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Construction of an evaluation system for the effectiveness of rural sewage treatment facilities and empirical research

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Introduction: Rural domestic sewage treatment is an important starting point to improve the quality of the rural ecological environment, an important part of new rural construction, and an inherent requirement to promote rural economic development. The operation of rural sewage treatment facilities is not good, and there is a lack of long-term operation guarantees and supervision mechanisms. It is urgent to carry out research on the evaluation index system, evaluation method, and evaluation benchmark of the operational effectiveness of rural sewage treatment facilities.

Methods: This article used rural sewage treatment facilities in a city in northern China as the research object and constructed an evaluation method for the operational effectiveness of rural sewage treatment facilities. This study selected evaluation indexes from three perspectives, namely, economy, technology, and management, which are divided into two stages, namely, planning and operation. A judgment matrix was constructed using the analytic hierarchy process (AHP), and index weights were calculated using Yaahp10.3 software to determine the evaluation criteria. Fifteen rural sewage treatment plant stations were selected to evaluate their planning and operation effectiveness.

Results: The results of the weight assignment show that the weight of the COD removal rate, operating load rate, and operating cost indexes are high, which is in line with the actual evaluation of the effectiveness of rural sewage treatment facilities at different stages. The empirical calculation results showed that the rural sewage treatment facilities have a comprehensive score of more than 80 points in 7 cases and 60–80 points in 8 cases, with an average score of 79.05 points; the overall performance of the score in the operation stage was better than that in the planning stage, and the overall operation effect was good.

Discussion: The calculation results were consistent with the actual operation, verifying the scientific nature and availability of the selected indices, the evaluation method constructed, and the evaluation benchmark determined. The research results can provide technical methods for evaluating the operational effectiveness of rural sewage treatment facilities in similar areas and provide technical support for the planning, design, optimization, upgrading, and transformation of rural sewage treatment plants.

KEYWORDS

ecological environment, rural sewage treatment facilities, index system, evaluation benchmark, operation effect, analytic hierarchy process, sustainable development

1 Introduction

Rural domestic sewage management is an important factor for improving the rural living environment, a significant livelihood project, a key measure for China to implement the "rural revitalization strategy," and an inherent requirement for building a moderately prosperous society in all aspects (Huang et al., 2020; Jiao et al., 2022; Zhou et al., 2023). The treatment of rural sewage has received increasing attention in recent years. Based on factors such as dispersion of populations (Chen et al., 2020), landform (Liu, 2020), and critical distance (Hu et al., 2021), researchers have discussed selecting rural sewage collection and treatment modes using life cycle assessment and economic analysis theory (Guan et al., 2020). The analytic hierarchy process (AHP) (Liu and Zhao, 2019; Wang, 2021), Delphi method (Xu et al., 2018; Wang et al., 2022), improved entropy weight TOPSIS model (Zhao et al., 2013), GA-BP model (Yu, 2012), and fuzzy merit coefficient method (Xu et al., 2017; Jin et al., 2021) and comprehensive methods such as the gray correlation TOPSIS comprehensive evaluation model (Cheng, 2014), subjective and objective comprehensive weighting method (Zhao et al., 2016), analytic hierarchy process–gray evaluation method (Shi et al., 2022), the group decision-making–analytic hierarchy process (Liu et al., 2023), and other integrated methods have been used to evaluate and optimize research on treatment technology. Scholars have also conducted discussions on multiple dimensions, such as process technology evaluation and optimization (Tian, 2021; Su, 2021; Xie et al., 2018; Zhang, 2022), operational effectiveness evaluation (Yuan, 2020; Cheng et al., 2020; Yang et al., 2021), maintenance supervision (Zhang et al., 2022), and process sustainability evaluation (Cao et al., 2015; Cui, 2022). Jiang et al. (2023) evaluated the suitability of rural sewage treatment facilities using the analytic hierarchy process and the technique for order preference by similarity to an ideal solution. Based on scenario analysis, Kalbar et al. (2012) evaluated the applicability of four common rural sewage treatment technologies in India under six scenarios. Cheng et al. (2020) used a data envelopment analysis model based on non-radial relaxation combined with cluster analysis to construct an index system and divided rural sewage treatment facilities into inefficient and efficient and classified and evaluated them. The existing research focuses on the evaluation and optimization of rural sewage treatment technology, and the research results provide strong technical support for the process selection in the planning and design stage of rural sewage treatment facilities. However, there are few reports on the evaluation of the operation effect of rural sewage treatment facilities, especially the classification and hierarchical evaluation of the treatment scale of sewage treatment facilities, the construction and operation time of the plant station, the receiving water body, the location, and other factors (Huang et al., 2020).

At present, the operation load rate of rural sewage treatment facilities is low, the operation effect of the facilities is poor, and there is a lack of long-term operational guarantees and supervision mechanisms (Huang et al., 2020). Therefore, there is an urgent need to study the evaluation index system, evaluation method, and evaluation benchmarks for rural sewage treatment facilities. On one hand, the evaluation methods and standards can support the effective implementation of national and local environmental protection industry-related policy planning. On the other hand, a standardized evaluation of facility operating effects can promote the high-quality and efficient operation of rural domestic sewage treatment facilities (Huang et al., 2020), improve the quality of the rural water environment, and improve the rural water ecological situation.

Based on the analysis of the planning, design, and operation of rural sewage treatment facilities in a city in North China, this paper selects 15 representative rural sewage treatment plants (stations and facilities) in terms of treatment scale, water purification process, and operation status. The economic, technical, and management indexes of the two stages of planning and operation are selected to construct the analytic hierarchy process evaluation model. The data on construction, operation, and inlet and outlet water quality in 5 years from 2018 to 2022 were collected. Empirical research on the comprehensive evaluation of rural domestic sewage treatment plants (stations and facilities) was carried out; through the analysis of the evaluation results, the successful experience of the project construction and the direction to be improved are summarized to provide a reference for ensuring the safety of rural drinking water and improving the rural living environment.

Our contributions can be summarized as follows:

(1) Few domestic and foreign studies have evaluated the operational effectiveness of rural sewage treatment facilities. This paper enriches the research content of the evaluation of the operation effect of rural sewage treatment facilities, combines the objectives and focuses of the different stages of concern of rural sewage treatment facilities, and constructs the evaluation index system with territorial characteristics.
(2) In this paper, the treatment scale of sewage treatment facilities, the construction and operation time of the plant station, the receiving water body, the area, and other factors are classified and hierarchical, and the operation effect of rural sewage treatment facilities is comprehensively evaluated, which enriches the research content of the operation effect evaluation of rural sewage treatment facilities.
(3) The research results were consistent with the actual operation, verifying the scientific nature and availability of the selected indices, the evaluation method constructed, and the

