesian model evaluation, gray correlation evaluation, neural network evaluation, and comprehensive technology evaluation.

5.1. Single-Factor Evaluation

The single-factor evaluation method is simple and intuitive. It is often used as an evaluation method when special requirements are needed for a certain pollutant. The selected factors become the decisive factor of the treatment technology and are often used in the comprehensive ecological and economic evaluation of a sewage treatment process [53]. Single-factor evaluation has the advantages of convenient calculation and intuitive evaluation results. Moreover, the pollution degree of water quality indicators can be directly reflected through the water quality monitoring data. In practice, the ratio of the monitored value of each water quality index (WQI) to the target water quality standard is calculated by detecting the effluent index of the integrated rural sewage treatment technology. Whether the treatment technology meets the standard requirements is evaluated according to whether the ratio is >1 . If the ratio is ≤ 1 , then the evaluated treatment technology meets the requirements; if the ratio is >1 , then the evaluated treatment technology does not meet the requirements. The factors often selected in evaluating sewage treatment technology are TN, TP, COD, suspended solids, energy consumption, and other easily quantifiable factors. However, this evaluation method is relatively negative. If the indicator has a relatively considerable pollution degree, the water quality grade in the final evaluation results is relatively low. In this case, the overall water quality of the water body cannot be reflected to a certain extent. Thus, this evaluation method should be used in combination with other methods to give full play to its benefits.

The formula of the single-factor evaluation method is as follows [54]:

$$Q = \frac{P_1}{P_2}, \quad (1)$$

where P_1 represents the detection value of effluent quality of integrated rural sewage treatment technology (mg/L), and P_2 represents the standard value of target water quality (mg/L).

5.2. Multifactor Weighted Evaluation

In the rural sewage treatment technology evaluation, the multifactor weighted evaluation method refers to the existence of multiple factors that are decision-making factors for the treatment technology; it also provides corresponding weight values to different factors, uses different weights to distinguish the importance of each factor, and determines the weight of each factor [55]. These factors also determine the score of each detection index on the satisfaction of each factor and the sum of the product of the weight of each factor to evaluate the treatment technology. The specific steps are shown in Figure 5. The multifactor weighted evaluation method requires a small amount of data and calculation workload. This method can quantify the whole complex problem, and the evaluation results are scientific and comprehensive. The establishment of an index system is one of the most critical parts of the evaluation. Whether the evaluation of index weight is reasonable directly affects the evaluation results. Compared with the single-factor evaluation method, the multifactor weighting method can provide a relatively scientific and comprehensive evaluation for the evaluation facilities. The evaluation method needs a small amount of data and calculation workload. It can quantitatively express the whole complex problem and evaluate the advantages and disadvantages through the calculation results of weight.

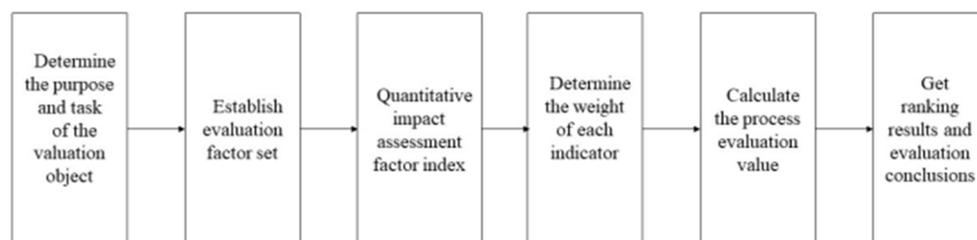


Figure 5. Multifactor weighted evaluation flow.

5.3. Expert Scoring Evaluation

The expert scoring evaluation method takes experts as the object of asking for information, draws lessons from the knowledge and experience of experts, and makes certain judgments, evaluations, and predictions on the research problems after experts visit, investigate, and study [56]. This method is mainly used in the following four situations: data are lacking, data cannot reflect the real situation, data collection time is too long, and data collection cost is too high to adopt quantitative evaluation methods. The data for the emerging technologies are either nonexistent or lacking when the evaluation content goes beyond the scope of technology, economy, and environment and involves public, political, and other factors. This method is intuitive and simple. It considers the evaluation items that can be calculated quantitatively and those that cannot be calculated. However, it is vulnerable to the influence of authority and the opinions of most people.

5.4. Fuzzy Comprehensive Evaluation

FSE is a method for comprehensive evaluation on systems affected by multiple factors through fuzzy mathematical theory. This method can comprehensively consider all evaluation factors, particularly when the evaluation index system has both quantitative and qualitative indexes and a hierarchical relationship exists between various indexes [57].

The integrated rural sewage treatment process involves the influence of the environment, technology, economy, and other factors. In the face of this complex system, some fuzzy indicators cannot be expressed by quantitative data (e.g., people's satisfaction and ecological coordination degree). This fuzzy indicator can only be quantified indirectly by experts in the industry. Thus, the uncertainty and singleness of the overall evaluation are increased. The steps of the evaluation method are as follows:

- I. Evaluation object set V is established.
- II. Evaluation factor set U is established.
- III. Each factor in the U set is weighted to establish the weight distribution vector A .

- IV. The fuzzy judgment matrix of each factor is obtained through the fuzzy evaluation of each single factor. Then, the fuzzy comprehensive judgment matrix R is obtained through the fuzzy judgment matrix of each single factor.
- V. The fuzzy comprehensive judgment matrix R and the weight distribution vector a are combined to obtain the final comprehensive evaluation result B.
- VI. The comprehensive evaluation result B is converted into the comprehensive score value N.
- VII. The final score result of each object is evaluated according to the comprehensive score N value.

The fuzzy comprehensive evaluation method establishes a membership matrix by establishing a membership set, which represents the relationship between each level of factors and each standard. Then, this method obtains a fuzzy product by multiplying the weighted set of factors and the membership matrix to obtain a comprehensive evaluation set, which can represent the membership of the evaluated water quality to each level of standard water quality and reflect the fuzziness of the comprehensive water quality grade [58].

The fuzzy comprehensive evaluation method can comprehensively summarize the opinions of various evaluation topics. It can also solve the fuzzy, difficult-to-quantify, multifactor, and multilevel problems in integrated rural sewage treatment technology. Moreover, it can solve the fuzzy problem between multiple factor evaluations that cannot be solved by traditional methods. It has the characteristics of qualitative evaluation and quantitative evaluation. The results are scientific and reasonable. This method is also suitable for the evaluation of river water function and water quality category. However, the calculation is complex, and the determination of the index weight vector is subjective. The result exhibits a super fuzzy phenomenon when the index set is large. Moreover, the resolution is very poor. Thus, distinguishing who has a high degree of membership is impossible and may even cause evaluation failure.

5.5. Bayesian Model Evaluation

Bayesian theory is a method based on mathematical statistics based on probability. This method regards all parameters as a group of random variables and considers the first test probability distribution to describe quantitatively the correlation degree between evaluation factors and elements and evaluate water quality through the probability inference of data information. It can also avoid the defect of the classical statistical method, which is effective only for large samples and weak for small samples [44]. At present, the Bayesian model is applied to evaluate wetland treatment, river pollution, and sea area condition [59]. However, the Bayesian water quality model is still insufficient in describing parameter uncertainty. Its model parameters are often input by the mean of measured data, which cannot consider the large parameter changes under different conditions. This scenario may lead to the lack of persuasion of evaluation results. Therefore, many scholars have improved the Bayesian model, particularly the commonly used Bayesian model based on triangular fuzzy optimization, to reflect the actual situation of the water treatment process objectively and comprehensively.

The evaluation method is as follows:

- I The monitoring indicators of the evaluation object are determined.
- II A triangular fuzzy number of the monitoring index is established.

If fuzzy variable $A = (a, b, c)$ and $a \leq b \leq c$, with a , b , and c representing the minimum possible value, most possible value, and maximum possible value of fuzzy variable A , respectively, then the corresponding membership function relationship is (x is a monitoring index variable)

$$\Phi_A = \begin{cases} 0, & x \leq a \text{ or } x \geq c \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \end{cases} . \quad (2)$$

Suppose that the average value of water quality monitoring data processed by certain equipment is \bar{x} , and the standard deviation is σ . In this case, $a = \bar{x} - 2\sigma$, $b = \bar{x}$, and $c = \bar{x} + \sigma$. In addition, β is set to confidence level, and $\beta \in [0, 1]$, β can convert the triangular fuzzy variable A into the value of a certain confidence level β interval. The greater the value of β is, the closer the value is to the average value and the greater the frequency of data is.