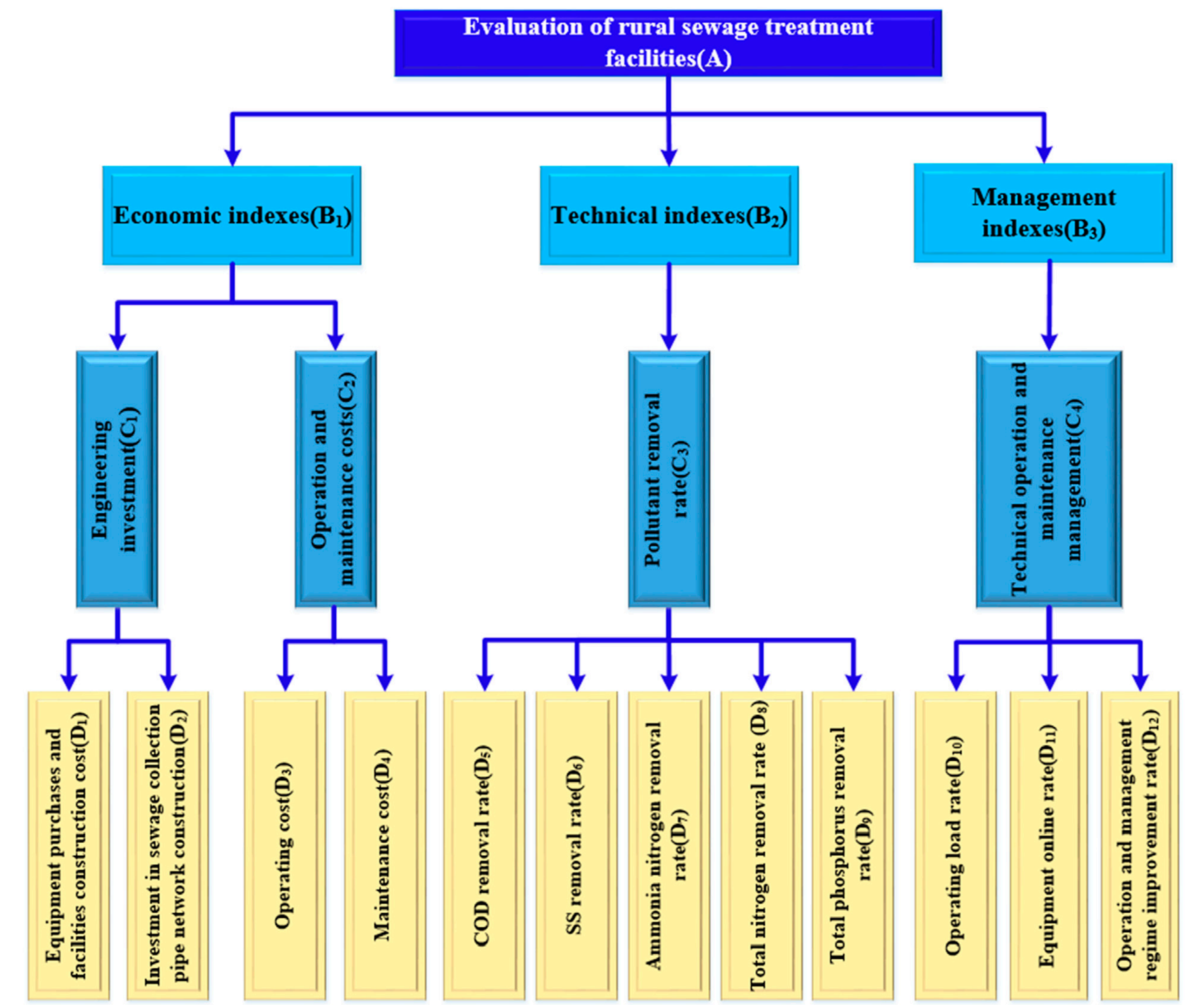

FIGURE 1
Rural sewage treatment facility operation effect AHP evaluation model and index system.

evaluation benchmarks determined; can provide technical support for the planning, design, optimization, upgrading, and transformation of rural sewage treatment plants and stations; and promote the high-quality and high-efficiency operation of rural domestic sewage treatment facilities.

2 Evaluation index system and AHP model construction

2.1 AHP evaluation model framework

The weight of each evaluation index was calculated using the analytic hierarchy process. AHP is a system planning method that was proposed by American logistics scientist T. L. Saaty in the mid-1970s. It is an objective, accurate, and effective method to obtain reasonable results by applying mathematical methods to combine qualitative and quantitative analyses in the decision-making planning process (Wang and Ma, 2022). This study referred to the evaluation index system of the operation effect of rural sewage treatment facilities at home and abroad based on a multivariate quantitative approach of the analysis hierarchical process combined with the goals and contents of the planning and operation management stages of rural sewage treatment facilities. Following the principles of feasibility, comparability, hierarchical optimization, independence, and development, and through extensive literature research, case analysis, and expert consultation, an evaluation index system with local characteristics was constructed, as shown in Figure 1. In the system, layer A is the target layer; layer B is the system layer, including 3 indicators; layer C is the guideline layer, including 4 indicators; and layer D is the indicator layer, including 12 indicators.

2.2 Evaluation indicators

The AHP evaluation index system for the operational effectiveness of rural sewage treatment facilities and its meanings are as follows:

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(1) Indicator 1: Equipment purchases and facility construction cost (D_1)

The cost of equipment and facility construction mainly includes civil engineering, equipment purchase, and installation costs. For different sewage treatment facilities, because of their different scales, the total investment in the project is quite different. For convenience of comparison, it is represented by the investment of equipment and facilities per unit sewage treatment capacity, with a unit of 10,000 yuan/ton, and Equation 1 is adopted:

$$W_1 = \frac{W_s}{Q}, \tag{1}$$

where W_1 represents the cost of rural sewage treatment facility purchases, 10,000 yuan/ton; W_s represents the total cost of equipment purchases, civil works, and installation of a rural sewage treatment facility, 10,000 yuan; and Q represents the daily sewage treatment capacity of rural sewage treatment facilities, ton/day.

(2) Indicator 2: Investment in sewage collection pipe network construction (D_2)

This investment refers to the construction cost of rural sewage collection pipelines and their auxiliary facilities (inspection wells, pump stations, etc.). The cost per unit of sewage collection pipe network represents the construction investment of the sewage pipe network, unit: yuan/meter, or the average construction investment of the village household pipe network is used, unit: 10,000 yuan/household. Equation 2 is adopted as follows:

$$W_2 = \frac{W_g}{L}, \tag{2}$$

where W_2 represents the construction cost of the rural sewage collection pipe network and its auxiliary facilities (inspection wells, pumping stations, etc.) in a village, yuan/m; W_g represents the total cost of construction of the rural sewage collection pipe network and its auxiliary facilities (inspection wells, pumping stations, etc.) in a village, yuan; and L represents the total length of the rural collection pipe network and its auxiliary facilities in a village, m.

Equation 3 is adopted as follows:

$$W_3 = \frac{W_g}{N}, \tag{3}$$

where W_3 represents the construction cost of the rural sewage collection pipe network and its auxiliary facilities (inspection wells, pumping stations, etc.) in a village, 10,000 yuan/household; W_g represents the total cost of construction of the rural sewage collection pipe network and its auxiliary facilities (inspection wells, pumping stations, etc.) in a village, 10,000 yuan; and N represents the number of the rural households in a village, household.

(3) Indicator 3: The power cost of equipment operation (D_3)

The operational power cost of rural sewage treatment facility equipment is one of the important factors in evaluating the operation effect of rural domestic sewage treatment facilities, mainly in terms of power consumption of all electricity-using equipment of sewage treatment facilities. For convenience of comparison, the electricity consumption of water treatment per ton is expressed as kWh/m^3, and Equation 4 is adopted as follows:

$$W_4 = \frac{KW}{Q_{day}}, \tag{4}$$

where W_4 represents the power cost of rural equipment operation in a village, kWh/m^3; KW represents the reading of electricity meter in a village, kWh; and Q_{day} represents the actual daily sewage treatment capacity of a village, m^3/day.

(4) Indicator 4: Maintenance cost (D_4)

The operation and maintenance costs mainly include the chemical consumption of the operation, the salary and welfare expenses of operation and maintenance personnel, the depreciation expenses of fixed assets, the equipment maintenance expenses, and the daily maintenance expenses, unit: yuan/ton. Equation 5 is adopted as follows:

$$W_5 = W_D + W_W + W_Q, \tag{5}$$

where W_5 represents the rural maintenance cost of a village, yuan/ton; W_D represents the overhaul cost of rural sewage treatment facilities and equipment of a village, yuan/ton; W_W represents the maintenance cost of rural sewage treatment facilities and equipment of a village, yuan/ton; and W_Q represents the other costs of rural sewage treatment of a village, yuan/ton.