$\overline{A^\beta} = [a + (b - a)\beta, c - (c - b)\beta]$, where $\overline{A^\beta}$ is the interval number processed by β .

Let amin and amax be the maximum and minimum values of $\overline{A^\beta}$, respectively, that is, amin = $a + (b - a)\beta$, amax = $c - (c - b)\beta$. Then, $\overline{A^\beta} = [\text{amin}, \text{amax}]$.

The triangular fuzzy optimization Bayesian model is applied.

The traditional Bayesian model is

$$P(B_{i,j}|A_j) = \frac{P(B_{i,j})P(A_j|B_{i,j})}{\sum_{i=1}^V P(B_{i,j})P(A_j|B_{i,j})}, \tag{3}$$

where j is the WQI; i is the water quality grade; $B_{i,j}$ refers to the standard value of class i water quality of the item j WQI in the effluent quality of the equipment; A_j refers to the monitoring value of the item j WQI; $P(B_{i,j})$ is the predetection probability of event $B_{i,j}$; $P(A_j|B_{i,j})$ is the conditional probability, that is, when the water quality category of the item j WQI is i , the possibility of the effluent WQI is A_j ; $P(A_j|B_{i,j})$ is the postinspection probability, that is, the possibility that the water quality of j belongs to class i under the condition that the effluent index of the equipment meets A_j .

If the concentration $a = (a, b, c)$ of each water quality monitoring in the triangular fuzzy number is transformed into the corresponding $\overline{A^\beta}$ by using β , the Bayesian model based on triangular fuzzy number optimization is

$$\overline{P^\beta}(B_{i,j}|\overline{A^\beta}_j) = \frac{P(B_{i,j})\overline{P^\beta}(\overline{A^\beta}_j|B_{i,j})}{\sum_{i=1}^V P(B_{i,j})\overline{P^\beta}(\overline{A^\beta}_j|B_{i,j})}, \tag{4}$$

where $\overline{P^\beta}(B_{i,j}|\overline{A^\beta}_j)$ is the posterior probability that the effluent quality of the equipment belongs to class i water quality when the measured value of the WQI of item j belongs to $\overline{A^\beta}_j$; $\overline{P^\beta}(\overline{A^\beta}_j|B_{i,j})$ is the probability that when the water quality monitoring level of item j is i , it just belongs to $\overline{A^\beta}_j$.

- III. The a priori probability P1 and conditional probability P2 are calculated according to the idea of layering and the concept of geometric distance.
- IV. The weight of WQI is determined, and the score value of sewage treatment equipment is calculated according to the weight value.
- V. The final score result of each object is evaluated according to the comprehensive score value.

The Bayesian model method of triangular fuzzy optimization integrates the advantages of the triangular fuzzy number and the traditional Bayesian model method. Moreover, it can deal with the uncertainty of monitoring data, sampling quantity, evaluation index standard parameters, and model structure in the process of effluent quality evaluation of integrated equipment. It aims to compensate for the shortcomings of the fuzziness and randomness of water quality monitoring information, lack of description, and homogenization of multi-index influence [60]. This method is conducive to objectively reflecting the decontamination effect of integrated equipment. The Bayesian model evaluation method is highly applicable to the case of a small sample size. It can also deal well with uncertainty. However, this method is complex and difficult to calculate.

5.6. Gray Relational Evaluation

The gray correlation evaluation method can be used to evaluate sewage treatment water quality. This method measures the correlation degree of factors according to the similarity or difference of the development trend between factors, namely, the “gray correlation degree.” When the water quality of the integrated sewage treatment equipment is evaluated, the measured value of the integrated equipment’s effluent quality is selected as the reference series, and the classification standard of the effluent quality is selected as the comparison series [61]. For the reference series, the level of the comparison series corresponding to the largest correlation degree in the correlation degree is the water quality classification standard corresponding to the water body to be evaluated [49].