(5) Indicators 5–9: Chemical oxygen demand (COD) removal rate (D_5), SS removal rate (D_6), ammonia nitrogen removal rate (D_7), total nitrogen removal rate (D_8), and total phosphorus removal rate (D_9).

The calculation method of indicators 5–9 involves determining the difference between the concentration of a certain pollutant at the inlet of the sewage treatment system and its concentration at the outlet. For example, the COD removal rate is the ratio of the COD removal amount in the influent of the sewage treatment system to the total COD in the influent. Equation 6 is adopted as follows:

$$\eta_P = \frac{P - P_1}{P} \times 100\%, \tag{6}$$

where η_P represents the pollutant removal rate of rural sewage treatment facilities in a village, %; P represents the influent content of pollutants in rural sewage treatment facilities in a village, mg/L; and P_1 represents the effluent content of pollutants from rural sewage treatment facilities in a village, mg/L.

(6) Indicator 10: Operating load rate of equipment and facilities (D_{10})

The operating load rate of rural sewage treatment facilities is the ratio between the actual sewage treatment capacity of the plant and the designed treatment scale of the facilities, and Equation 7 is adopted as follows:

$$\eta = \frac{Q_{day}}{Q_d} \times 100\%, \quad (7)$$

where η represents the operating load rate of the rural sewage treatment equipment and facilities in a village, %; Q_{day} represents the actual daily sewage treatment capacity of rural sewage treatment facilities in a village, m^3/day; and Q_d represents the designed daily sewage treatment capacity of rural sewage treatment facilities in a village, m^3/day.

(7) Indicator 11: Equipment online rate (D_{11})

The online supervision of rural sewage treatment facilities is an integral aspect of information construction. The equipment online rate is the ratio of the actual online time of equipment and the time that it should be online, and Equation 8 is adopted as follows:

$$\eta_Z = \frac{t_{day}}{t_d} \times 100\%, \quad (8)$$

where η_z represents the online rate of rural sewage treatment equipment in a village, %; t_{day} represents the actual online time of rural sewage treatment equipment in a village, h; and t_d represents the expected online time of rural sewage treatment equipment in a village, h.

(8) Indicator 12: Operation and management regime improvement rate (D_{12})

The operation and management regime improvement rate mainly evaluates four aspects: the establishment and implementation of the operation management system, the completeness of operation and maintenance records, the completeness of the plant environment and identification, and the establishment and implementation of the safety management system for third-party operation and maintenance unit operation management system for rural sewage treatment facilities.

3 Evaluation methodology and determination of indicator weights

3.1 Single-factor assessment

3.1.1 Economic indexes (B_1)

Indicator 1: Equipment purchases and facility construction cost (D_1).

Different treatment scales and effluent qualities have different purchase costs for the construction of plants, stations, or integrated facilities, and the evaluation benchmark value should be determined according to the relevant provisions of local government documents. The economic indexes of rural sewage treatment were divided into four grades according to 0–100 points. For indexes for which there is already a quota standard, they are divided directly by reference to the relevant data according to the linear interpolation method. The specific operations were as follows: those greater than the quota standard were unqualified, those less than the quota standard were excellent, the upper part of the quota standard interval was qualified, and the lower part was good. Experts in the rural sewage treatment industry are invited to refer to the construction cost of the plant and station and score the economic evaluation indexes. Then, we add up the grading values of each index of all experts to take the average value as the grading benchmark value of economic indexes for rural domestic sewage treatment scheme evaluation. For example, for facilities with a processing capacity greater than 500 m^3/d that are discharged into class II and III water bodies, assuming that the construction cost statistical value specified in local government documents is 4,500–6,000 yuan/ton, a score of 90 points was given for 4,500 yuan/ton. The lower the cost, the higher the score. One point was added for every 80 yuan/ton reduction. One hundred points were given for items below 3,700 yuan/ton, with a maximum score of 100 points. A score of 75–90 points was assigned between 4,500 (exclusive) and 5,250 (inclusive) yuan/ton. A total of 75 points was given for 5,250 yuan/ton, and 1 point was added for every 50 yuan/ton decrease. A score of 60–75 points was given between 5,250 (exclusive) and 6,000 (inclusive) yuan/ton, and 60 points were given for 6,000 yuan/ton. For each 50 yuan/ton decrease, 1 point was added. A score of 10 points was given if the price was above 10,000 yuan/ton, and 1 point was added for each decrease of 80 yuan/ton. The formula is shown in Equation 9:

$$F_{s1} = f_{s1} - \frac{(f_{s1} - f_{s2}) \cdot (f_{s3} - f_{s5})}{(f_{s4} - f_{s5})}, \quad (9)$$

where F_{s1} represents the total score of the index of the equipment purchases and facility construction cost, point; f_{s1} represents the highest score in the interval in which the actual equipment purchases and facility construction cost are located, point; f_{s2} represents the lowest score in the interval in which the actual equipment purchases and facility construction cost are located ($f_{s2} \geq 10$), point; f_{s3} represents the actual equipment and equipment purchases and facility construction cost, yuan/ton; f_{s4} represents the highest equipment purchases and facility construction cost in the interval in which the actual value is located, yuan/ton; and f_{s5} represents the lowest equipment purchases and facility construction cost in the interval in which the actual value is located, yuan/ton.

Indicator 2: Investment in sewage collection pipe network construction (D_2).

Investment in the construction of sewage collection pipe networks can be classified into two categories according to the relevant provisions of local government documents, namely, trunk pipe network and non-trunk pipe network, and the evaluation benchmark value can be divided according to the quota standard, as well as the allocation method of equipment purchase and facility construction cost. The other method is based on investment data collected from sewage pipe network construction. The specific calculation process is as follows: pipeline construction data were collected on a village basis, and the unit was converted into 10,000 yuan/household. Taking the 25th, 50th, and 75th percentiles of the sample as the interval points, the pipeline network construction investment is classified into four parts, as shown in Figure 2. A score below the 25th percentile (inclusive) was 90 points and above, and the lower the cost, the higher the score, with a maximum of 100 points. A score between the 25th (exclusive) and 50th percentiles (inclusive) is 75–90 points, and a score between the 50th (exclusive) and 75th percentiles (inclusive)

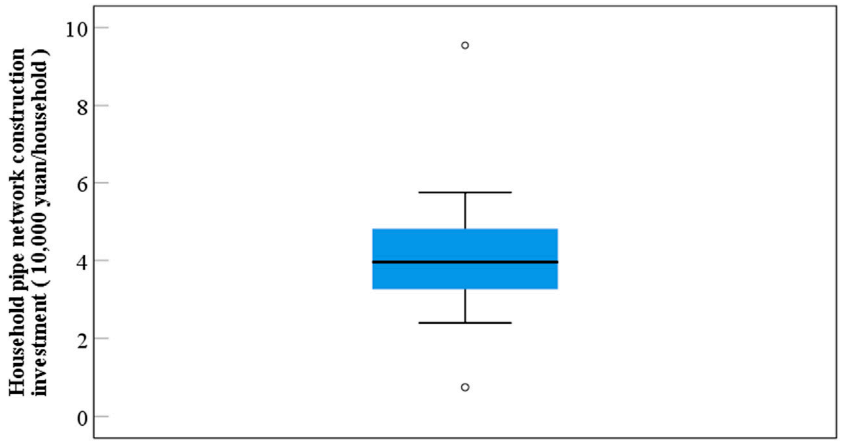

FIGURE 2
District sewage pipe network construction investment.

is 60–75 points. A score greater than the 75th percentile was less than 60 points. Assuming that the 25th percentile is 21,600 yuan/household, the 50th percentile is 29,100 yuan/household, the 75th percentile is 37,700 yuan/household, and 21,600 yuan/household will be given 90 points. For every decrease of 1,500 yuan/household, 1 point was added. Below 6,600 yuan/household, a score of 100 points is given. A score of 75–90 points was assigned for costs between 21,600 (exclusive) and 29,100 (inclusive) yuan/household, with 1 additional point for every decrease of 500 yuan/household. A score of 60–75 points was assigned for costs between 29,100 (exclusive) and 38,100 (inclusive) yuan/household, with 1 additional point for each decrease of 600 yuan/household. A score of 10 points was given for 93,100 yuan/household, and 1 point was added for each decrease of 1,100 yuan/household. The formula is shown in Equation 10:

$$F_{w1} = f_{w1} - \frac{(f_{w1} - f_{w2}) \cdot (f_{w3} - f_{w5})}{(f_{w4} - f_{w5})}, \tag{10}$$

where F_{w1} represents the total score of the investment index for sewage collection pipe network construction, point; f_{w1} represents the highest score in the interval in which the actual investment in sewage collection pipe network construction is located, point; f_{w2} represents the lowest score in the interval in which the actual investment in sewage collection pipe network construction is located ($f_{w2} \geq 10$), point; f_{w3} represents the actual investment in sewage collection pipe network construction, yuan/household; f_{w4} represents the highest investment in sewage collection pipe network construction in the interval in which the actual value is located, yuan/household; and f_{w5} represents the lowest investment in sewage collection pipe network construction in the interval in which the actual value is located, yuan/household.

Indicator 3: Power cost of equipment operation (D_3).

The evaluation benchmark for the equipment operating power cost is based on the second method of determining the investment in pipeline construction. Then, we assessed the operating electricity cost data of the rural sewage treatment plant stations in long-term operation in the area. The unit was uniformly converted into kWh/m^3 of sewage. Taking the 25th, 50th, and 75th percentiles of the sample as interval points, the construction investment was divided into four parts. A score below the 25th percentile (inclusive) was 90 points and above, and the lower the cost, the higher the score, with a maximum of 100 points. A score between the 25th (exclusive) and 50th percentiles (inclusive) was 75–90 points, and a score between the 50th (exclusive) and 75th percentiles (inclusive) was 60–75 points. A score greater than the 75th percentile was less than 60 points. The formula is shown in Equation 11:

$$F_{y1} = f_{y1} - \frac{\left(f_{y1} - f_{y2}\right) \cdot \left(f_{y3} - f_{y5}\right)}{\left(f_{y4} - f_{y5}\right)}, \tag{11}$$

where F_{y1} represents the total score for the index of the power cost of equipment operation, point; f_{y1} represents the highest score in the interval in which the actual power cost of equipment operation is located, point; f_{y2} represents the lowest score in the interval in which the actual power cost of equipment operation is located ($f_{y2} \geq 10$), point; f_{y3} represents the actual power cost of equipment operation, kWh/m^3; f_{y4} represents the highest power cost of equipment operation in the interval in which the actual value is located, kWh/m^3; and f_{y5} represents the lowest power cost of equipment operation in the interval in which the actual value is located, kWh/m^3.

Indicator 4: Maintenance cost (D_4).

The cost evaluation benchmark for the maintenance of plants, stations, integrated facilities, and pipe networks is based on the quota standard stipulated in local government documents, and the evaluation benchmark value is divided into the cost index of equipment purchases and facility construction.

3.1.2 Technical indexes (B_2)

Technical indexes include indicators 5–9: COD removal rate (D_5), SS removal rate (D_6), ammonia nitrogen removal rate (D_7), total nitrogen removal rate (D_8), and total phosphorus removal rate (D_9).

Rural sewage treatment technology focuses on five water quality indexes: SS, COD, ammonia nitrogen, total nitrogen, and total phosphorus. Taking the reference value of the excellent grade of COD as an example, this paper introduces the calculation method for grading the reference value of the pollutant COD removal rate evaluation index in technical indexes. This is according to the measured ratio of the difference between the influent COD concentration (mg/L) and effluent COD concentration (mg/L) to the raw water COD concentration. That is, (COD influent − COD effluent)/COD influent × 100%), and the percentage value of the removal rate is the score value. For example, a 90% score will be 90 points. The higher the treatment rate, the higher the score. If the discharged water body meets the relevant local or national standards, a score of 90 or more will be obtained, and the total score calculation process will be according to Equation 12. If the discharged water body does not meet the relevant local or national standards, the score will be between 40 and 50 points, and the total score calculation process will be according to Equation 13. The same applies to the other technical indexes.

$$F_1 = 90 + \eta_P/10, \quad (12)$$

$$F_2 = 40 + \eta_P/10, \quad (13)$$

where F_1 represents the total score of the discharge into the water body that meets relevant local or national standards, point; F_2 represents the total score of the discharged water body failing to meet relevant local or national standards, point; and η_P represents the pollutant removal rate of rural sewage treatment facilities in a village, %.

3.1.3 Management indexes (B_3)

Indicator 10: Operating load rate of equipment and facilities (D_{10}).

According to the evaluation benchmark of the sewage collection pipe network construction cost and equipment operation power cost, the 25th, 50th, and 75th percentiles were used as intervals to assign points.

Indicator 11: Equipment online rate (D_{11}).

The online rate of equipment was assigned according to the actual online rate, which is the online rate multiplied by 100 to equal the total score, with a score of 90 points for online 90% and 40 points for online 40%.

Indicator 12: Operation and management regime improvement rate (D_{12}).

The established operational management system and procedures were completed and implemented in place. The plant operated in a safe and stable manner. The operation manual was complete, in line with the actual plant, and guided the operation of the plant. There was a complete personnel training system and implementation. The technical regulations and monitoring methods complied with national and local standards and regulations. The records of water volume, water quality, online equipment condition, electricity consumption, chemical consumption, and sludge transportation and disposal during operation and maintenance were complete and detailed, and the records of equipment maintenance and replacement were clear. The factory environment was clean, with clear and complete signage and complete information. There was a complete safety management system, including a safety production system, accident reporting system, safety training system, safety operation regulations, and accident emergency response plan, which were complete and applicable to the actual situation of the factory and station. Points were assigned based on information and on-site conditions. The operation and management regime improvement rate multiplied by 100 equals the total score.

3.2 Determination of the index weight

The weight of each evaluation index is calculated using the index scale method. This method decomposes a complex problem into several levels and factors, compares evaluation indexes, determines the importance of each index, and establishes a judgment matrix. By calculating the maximum eigenvalues and corresponding eigenvectors of the judgment matrix, the weights of the different schemes are obtained, which provide a basis for choosing the best solution (Guo et al., 2008; Chen et al., 2021). The calculation process of the index weight was as follows.

3.2.1 Construction of the judgment matrix

The literature research and expert consultation methods were used to determine the interrelationships between different evaluation indicators in the decision-making objectives, and a total of six judgment matrices were constructed, namely, B_1–B_3, C_1–C_2, D_1–D_2, D_3–D_4, D_5–D_9, and D_{10}–D_{12}.