The steps of the grey correlation analysis method are as follows:

- I. The indexes of effluent quality measurement of integrated equipment are listed as the reference series, whereas the grade of water quality standard is listed as the comparison series.

In particular, let the comparison sequence be $X_i(k) = \{X_i(1), X_i(2), X_i(3), \dots, X_i(n)\}$, and the reference sequence is $Y_i(k) = \{Y_i(1), Y_i(2), Y_i(3), \dots, Y_i(n)\}$, where $X_i(k)$ represents the value of the k -th WQI in the class I water quality standard, and $Y_i(k)$ represents the measured value of the k -th index in the j -th water sample.

- II. The comparison sequence $X_i(k)$ and the reference sequence $Y_i(k)$ are normalized. Normalizing and making the original data dimensionless are necessary to obtain $X'_i(k)$ and $Y'_i(k)$ and ensure that all factors have the same order and equivalence.
- III. The difference sequence is searched.

$$\Delta_{ji} = Y'_i(k) - X'_i(k) \quad (5)$$

- IV. The correlation coefficient is searched.

$$\xi_{ji}(k) = \frac{\Delta_{\min} - \Delta_{\max}}{\Delta_{ji}(k) + \rho \Delta_{\max}}, \quad (6)$$

where $\Delta_{\max} = \max(x) - \max(k) \mid Y'_i(k) - X'_i(k) \mid$, $\Delta_{\min} = \min(x) - \min(k) \mid Y'_i(k) - X'_i(k) \mid$, $\rho = 0.5$.

- V. The correlation degree is searched.

$$R_{ji} = \frac{1}{n} \sum \xi_{ji}(k) \quad (7)$$

- VI. The correlation degree is sorted according to the value, and the largest one is searched in each row in the correlation degree matrix to determine the effluent quality grade of the integrated equipment.

The grey correlation evaluation method can avoid the inaccuracy of the evaluation results caused by the slight change in the critical value of the evaluation index grade. It can also truly reflect the differentiation of grade distribution. Many examples of grey correlation analysis are applied to environmental assessment, such as water quality and air quality. The grey correlation evaluation method is practical and effective. However, this method has a certain randomness and subjectivity and affects the evaluation results. When grey correlation analysis is used to evaluate water quality, the evaluation value of grey correlation degree tends to be homogenized because of the influence of the two-level difference in the correlation coefficient. Moreover, the resolution is low, so distinguishing the differences between the two levels is challenging.

5.7. Artificial Neural Network Evaluation

The application of the artificial neural network evaluation method to water quality evaluation can overcome the practical difficulties of traditional water quality evaluation

methods in dealing with nonlinear problems [62]. Artificial neural network evaluation is based on a computer network. It uses a program algorithm, allowing the computer to obtain learning and reasoning abilities similar to those of the human brain. It solves the immeasurable nonlinear relationship between the integrated sewage treatment technology and the evaluation index. It also has strong self-learning, self-organization, self-adaptation, and self-reasoning abilities. It can express complex phenomena by mapping the composition of simple nonlinear action functions. An artificial neural network usually consists of an input layer, hidden layer, and output layer. Each layer comprises multiple neurons. The neurons in the same layer have no correlation, and the neurons in different layers are connected forward. Depending on the complexity of the object, selecting the appropriate network structure can realize the mapping of any nonlinear function from input space to output space.

The artificial neural network evaluation method uses the powerful autonomous learning function of computers to reduce substantially the subjective influence in the evaluation process [63]. The evaluation accuracy of the effluent quality of the integrated equipment is high. Moreover, the artificial neural network model for water quality evaluation does not need too much mathematical statistical knowledge. In addition, it does not need to copy the pretreatment of water quality monitoring indicators. It only needs to standardize the data and input these into the model to obtain the output level of water quality. It can also identify the difference in pollution degree at the same level and obtain the level close to which the output value is, making the evaluation results scientific and reasonable. The network structure of the specific evaluation work is shown in Figure 6 [64].