3.2.2 Judgment matrix assignment

Sewage treatment authorities, sewage treatment plants, and industry experts were invited to score the two-by-two relativities in the discriminant matrix based on the index scale method. According to the scale method of 1–9, the relative significance of each factor within a criterion layer is scaled, and the judgment matrix scale meaning is provided in Table 1.

Then, the judgment matrix A between the evaluation indexes can be expressed using Equation 14:

$$A = \left(a_{ij}\right)_{n\times n} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix}, \quad (14)$$

where n is the order of the matrix.

Analytic hierarchy process software (Yaahp10.3) is used to check the consistency of the judgment matrix, and the weight value W_i is calculated.

3.2.3 Consistency test

The consistency test is performed on each judgment matrix, and the consistency index CI is calculated using Equation 15:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (15)$$

where CI is the consistency index; λ_{max} is the largest eigenvalue of the matrix; and n is the number of indicators in the matrix, i.e., 1.

The average random consistency index (RI) was introduced, and the values are listed in Table 2.

On this basis, the consistency ratio (CR) is obtained, as shown in Equation 16:

$$CR = \frac{CI}{RI}, \quad (16)$$

TABLE 1 Relative importance scale method.

Scale	Meaning
1	The two factors are of equal importance compared with each other
3	Among the two factors, one is slightly more important than the other
5	Among the two factors, one factor is obviously more important than the other
7	Among the two factors, one factor is strongly more important than the other
9	Among the two factors, one factor is extremely more important than the other
2, 4, 6, and 8	Median of the two adjacent judgments
Reciprocal	There is a judgment a_{ij} of comparison between factors *i* and *j*, and then there is the judgment $a_{ij} = 1/a_{ij}$ of comparison between factors *j* and *i*

TABLE 2 Average random consistency index.

Matrix order	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

where *CI* is the consistency index; *RI* is the average random consistency index; and *CR* is the consistency ratio.

When CR = 0, the judgment matrix reaches complete consistency. The greater the CR, the worse its consistency. Generally, when CR < 0.10, the judgment matrix has satisfactory consistency; otherwise, the matrix must be readjusted until it meets CR < 0.10.

3.2.4 Weight calculation

3.2.4.1 Intra-level calculation

For the discriminant matrix that passes the consistency test, the sum–product method or square root method can be used to solve the judgment matrix. In this paper, Yaahp10.3 software was used to input the data of each discriminant matrix and obtain the corresponding relative weights of the six judgment matrices.

3.2.4.2 Comprehensive weight

According to the hierarchical modeling relationship given in Figure 1, the layer-by-layer calculation is used to obtain the results. The calculation formula is shown in Equation 17:

$$W_{Ai} = W_{Bi} \cdot W_{Ci} \cdot W_{Di}, \tag{17}$$

where W_{Ai} represents the combined weight of the ith indicator relative to the target layer; W_{Bi} represents the weight of the system layer where the ith indicator is located relative to the target layer; W_{Ci} represents the weight of the criterion layer where the ith indicator is located relative to the system layer; and W_{Di} represents the weight of the indicator layer in which the ith indicator is located relative to the criterion layer.

The results of the calculation of the relative and combined weights of the indicators at the system, guidelines, and indicator levels are shown in Table 3.

3.3 Comprehensive assessment

The method for evaluating the effect of rural sewage treatment facilities is based on national and local laws, regulations, and standards related to environmental protection and rural sewage treatment and is expressed by the comprehensive evaluation value of rural sewage treatment facilities (plants or stations). The comprehensive evaluation score is calculated using Equation 18:

$$L_i = \sum_{j=1}^{n} w_j l_{ij}, \tag{18}$$

where L_i represents the comprehensive evaluation score of the ith facility (plant or station), point; w_j represents the combined weight of the jth evaluation index, point; and l_{ij} represents the score of the jth index of the ith facility (plant or station), point.

3.4 Grading of evaluation

The comprehensive evaluation score of rural sewage treatment plants is high, indicating that the comprehensive effect of sewage treatment facility construction and operation is good. According to the actual situation of sewage treatment in the study area, the rural sewage treatment facilities (plants and stations) were divided into four grades: excellent, good, qualified, and unqualified. A score of <60 points was considered unqualified, 60–75 points were considered qualified, 75–90 points were considered good, and ≥90 points were considered excellent. The grading reference value of the effect evaluation index of rural sewage treatment facilities (plants or stations) was determined through statistical analysis based on relevant government documents and actual operation data.

Taking a rural sewage treatment facility in northern China as an example, 15 rural sewage treatment plant stations were randomly selected for evaluation. The design scale ranged from 24 to 1,000 m^3/d, of which more than 500 m^3/d accounted for 40%. Among the 15 treatment plant stations, 10 adopt a membrane treatment process, 3 adopt an activated sludge process, and 2 adopt a biofilm process. The relevant economic indicators, technical indicators, and management indicators are shown in Table 4. The number of levels is obtained (Table 5).

4 Results and discussion

4.1 Analysis of results

As shown in Table 3, the top four indexes that had significant influences on the evaluation results are the COD removal rate, operating load rate, operation cost, and maintenance cost. The COD removal rate is the most important factor in the operation of sewage treatment facilities, and the operating load rate and operation maintenance cost are also important evaluation indexes for the efficient operation of sewage treatment facilities, which all play a key role in the evaluation of sewage treatment facilities.

As shown in Table 5, 12 sewage treatment plants and stations scored more than 75 points, which is in the "good" level, 3 plants and stations scored between 60 and 75 points, which is in the "qualified" level, and no plants and stations were "unqualified," with an average

TABLE 3 Comprehensive weight.

Target layer	System layer	Relative weight (W_{Bi})	Criterion level	Relative weight (W_{Ci})	Indicator layer	Relative weight (W_{Di})	Comprehensive weight (W_{Ai})
Evaluation of rural sewage treatment facilities (A)	Economic indexes (B_1)	0.2941	Engineering investment (C_1)	0.1667	Equipment purchases and facility construction cost (D_1)	0.4000	0.0196
					Investment in sewage collection pipe network construction (D_2)	0.6000	0.0294
			Operation and maintenance costs (C_2)	0.8333	Operating cost (D_3)	0.5333	0.1307
					Maintenance cost (D_4)	0.4667	0.1144
	Technical indexes (B_2)	0.4706	Pollutant removal rate (C_3)	1.0000	COD removal rate (D_5)	0.2941	0.1384
					SS removal rate (D_6)	0.0882	0.0415
					Ammonia nitrogen removal rate (D_7)	0.2059	0.0969
					Total nitrogen removal rate (D_8)	0.1765	0.0831
					Total phosphorus removal rate (D_9)	0.2353	0.1107
	Management indexes (B_3)	0.2353	Technical operation and maintenance management (C_4)	1.0000	Operating load rate (D_{10})	0.5556	0.1307
					Equipment online rate (D_{11})	0.3330	0.0784
					Operation and management regime improvement rate (D_{12})	0.1111	0.0261

composite score of 79.05. Among the 15 sewage treatment plants, the NW plant had the highest comprehensive score, and the YF plant had the lowest comprehensive score. The technical indexes of the NW sewage treatment plant had great advantages in the entire evaluation index system, and the weight was the largest. All indexes scored above 65 points, which determined the optimal position of the NW plant. However, the YF sewage treatment plant had the highest operating cost, the indexes of the maintenance cost and total phosphorus removal rate were small, and the weight of the COD removal rate was the highest, which led to its poor score. Although the ammonia nitrogen removal rate and the SS removal rate were high, the comprehensive score could not be significantly changed.