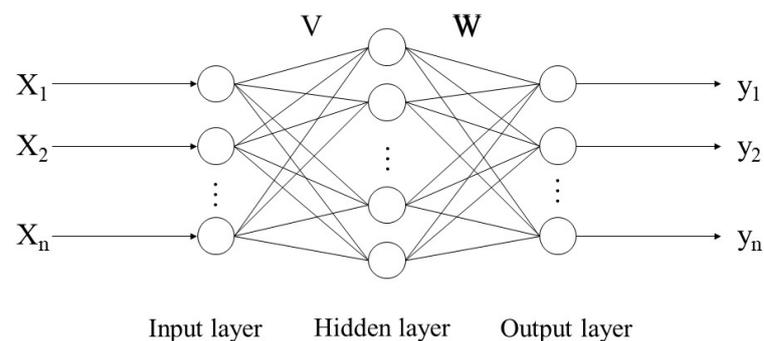


Figure 6. Structure of artificial neural network.

The evaluation process is mainly as follows:

- I The evaluation index of the integrated processing equipment is selected, and the data of the monitoring and assessment index are normalized.
- II The processed standard training samples are propagated forward from the input layer.
- III The error information fed back by the computer network is inversely transmitted from the output layer to each layer unit. The weight and threshold are continuously improved according to the feedback data to minimize the mean square deviation of the output value.
- IV The trained computer is used to evaluate independently the integrated processing system and obtain the evaluation results.

The artificial neural network evaluation method eliminates the influence of setting the weight of each pollution factor and relying on empirical formulas. The results of classification and pattern recognition are objective and reliable. This method has strong adaptability and good dynamics. It can also realize dynamic tracking. Moreover, the evaluation error is relatively small. The artificial neural network method has broad application prospects in other fields of environmental quality assessment, such as river water quality, air pollution, urban noise, and urban comprehensive environment. However, this method adopts the optimization algorithm, and the error surface is complex. The error propagates backward through the output layer. The higher the number of the hidden layers, the more inaccurate

the reverse propagation deviation is when it is close to the input layer. The evaluation efficiency is also affected to a certain extent.

5.8. Other Comprehensive Technology Evaluation

At present, most of the evaluation methods of sewage treatment studied by scholars mainly focus on the treated water quality. However, in the practical application process, these methods are affected by many factors, such as water quality, technology type, environmental conditions, and social influence. Some scholars have also conducted preliminary research on the comprehensive technology evaluation method, which mainly adopts the construction of a multilevel index system and the comprehensive evaluation index method for evaluation. At present, some scholars use the life cycle assessment method [65] and footprint method [66] or combine different methods to achieve accurate evaluation and prediction. Therefore, in the future, we must study comprehensive models and methods to identify suitable integration technologies accurately.

In developing countries, researchers or environmental impact assessment workers have applied these evaluation methods to evaluate rural sewage treatment. Zhang [67] and others used the agricultural comprehensive evaluation model based on FSE and the analytic hierarchy process method in evaluating China's rural domestic sewage treatment technology. The case analysis verified the applicability of the model, which can support the technology selection of China's rural domestic sewage treatment market. Sharvini [68] and others used Gabi software and the midpoint method of recipe to conduct life cycle assessment when evaluating the decentralized sewage treatment technology in Malaysia. They also analyzed the potential environmental impact of different decentralized sewage treatment technologies. Given the rapid development of rural areas in developing countries in recent years, the country has proposed new requirements for rural governance. Thus, the evaluation method of rural sewage treatment should be selectively evaluated according to the requirements of different countries and local governments. Given the heightened requirements, these evaluation methods cannot fully meet the evaluation goals of sewage treatment in developing countries. Thus, we need to improve the evaluation methods further or establish new ones.

The following are the three suggestions for combining methods or techniques to make an accurate evaluation. The first point is to optimize the parameters of the existing research models. For example, Md et al. proposed an improved WQI model to evaluate coastal water quality, using Cork Port, Ireland, as a case study [69]. The model involves four common WQI components: selected water quality indicators, subindexes of index values, subindex weights, and subindex aggregation. The model is improved to make the method objective, data driven, and vaguely susceptible to food and ambiguity errors. The second point is to combine different evaluation methods, combine the advantages of each evaluation method, and make up for its shortcomings. For example, Wei et al. organically combined fuzzy rules, membership functions, and neural networks to propose a comprehensive evaluation method [70]. The water quality evaluation based on a TS fuzzy neural network is convenient and adaptable. The third point is to develop a new evaluation model. For example, Hu et al. developed a comprehensive probability FSE method to assess the drinking water quality of rural and remote communities through health risks and aesthetic impacts [57]. Probabilistic health risk assessment can deal with the accidental uncertainty caused by the change of pollutant concentration, whereas FSE can solve the fuzziness and fuzziness of human perception of risk and aesthetic impact. Zhang et al. established a new water quality evaluation model based on projection pursuit technology [67]. A new method combining a genetic algorithm with a conditional optimization method is proposed and applied to model optimization. This new method can effectively solve the global optimization problem under various constraints.

6. Operation and Maintenance Management Mode of Integrated Processing System

Some developed countries, such as the United States and Japan, have legislated the discharge of domestic sewage on the issue of rural sewage treatment. Rural sewage treatment in the United States started early, and legislation was passed to strengthen the government's and citizens' participation in domestic sewage treatment. The United States has promulgated the Clean Water Act, the Safe Drinking Water Act, the Water Quality Act, the manual of the decentralized treatment system, and the management guide of the decentralized treatment system. This management guide stipulates the management method of combining emission limits and water quality standards based on pollution control technology, changes the management method based on water quality standards, and stipulates that the federal government supports the construction of sewage treatment projects. The rural domestic sewage treatment technology in Japan is relatively mature, and different sewage treatment legal systems have been formulated for rural areas. The Purification Tank Law has made comprehensive provisions for the rural scattered sewage treatment. This law is the main legal basis for rural sewage treatment in Japan at present. In developing countries, the discharge of rural domestic sewage has also developed relevant standards and regulations according to local conditions. However, it has not risen to the level of national legislation.

6.1. Operation Mode of Rural Sewage Treatment Facilities in America

The United States has clear laws, regulations, and a guidance system for the management of rural sewage treatment equipment. It regulates the construction and operation of rural sewage treatment equipment through the management mode of hierarchical legislation of the federal government, the National Environmental Protection Agency, and state governments. The federal government of the United States has formulated a series of bills to provide a basis for rural sewage treatment and equipment operation. As the supervision and guidance department, the State Environmental Protection Administration provides technical guidance and support for rural sewage treatment and equipment operation by issuing manuals and guidelines. The state government formulates the implementation plan in line with the state according to the specific regulations and guidelines, which are combined with the field conditions. It also guides farmers in administering sewage treatment and equipment operation and maintenance.

The financial subsidy policy for integrated rural sewage treatment facilities in the United States was formulated in the Clean Water Act of 1987. The bill points out that the financial subsidies for the integrated rural sewage treatment system are funded by the federal government and the state governments, and a rolling fund is established for the states. The fund supports the state's sewage treatment system and water pollution control projects with a low interest or in an interest-free manner. The repaid loan and interest are returned to the rolling fund to fund other sewage treatment projects. State governments also adopt related financial subsidy policies to support the construction, operation, and maintenance of sewage treatment facilities in rural areas.

6.2. Operation Mode of Rural Sewage Treatment Facilities in Japan

The operation and management of rural sewage treatment facilities in Japan are mainly based on the Purification Tank Law. The law requires that farmers apply to the government when they need to install, change, or abolish a sewage treatment system. The government approves and files the application submitted by farmers and entrusts a third-party organization to construct, transform, or replace the farmers' sewage treatment system. As a third-party organization, the company also undertakes the work of monitoring the effluent quality and evaluating the operation status of farmers' sewage treatment systems. The company also reports to its subordinate government departments for filing to ensure the effective operation of the rural sewage treatment system.

Japan has two main modes of financial support for rural sewage treatment facilities: the subsidy system for farmers' self-construction, and the overall promotion of villages. In

the subsidy system for farmers' self-construction, the farmers construct or transform their sewage treatment facilities, with the state bearing half of the construction cost to support the construction of the farmers' sewage treatment equipment. The village promotion system is an area sensitive to effluent quality. The whole village promotion of the sewage treatment system is implemented, which is 90% funded by the state and local governments. Farmers only need to bear 10% of the cost. In addition, the public enterprises set up by governments at all levels are specifically responsible for the regular overhaul and maintenance of rural sewage treatment facilities.