4.2 Discussion

Among the 12 indicators, the equipment purchases and facility construction cost and the investment in sewage collection pipe network construction are the main factors considered in the planning stage, and the remaining 10 indicators are important considerations in the operation stage. According to the analysis, the stations with higher scores in the planning stage accounted for 53.33%, and the stations with lower scores accounted for 13.33%. The stations with higher scores in the operation stage accounted for 46.67%. The top four stations with high total scores are NW, XFY, SSY, and YL, and the last four stations with low total scores are MZ, QQ, TZT, and YF. The scores of YL, XFY, and NW stations in the planning and operation stages are high, which reflects the good continuity of planning, construction, and operation. Although the CS plant station has a low score in the planning stage, it makes up for the deficiency in the planning stage through effective management channels and means in the later operation. Both the planning and operation stages of the TZT plant and station have low scores. Although YF has a high score in the planning stage, it has a low score in the operation stage, and the score in the operation stage is higher than that in the planning stage. Both of them have not learned from the shortcomings of the previous planning stage, and the operation and maintenance management in the later stage is not in place, resulting in low total scores of the TZT and YF plant and station.

According to the evaluation results, the plants and stations with index scores below 60 were analyzed, the investment index scores of the sewage collection pipe network construction in six plants and stations (MST, CS, TZT, MZ, SSY, and DYZ) were low, and the plant stations accounted for 40%. Because the average investment in sewage collection pipe network construction in this area is 29,000 yuan/household, the actual cost is high (the investment

TABLE 4 Data characteristics of rural sewage treatment plant stations.

Indexes	Name of the indicator	Index classification	Number of plant stations
Economic indexes	Design scale of the sewage treatment station (m^3/d)	≥850	3
		500–850	3
		<500	9
	Sewage treatment process	Membrane treatment process	10
		Activated sludge process	3
		Biofilm process	2
	Equipment purchases and facility construction cost (yuan/ton)	≥20,000	1
		10,000–20,000	4
		5,000–10,000	5
		<5,000	5
	Investment in sewage collection pipe network construction (10,000 yuan/household)	≥4	6
		3–4	5
		<3	4
	Power cost of equipment operation (kWh/m^3)	≥4	3
		3–4	3
		2–3	3
		<2	6
	Maintenance cost (yuan/ton)	≥4	4
		3–4	1
		2–3	6
		<2	4
Technical indexes	COD removal rate (%)	≥90	10
		70–90	3
		<70	2
	SS removal rate (%)	≥90	9
		70–90	4
		<70	2
	Ammonia nitrogen removal rate (%)	≥90	12
		70–90	3
	Total nitrogen removal rate (%)	≥90	2
		70–90	6
		<70	7
	Total phosphorus removal rate (%)	≥90	11
		70–90	3
		<70	1
Management indexes	Operating load rate of equipment and facilities (%)	>120	2
		60–120	7
		<60	6

(Continued on following page)

TABLE 4 (*Continued*) Data characteristics of rural sewage treatment plant stations.

Indexes	Name of the indicator	Index classification	Number of plant stations
	Equipment online rate (%)	≥85	9
		<85	6
	Operation and management regime improvement rate (%)	≥85	12
		<85	3

TABLE 5 Comprehensive score of sewage treatment facilities.

Ordinal number	Name	Economic index score	Technical index score	Management index score	Comprehensive score	Rank	Level
1	ZJT	12.05	46.47	18.86	77.38	9	Good
2	MST	10.77	46.99	19.52	77.28	10	Good
3	BSW	11.65	41.75	22.63	76.03	11	Good
4	XBT	22.57	46.59	14.62	83.77	5	Good
5	CS	17.90	41.75	20.63	80.28	7	Good
6	QQ	9.44	45.48	19.69	74.61	13	Qualified
7	YL	20.59	46.53	17.22	84.34	4	Good
8	TZT	10.55	46.25	13.82	70.62	14	Qualified
9	YF	8.51	39.57	21.53	69.60	15	Qualified
10	MZ	18.26	46.53	10.68	75.47	12	Good
11	HFK	14.36	46.67	20.25	81.27	6	Good
12	SSY	20.09	46.52	18.03	84.64	3	Good
13	DYZ	20.94	45.91	12.04	78.89	8	Good
14	XFY	20.75	46.93	17.17	84.85	2	Good
15	NW	21.09	46.83	18.87	86.79	1	Good

cost of the pipe network is approximately 2.5 times that of the sewage treatment structure), so the score is low. Eight plants and stations (ZJT, MST, BSW, QQ, YL, TZT, YF, and SSY) had lower operating cost scores, with plant stations accounting for 53% of the total, which can optimize the operating parameters of existing treatment facilities, and the operation cost can be reduced by reducing energy consumption for sewage treatment and the rational use of chemicals (Wang, 2022; Hanafiah et al., 2024). The maintenance cost indexes of nine plants and stations (ZJT, MST, BSW, CS, QQ, TZT, YF, MZ, and HFK) were low, and the plant stations accounted for 60%. Therefore, it is necessary to do a thorough patrol inspection of equipment in time and carry out effective training for management personnel on equipment maintenance and use (Xiao, 2022) to reduce the accident rate of equipment, prolong its service life, and reduce maintenance costs. The proportion of plants and stations with less than 60 points in the above three indicators is more than 40%, which is in line with the *status quo* of rural domestic sewage treatment, characterized by large amount of investment and high operation and maintenance costs (Wang et al., 2023). Therefore, the focus should be on the economic indicators of sewage treatment, which can be achieved by adopting sewage treatment technologies such as low-cost, low-consumption resource recycling, easy maintenance, or reclaimed water reuse to realize environmental benefits and reduce the cost of rural sewage treatment.

There was a low ammonia nitrogen removal rate at the BSW and CS plant stations and a low total phosphorus removal rate at the YF plant station; the percentage of plant stations with high pollutant removal rate scores reaches 80%, and the overall score of technical indicators is high, which is in line with the actual operating condition of the sewage treatment plant, is a reflection of the emphasis on the outcome type of indicators in the process of evaluating the performance of the sewage treatment industry (Wei, 2022), and is also in line with the policy of the state to pay attention to the treatment and discharge of rural domestic sewage in recent years. For the stations with a low ammonia nitrogen removal rate, measures such as adding biological fillers, replacing aeration pipelines, increasing hydraulic retention time, and improving the intermittent aeration system can be taken to reduce the frequency of biofilm shedding, slow down the bubble rising speed and impact force, adjust the intermittent aeration time according to the actual situation, and ensure the full degradation of ammonia nitrogen pollutants. For the stations with a low total phosphorus removal rate, measures such as extending the process chain, increasing the sludge discharge frequency, and adjusting the sludge reflux ratio can be taken to regularly remove the sludge from the sedimentation tank, increase the biological filter or constructed wetland with phosphorus removal function, and select the filler with phosphorus removal function for the improvement of total phosphorus removal (Yuan, 2020). The process parameters of sewage treatment facilities in each station are optimized to maximize the operation effect of various sewage treatment facilities.

The low scores of four plants and stations (XBT, TZT, MZ, and DYZ) were due to the low or high operating load rate. Most of the plant stations with a load rate lower than 60% are those with a small treatment scale, which is consistent with the phenomenon of idle facilities (Qiu, 2016; Li and Xu, 2015). Therefore, for plants and stations with low operating load rates, the sewage pipe network construction should be improved to increase the sewage collection rate or optimize operating methods and reasonably design the scale of treatment facilities to ensure operating load rates. For the plant station with a high operating load rate, the scale of sewage treatment can be expanded, and the storage facilities can be appropriately constructed to optimize operating conditions.