6.3. Operation Mode of Rural Sewage Treatment Facilities in New Zealand

Rural sewage treatment facilities in New Zealand are mainly local treatment systems based on mature septic tank technology. Given the lack of daily maintenance, improper installation site selection, and long service life without replacement, 15–50% of rural sewage treatment systems in New Zealand cannot be used normally. In response to this problem, the Ministry of Environment of New Zealand formulated the national standard for the local sewage treatment system, put forward mandatory requirements for the construction and maintenance of the sewage treatment system, and defined the management responsibility system of the local sewage treatment system. In this national standard, "Warrant of Fitness" is an important management measure for the operation of sewage treatment facilities in rural areas. This national standard requires the owner of the sewage treatment system to hold a "Warrant of Fitness" and prove that its sewage treatment system is in normal operation and maintenance. It also stipulates the management responsibilities of regional meetings (governments), system owners, and system inspectors. The regional meeting is responsible for evaluating and deciding the implementation area of the standard and for providing the information of the contractor and inspector of the sewage treatment system to the farmers. The system owner is responsible for ensuring that the "Warrant of Fitness" is held and for paying the expenses of facility operation and maintenance and inspection. The system inspector is responsible for checking whether the sewage treatment equipment meets the specified standards, deciding whether to issue a "Warrant of Fitness," and reporting to the regional meeting for filing.

6.4. Operation Mode of Rural Sewage Treatment Facilities in China

The operation and management of rural sewage treatment facilities in China have not yet formed a unified and effective model. However, relevant standards exist, and the corresponding operation and maintenance methods are given in the standards. For example, the Technical Standard for Rural Sewage Treatment Engineering (GB/T 51347-2019) prepared and issued by the Ministry of Housing and Urban-Rural Development, the local standard DB34/T 2297-2015 Integrated Device for Village and Town Sewage Treatment implemented in Anhui Province, and the industrial standards for the operation and management of sewage treatment facilities include CJJ/T 228 Evaluation Standard for the Operation Quality of Urban Sewage Treatment Plants, HJ 2038-2014 Technical Code for the Operation Supervision and Management of Urban Sewage Treatment Plants, CJ/T 355-2010 Complete Set of Small Domestic Sewage Treatment Equipment, and CJ/T 441-2013 Household Domestic Sewage Treatment Plant. The provinces and cities in China are also actively starting the demonstration research of the rural sewage treatment technology scheme. However, many problems exist, such as "emphasizing construction, neglecting management, and having money for construction but running without money." According to statistics [71], the effective operation rate of the established rural sewage facilities is less than 20% because of the lack of professional operation and maintenance personnel and sufficient operation and maintenance funds. Therefore, China can learn from the mature operation and maintenance model of rural sewage treatment facilities in other countries and combine them with its policy advantages. China should also actively develop professional operation and maintenance service teams and ensure the operation and maintenance funds.

These steps ensure that the rural domestic treatment facilities can continuously and stably give full play to their due efficiency.

7. Recommendation

At present, the use of decentralized integrated sewage treatment equipment for the efficient treatment of rural decentralized sewage has a broad prospect for rural sewage treatment in developing countries with diversified residential forms. However, the rapid development of integrated sewage treatment technology has led to problems and defects in practical application. The integrated rural sewage treatment technology started late in developing countries, and some problems that need to be improved still exist. The first point is that the investment and operation costs of integrated sewage treatment technology are relatively high. The second point is that professional personnel are needed for maintenance during operation. The third point is the lack of standards and norms for products related to integrated sewage treatment technology and environmental monitoring, thereby resulting in poor quality of related products, and disruption of the market. The fourth point is the lack of a sound management system for rural sewage treatment. A complete and comprehensive hierarchical management system is the guarantee for rural sewage treatment. Further improvements and developments in the following aspects are suggested to give full play to the wide application of integrated sewage treatment in rural areas in the future.

- (1) Process modules should be optimized to save energy and reduce consumption, enhance resource-based research and development, and reduce investment costs. Building a drainage pipe network is unrealistic for areas with scattered settlements far from the urban center. It has the advantages of a fast treatment rate, high efficiency, space saving, and flexible handling. The integrated sewage treatment equipment shows its high application space. However, compared with the traditional ecological sewage treatment technology, the integrated sewage treatment equipment has a relatively high investment and operation costs. Moreover, a certain pressure is present on the economic strength and environmental awareness of most farmers in underdeveloped or developing countries. A high effluent standard is indeed ideal, but it inevitably increases the process modules and energy consumption of integrated equipment. Therefore, the integrated equipment needs technological innovation. Reducing the production and operation cost of the equipment, optimizing the equipment process combination, reducing the number of modules, reducing the energy consumption of modules, and exploring and developing process modules or path methods that can be used as resources are important development directions in the future to ensure water quality.
- (2) An intelligent man–machine exchange remote management mode should be created. In the actual operation of integrated rural sewage treatment equipment, the core components of the equipment must be checked and repaired. The process parameters must be adjusted to ensure the stable operation of the equipment and the quality of the effluent. Regular on-site operation and maintenance of the equipment greatly increase the cost of transportation and human resources. If the Internet of Things technology is adopted to improve the automation and intelligence of integrated equipment, such as automatic optimization and adjustment of process parameters, fault early warning, and recovery, then the operation of equipment can be realized through the man–machine exchange function. The operation and maintenance cost of equipment can be greatly reduced as long as the instructions can be completed through mobile phone operation. Creating an automatic and intelligent technology management mode is an important aspect of reducing the cost of rural integrated treatment.
- (3) Standards and specifications for relevant products and environmental monitoring should be established. At present, the integrated sewage treatment lacks the standardization of technical products, resulting in the poor quality of equipment products, poor application effect, and even secondary pollution to the environment. Therefore,

the standardization of process technology through relevant standards and specifications must be urgently strengthened to improve the effective maintenance efficiency of equipment and the pollution control effect of equipment. Standardized environmental monitoring can comprehensively and truly reflect the performance and quality of integrated sewage treatment equipment. It can also effectively standardize the market, control products, and provide an important reference basis for users to select appropriate technical equipment. Therefore, standards and specifications for integrated product production, process technology, and environmental monitoring must be urgently issued.

- (4) A comprehensive risk identification and evaluation system and a hierarchical management system should be established. Rural sewage treatment systems are gradually promoted in most developing countries. However, the embarrassing situation of “able to build but unable to operate” exists. The quality of a large part of sewage treatment equipment cannot be guaranteed because it does not have a timely professional evaluation and management system. Lack of effective supervision mechanisms, weak basic support capacity of operation and maintenance management, and lack of effective evaluation and incentive mechanisms result in insufficient market development power. At present, most of the evaluation methods for sewage treatment are mainly aimed at the treatment water quality. However, the practical application process has many other factors, such as water quality, technology type, environmental conditions, and social influence. Moreover, the research is not deep enough. Therefore, the establishment of comprehensive risk identification and evaluation system methods, such as economic benefits, social benefits, and ecological benefits, and a hierarchical management system must be strengthened to promote the efficient application of integrated sewage treatment technology.

8. Conclusions

Rural sewage treatment has become the recommended focus of rural construction in developing countries. The continuous renewal and upgrading of the rural industrial economy in developing countries have diversified the rural areas and residential forms. Sewage treatment requires high hydraulic load and pollution load capacities. The traditional ecological treatment can no longer meet the requirements of sewage treatment; thus, integrated sewage treatment should be considered. In this study, the technical process, performance effect, and engineering applicability of the typical process module of the integrated sewage treatment are summarized. The findings show that the integrated sewage treatment process has high removal effect and impact resistance in nitrogen and phosphorus removal and organic degradation. Moreover, this treatment process can overcome the problems of traditional technology, including large floor area and matrix blockage. Choosing appropriate evaluation methods is conducive to the accurate identification of the application effect of integrated sewage treatment technology. Given the existing problems in integrated sewage treatment, the optimization and assembly of process modules, energy conservation and consumption reduction, the creation of intelligent management methods, and the formulation of standards and regulations are proposed as the key points of the integrated improvement in the future. This review will help the comprehensive understanding of the current development of integrated rural sewage treatment technology, evaluation methods, and operation modes. It will also help clarify the optimization and development direction of integrated rural sewage treatment technology in developing countries in the future.

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