The analysis of the evaluation results helps rural sewage treatment plants and their operating units to discover their own deficiencies, clarify the key contents of planning and design, operation and maintenance, optimization and transformation, and upgrading of rural domestic sewage treatment facilities, further improve operation and management capabilities, and promote the high-quality and efficient operation of rural sewage treatment plants and stations. It can also guide local governments in scientific decision-making and orderly deployment, avoid the possible blindness and "one-size-fits-all" problem in the work, and provide a reference for the region to promote categorization and effective governance. In addition, the evaluation of rural sewage treatment facilities can lead to the formation of good and bad stratification within the rural sewage treatment industry, and this stratification helps in promoting and establishing the rural sewage treatment industry incentive mechanism, encouraging the management and operational units to form pressure-driven, thereby fostering competition and promoting healthy development of the industry.

This study established a classification evaluation system for rural sewage treatment facilities based on the analytic hierarchy process. Due to the subjective nature of the hierarchical analysis method, it is recommended that the weights be assigned in the subsequent study in conjunction with the objective evaluation method. In addition, the indexes in this paper are based on references and case studies; taking into account the difficulty of obtaining data for the indexes, the selection of the indexes cannot completely cover the overall situation of the facilities due to the differences and complexity of rural sewage treatment. The future can be analyzed for a larger regional scope of rural sewage treatment facilities, improve the selection of the indexes, and enrich the index connotations. At the same time, the base value of the evaluation is determined according to local government documents and actual local conditions, and the results may not be applicable to all rural sewage treatment facilities. Therefore, it is possible to carry out and expand relevant studies in other rural areas in the future to enrich the criteria for the division of benchmark values and expand the scope of the extended evaluation.

5 Conclusion

This study constructed a classification and evaluation system for rural sewage treatment facilities, which included three criterion levels, namely, economic, technical, and management, and 12 indexes. Based on the analytic hierarchy process, the weight values of the indicators were determined in the planning and operation stages. Fifteen sewage treatment plants were verified, and the following points were concluded:

(1) Based on the established evaluation method, 15 sewage treatment plants were verified, and 60% of the plants were "good." The overall performance of the operation stage was better than that of the planning stage. The empirical calculation results were in line with the actual conditions, which is consistent with the focus on rural sewage treatment facilities at different stages. The evaluation method is scientific and reasonable, and the required data are easy to obtain and exhibit distinctive local characteristics.
(2) The average composite score for the 15 sewage treatment plant stations was 79.05, among which the indexes with higher scores were COD removal rate, ammonia nitrogen removal rate, and total phosphorus removal rate (12 plants and stations were above 90 points), while the indexes with lower scores were maintenance cost (9 plants and stations were below 60 points) and operating cost (8 plants and stations were below 60 points). This indicates that rural sewage treatment plants and stations can effectively remove pollutants. However, it is still necessary to further reduce the cost, strengthen inspection and maintenance, optimize operation parameters, reduce the accident rate, reduce power consumption, and reduce the operation and maintenance costs.
(3) The evaluation method, selected indexes, and determined evaluation benchmark of rural sewage facilities based on AHP are scientific and reasonable, and the evaluation results are in line with local conditions, which play an auxiliary role in industry supervision and management and promote the high-quality and efficient operation of rural domestic sewage treatment facilities. However, the evaluation benchmark value in this paper is determined according to local government documents and actual local conditions. The results may not be applicable to all rural sewage treatment facilities, and the analytic hierarchy process is subjective. In the follow-up study, the objective evaluation method can be used to calculate the weight, enrich the relevant research in other rural areas, and explore the long-term sustainability of sewage treatment facilities. The effective treatment of rural domestic sewage reduces the discharge of pollutants, reduces harm to aquatic organisms, enhances the quality of the rural water environment, improves sanitary conditions in rural areas, improves the utilization of water resources, promotes rural ecological revitalization, and facilitates the construction of an

ecologically pleasant and beautiful countryside. Simultaneously, a beautiful rural environment can promote the development of farm caravans and tourism, increase economic income for villagers, and promote the sustainable development of the local economy.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YH: conceptualization, project administration, and writing–original draft. LY: software and writing–original draft. HX: data curation, project administration, and writing–original draft. XH: conceptualization, methodology, and writing–original draft. CS: formal analysis, investigation, resources, and writing–original draft. YD: conceptualization, data curation, and writing–review and editing. TZ: conceptualization, funding acquisition, project administration, resources, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Cao, X. Q., Zhang, N., and Lv, X. F. (2015). Sustainability evaluation of rural sewage treatment process based on energy analysis. *Chin. J. Environ. Eng.* 9, 5447–5454. doi:10.12030/j.cjee.20151150

Chen, J., Wang, C., Wang, P. F., Hu, B., Li, X. J., and You, G. X. (2020). Choice of rural domestic sewage treatment mode based on dispersion degree of rural resident. *China Water & Wastewater* 36, 81–88. doi:10.19853/j.zgjsps.1000-4602.2020.23.014

Chen, T. T., Peng, Y. M., Gao, Y. L., Zhong, Y. P., and Pan, Z. C. (2021). Study on comprehensive efficiency of municipal sewage treatment plant based on analytic hierarchy process. *Water & Wastewater Eng.* 57, 81–85. doi:10.13789/j.cnki.wwe1964.2021.S2.015

Cheng, P. P., Jin, Q., Jiang, H., Hua, M., and Ye, Z. (2020). Efficiency assessment of rural domestic sewage treatment facilities by a slacked -based DEA model. *J. Clean. Prod.* 267, 122111. doi:10.1016/j.jclepro.2020.122111

Cheng, X. H. (2014). Study on the evaluation of comprehensive performance of rural domestic sewage treatment process based on the Grey correlation-TOPSIS model. Master's thesis, China (Shanghai Province): East China Normal University.

Cui, T. (2022). Optimization of rural sewage treatment model in China, based on coupled model of life cycle sustainability assessment and multi-criteria decision analysis. Master's thesis. China (Shandong Province): Qingdao University.

Guan, R., Huang, Y. S., and He, Y. L. (2020). Environmental and economic comparative analysis of *in-situ* and decentralized domestic sewage treatment modes in rural areas of Hekou Islands. *Acta Sci. Circumstantiae* 40, 1894–1901. doi:10.13671/j.hjkxxb.2019.0461

Guo, J. Y., Zhang, Z. B., and Sun, Q. Y. (2008). Research and application of analytic hierarchy process. *China Saf. Sci. J.* 5, 148–153. doi:10.16265/j.cnki.issn1003-3033.2008.05.018

Hanafiah, M. Z., Mohtar, W. M. H. W., Mohtar, W. I. Q. A. A. W., Bithi, S. A., Rohani, R., Indarto, A., et al. (2024). Removal of pharmaceutical compounds and toxicology study in wastewater using Malaysian fungal Ganoderma lucidum. *Chemosphere* 358, 142209. doi:10.1016/j.chemosphere.2024.142209

Hu, M., Wang, P. J., Qiu, Y. Z., Xiao, J. Y., Yan, Y. L., and Yang, L. Q. (2021). Research on the optimal selection of domestic sewage treatment modes based on economic evaluation in rural plain areas of Beijing. *Acta Sci. Circumstantiae* 41, 133–142. doi:10.13671/j.hjkxxb.2020.0504

Huang, J., Wang, J. A., Zhao, X. L., Lin, L., Zhang, X. X., and Wei, W. L. (2020). Research on the technical standard of operation performance assessment for rural domestic sewage treatment facilities. *Stand. Sci.* 7, 104–109. doi:10.3969/j.issn.1674-5698.2020.07.018

Jiang, J. P., Hu, X., Gu, Y., Wang, W. Z., Bi, Z. S., Yao, C. S., et al. (2023). Suitability evaluation of rural sewage treatment facilities in China considering lifcycle environmental impacts and regional differences. *J. Environ. Manag.* 344, 118516. doi:10.1016/J.JENVMAN.2023.118516

Jiao, J., Yang, Z. H., Zhang, Y., Shi, B. Y., Dogot, T., and Yin, C. B. (2022). Are farmers willing to pay for centralized mode provision of rural domestic sewage treatment? A large-scale assessment in North China. *Front. Environ. Sci.* 10. doi:10.3389/fenvs.2022.861871

Jin, H. F., Cheng, M., Shi, P., and Jin, J. W. (2021). Optimization and evaluation of rural domestic sewage technology in Shaoxing Keqiao district. *Water & Wastewater Eng.* 57, 183–188. doi:10.13789/j.cnki.wwe1964.2021.S2.034

Kalbar, P. P., Karmakar, S., and Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. *J. Environ. Manag.* 113, 158–169. doi:10.1016/j.jenvman.2012.08.025

Li, X. F., and Xu, J. Q. (2015). Reflections on the widespread idleness of Beijing's rural sewage treatment facilities (Ⅰ). *Water & Wastewater Eng.* 51, 48–50. doi:10.13789/j.cnki.wwe1964.2015.0191

Liu, G. L. (2020). Study on the evaluation and technology selection of rural domestic wastewater treatment efficiency in the northeast cold region. master's thesis. China (Jilin Province): Jilin University.

Liu, J. W., and Zhao, G. H. (2019). AHP-based evalution on applicability of typical rural sewage treatment technology in Beijing. *Water Resour. Hydropower Eng.* 50, 260–267. doi:10.13928/j.cnki.wrahe.2019.05.031

Liu, L., Zhang, W. Q., Hu, F. C., Pang, K., Guo, Y. L., Zhang, T., et al. (2023). Evaluation and optimization of rural sewage treatment technologies in the middle reaches of the yangtze river based on group decision making and analytic hierarchy process. *Environ. Sci.* 44, 1191–1200. doi:10.13227/j.hjkx.202203043

Qiu, Y. Z. (2016). Investigation of status of Beijing rural sewage treatment facilities and research on operation management measures. Master's thesis. China (Beijing Province): Beijing University of Chemical Technology.

Shi, S. Q., Wang, P. J., Hu, M., and Liu, J. W. (2022). Evaluation of Beijing rural sewage treatment technology in based on analytic hierarchy process-grey relation analysis. *Acta Sci. Circumstantiae* 42, 13–21. doi:10.13671/j.hjkxxb.2021.0535

Su, G. L. (2021). Research on applicability of decentralized rural sewage treatment technology in Doumen District. Master's thesis. China (Guangdong Province): Guangzhou University.

Tian, Y. (2021). Research on adaptability technology of typical urban and rural sewage treatment. master's thesis. China (Shaanxi Province): Xi'an University of Architecture and Technology.

Wang, C. S. (2021). The AHP about rural domestic sewage treatment techniques in different regions: taking Xinjiang Uygur Autonomous Region as an example. *Environ. Impact Assess.* 43, 61–65. doi:10.14068/j.ceia.2021.02.014

Wang, D., and Ma, S. C. (2022). Establishment of post-legislative evaluation index system of Construction Law based on analytic hierarchy process. *J. Beijing Univ. Civ. Eng. Archit.* 38, 96–102. doi:10.19740/j.2096-9872.2022.06.11

Wang, L. X. (2022). Analysis of digital operation of rural sewage treatment system in big data environment by discrete dynamic modeling technology. *Front. Energy Res.* 10. doi:10.3389/FENRG.2022.931031

Wang, P. J., Meng, Q. Y., Xiao, J. Y., Hu, M., Zhao, R., Yan, Y. L., et al. (2022). Optimization of rural domestic wastewater treatment technology based on Delphi method and scenario analysis in Beijing. *Acta Sci. Circumstantiae* 42, 22–29. doi:10.13671/j.hjkxxb.2021.0524

Wang, S. Y., Gong, Z., Wang, Y. C., Cheng, F. K., and Lu, X. W. (2023). An anoxic-aerobic system combined with integrated vertical-flow constructed wetland to highly enhance simultaneous organics and nutrients removal in rural China. *J. Environ. Manag.* 332, 117349. doi:10.1016/J.JENVMAN.2023.117349

Wei, X. X. (2022). *Research on performance evaluation of urban sewage treatment plant*. Master's thesis. China (Beijing Province): North China University of Technology.

Xiao, X. (2022). Evaluation of operation cost control of urban sewage treatment plants in China. *Mod. Salt Chem. Industry* 49, 111–112. doi:10.19465/j.cnki.2095-9710.2022.05.021

Xie, L. H., Wu, D. L., and Zhang, Y. L. (2018). Analysis and evaluation of China's rural domestic sewage treatment technology. *J. Ecol. Rural Environ.* 34, 865–870. doi:10.11934/j.issn.1673-4831.2018.10.001

Xu, H. F., Wang, X. Y., and Kuang, W. (2018). Applicability assessment of rural domestic wastewater treatment technology in typical areas of Anhui Province. *J. Anhui Agric. Sci.* 46, 191–195. doi:10.13989/j.cnki.0517-6611.2018.19.055

Xu, R. L., Han, B., Yu, R., and Bu, X. Q. (2017). Comprehensive evaluation of rural sewage treatment technology in Guangxi. *J. Guilin Univ. Technol.* 37, 354–359. doi:10.3969/j.issn.1674-9057.2017.02.018

Yang, F. L., Zhang, H. R., Zhang, X. Z., Zhang, Y., Li, J. H., Jin, F. M., et al. (2021). Performance analysis and evaluation of the 146 rural decentralized wastewater treatment facilities surrounding the Erhai Lake. *J. Clean. Prod.* 315, 128159. doi:10.1016/J.JCLEPRO.2021.128159

Yu, J. (2012). The study of rural sewage treatment plan optimization based on GA-BP. master's thesis. China (Wuhan Province): Huazhong University of Science and Technology.

Yuan, P. (2020). Current operating status and diagnostic evaluation of rural domestic sewage treatment facilities in Zhejiang Province. Master's thesis. China (Zhejiang Province): Zhejiang University.

Zhang, K. K., Lei, M. J., Kong, W. Z., Yang, Z. M., Yi, X. H., and Long, Y. (2022). Design and application of rural sewage intelligent monitoring system based on internet of things technology. *Technol. Innovation Appl.* 12, 113–116. doi:10.19981/j.CN23-1581/G3.2022.36.025

Zhang, S. (2022). Research on the evaluation of rural domestic wastewater treatment technology based on AHP—fuzzy comprehensive evaluation method——a case from Z Town in L County. Master's thesis. China (Wuhan Province): Yunnan Normal University.

Zhao, B., Wu, X. H., Wang, Q., and Qin, J. (2016). Technique effect evaluation for treatment of rural domestic sewage from the north shore of Fuxian Lake based on Fuzzy Integral model. *J. Yuxi Normal Univ.* 32, 22–26. doi:10.3969/j.issn.1009-9506.2016.12.005

Zhao, L. P., Zhang, F. E., Dong, L. F., and Tu, B. H. (2013). Application of improved entropy weight TOPSIS model in optimization of rural sewage treatment technology. *Water Sav. Irrig.* 12, 52–54+58. doi:10.3969/j.issn.1007-4929.2013.12.014

Zhou, C., Yu, Z. H., and Wang, Q. (2023). Analysis of temporal and spatial changes and influencing factors of sewage treatment rates of small towns in Chongqing. *Front. Environ. Sci.* 11. doi:10.3389/FENVS.2023.1066371